Discover Sustainability

Review

Climate change and its effects on poultry industry and sustainability

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Abstract
By 2050, the need for poultry products is predicted to quadruple globally, mostly as a result of rising living standards. In the meantime, the quality of feed crops and forage, availability of water, poultry diseases, and poultry reproduction are all threatened by climate change, which poses a challenge to poultry production. This analysis assesses the effects of climate change on poultry production globally, the role that poultry production plays in climate change, and the particular tactics used by the poultry industry to adapt to and mitigate the effects of climate change. Climate variability will limit poultry production because it will raise the amount of water that chickens consume by a factor of three, increase the demand for agricultural lands due to the significant rise in production, and raise concerns about food security. After all, approximately one-third of the world's cereal harvest is used to feed animals, including poultry. In the meantime, 8% of the livestock sector's emissions of greenhouse gases (GHG) come from the poultry industry, which accelerates climate change. As a result, the poultry industry will play a significant role in reducing greenhouse gas emissions and enhancing global food security. Therefore, assessments of the application of adaptation and mitigation measures specific to the region and poultry production system in use, as well as policies that encourage and facilitate the implementation of these measures, are necessary for converting to sustainable poultry production.

Keywords Climate change · Greenhouse gas · Heat stress · Mitigation · Poultry

1 Introduction

In many developing nations, poultry is a major source of food, income, and cultural identity for rural people—poultry birds, including ostriches, ducks, turkeys, and chickens. In comparison to other domestic animals, they provide economic services as well as a substantial contribution to the human diet as a key source of meat, eggs, raw materials for industries (feathers, waste byproducts), and a source of revenue and employment for humans [1]. This demonstrates the significant role that the poultry subsector has in the livestock industry. Chicken farming is a significant industry in the nation's food production, giving chicken producers financial stability. Poultry has been popular

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among small-holder farmers who have boosted the nation's economy, so its significance to the economy cannot be overstated [2]. In a short amount of time, poultry are effective converters of grain into eggs and meat. Poultry eggs are ranked second in terms of nutritional value [3], after cow milk. According to a consensus among agriculturists and nutritionists, expanding the chicken sector in many developing nations is the quickest way to close the current gap in protein deficit [4]. Raising chickens is negatively impacted by extremely high or low temperatures. Due to a worldwide shift in the climate, this influence has increased [5].

Ayoade [6] defined climate as the average atmospheric status of a place or region during a specified 30-year period. Nevertheless, according to Agboola et al. [7]and Ault [8], climate change is a substantial difference among two mean climatic situations or conditions of climate that have a major effect on the environment. It covers both anthropogenic and natural change. In addition to natural climate variability seen over comparable periods, the United Nations Framework Convention on Climate Change (UNFCCC) specified climate change as a change in climate that is attributed, either directly or indirectly, to human activity that modifies the composition of the global atmosphere [9]. Variability in the climate encompasses changes in the average condition of the climate as well as additional statistics (such as standard deviations, the frequency of extreme occurrences, etc.) over all temporal and spatial scales, extending beyond the scope of individual weather events.

This definition makes it clear and intelligible that climate change is an innate and essential feature that is brought about by both natural and human-caused processes. The emissions of greenhouse gases (GHG) such as carbon dioxide (CO2), methane (NH4), nitrogen oxide (N2O), and other gases are to blame for the change in the composition and structure of the atmosphere. Numerous human activities, including inadequate environmental sanitation, deforestation, bush burning, borehole drilling, fuel combustion, and cement production, are responsible for global climate change [10]. However, it has been predicted that Sub-Saharan Africa's poultry output will be most affected by climate change [11]. Thus, reducing the negative effects of extreme weather and adapting to it has been crucial in reducing the impact of climate change on poultry [12]. Without a doubt, the productivity of chicken eggs will be impacted by climate change in many parts of the world. Weather extremes, such as intense heat waves, droughts, and floods, are a problem for cattle. Poultry deaths result from acute events such as disease or infection attacks in addition to output deficits [13]. Climate change manifests as rising temperatures that cause relative humidity to drop and offer an ideal environment for the growth of bacteria and fungi. Diseases include coccidiosis, poultry typhoid, hemorrhagic syndrome, chronic respiratory disease, chicken pox, and bronchitis, which will, therefore, grow as an epidemic of disease becomes unavoidable [14]. According to Rowlinson [15], a small temperature shift will cause a decrease in the rate at which poultry birds consume feed, which would result in subpar performance. Thermos-Neutral Zone (TNZ) is the ideal temperature range for animal growth, development, and comfort; it varies depending on the species, age, and physiological stature of the cattle, relative humidity, and other factors. Livestock in TNZ has the highest level of output and the best feed conversion efficiency. Low temperatures will cause poultry birds to consume more feed in order to meet their increased needs for energy and maintenance of vigor. Outside of the TNZ, extreme temperatures that cause heat stress in cattle can lead to limited feed intake, a drop in egg production, a high death rate, and low reproduction. One of the biggest obstacles to attaining the best possible results for chicken growth and production is the changing climate. It upsets the delicate equilibrium of environmental elements required for the genetic potential of poultry to be expressed. Therefore, it is essential to comprehend and mitigate how climate change affects chicken production in order to guarantee security of food and sustainability [16]. Finally, the purpose of this review is to clarify the difficulties encountered by the chicken business and investigate possible paths toward resilience and sustainable operations. In the end, mitigating the effects of climate change and maintaining the long-term viability of poultry production depend on an understanding of these dynamics.

In conclusion, climate change significantly impacts the poultry industry, affecting production efficiency, animal health, and sustainability. Rising temperatures, water scarcity, and climate-induced diseases pose challenges to maintaining poultry health and productivity. This paper will discuss various sections, beginning with an overview of climate change and its direct impact on poultry production, followed by a detailed analysis of water scarcity, carbon footprint, and gene expression adaptations in poultry. It will then explore practical mitigation strategies, such as improved housing, nutritional adjustments, and genetic approaches, that can enhance poultry resilience to climate stress. Lastly, the paper will look into future directions for sustainable poultry production, including technological advancements, policy implications, and collaborative efforts toward climate-conscious practices. Through these comprehensive sections, we aim to provide insights into how the poultry industry can adapt and thrive in the face of climate change, ensuring sustainability for future generations.

1.1 Methodology

This review paper utilizes a systematic approach to gather, analyze, and synthesize existing literature on climate change and its effects on the poultry industry. The methodology section outlines the data collection methods and statistical approaches employed to ensure a comprehensive and objective analysis.

1.2 Data collection

Data for this review were gathered from peer-reviewed articles, industry reports, government publications, and databases including PubMed, Scopus, and Web of Science. The following steps were taken in the data collection process:

- *Inclusion criteria* studies included were published between up to 2024, focused on climate change's impact on poultry production, and addressed areas such as heat stress, water scarcity, greenhouse gas emissions, and sustainable farming practices.
- *Search Terms* keywords like "climate change," "poultry industry," "heat stress in chickens," "sustainability in poultry farming," "water scarcity," and "greenhouse gas emissions in poultry" were used to identify relevant articles.
- *Screening process* An initial screening was conducted based on the title and abstract to identify relevant studies. Full-text articles were further reviewed to ensure relevance to the research questions posed in the paper.
- *Data Extraction* Key data related to the effects of climate change on poultry production, mitigation strategies, and sustainability were extracted, categorized, and documented in a structured format.

1.3 Statistical analysis

The following statistical tools and techniques were used to assess the impact of climate change on the poultry industry:

- *Descriptive statistics* Basic descriptive statistics, such as averages and percentages, were calculated to summarize data trends related to rising temperatures, changes in poultry production, water usage, and greenhouse gas emissions.
- *Trend analysis* Time-series data from reports and studies were analyzed to observe trends in poultry production, egg and meat output, water consumption, and mortality rates in response to climate variability over time.
- *Comparative analysis* Comparative methods were used to assess differences in production rates, carbon emissions, and resource consumption in poultry farms adopting sustainable practices versus traditional methods.
- *Graphical representation* Charts and graphs were generated to visualize the trends in water usage, greenhouse gas emissions, and the effects of heat stress on poultry performance, using data from various sources. These visualizations help communicate key insights and support findings discussed in the paper.

1.4 Trends and variations in the number of birds and production of broiler meat

Egg-laying hens and broiler chickens are the two main varieties of chickens raised worldwide. As their names imply, one is raised for meat, while the other produces eggs. With an astounding 584 billion eggs produced in 2022, China led the world in egg production. Conversely, Indonesia, the second-largest producer, managed to produce a mere 132 billion eggs during that same year [17]. Additionally, poultry has surpassed pigs in recent years to become the most-produced meat variety globally [18]. With an estimated 21.3 million metric tons of broiler meat produced in 2023, the United States leads all other nations in this regard. In terms of the production of broiler meat, Brazil and China ranked second and third, with 14.9 million and 14.3 million metric tons, respectively [19].

Because of the great demand for chicken meat and the climate's potential for year-round farming, broiler production is especially important [20]. Because of its shorter production cycle, higher acceptance, and the poultry industry's explosive expansion in recent years, the production of chicken meat and eggs contributes significantly to the world's protein needs. The Food and Agriculture Organization of the United Nations reports that during the past few decades, chicken populations and meat output have grown dramatically worldwide (Fig. 1, 2) Figs. 1 and 2 present global data on poultry populations and chicken meat production in 2022. Figure 1 shows the total number of poultry birds worldwide, while Fig. 2 illustrates chicken meat production measured in tons annually. The data for both figures are sourced from the Food and Agriculture Organization of the United Nations (FAO). According to Oke et al. [16], there could be several reasons for the sharp rise in broiler production in developing nations, including their fast-expanding populations, increased

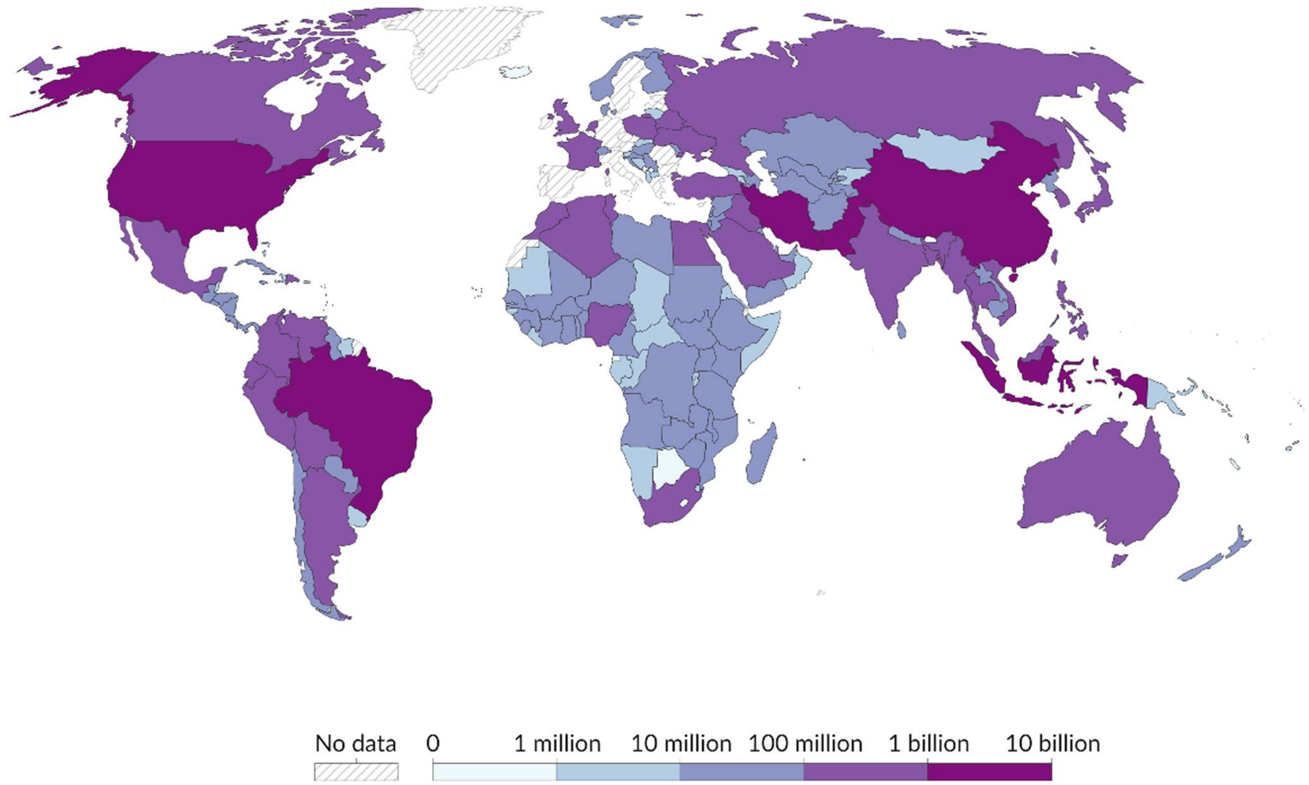
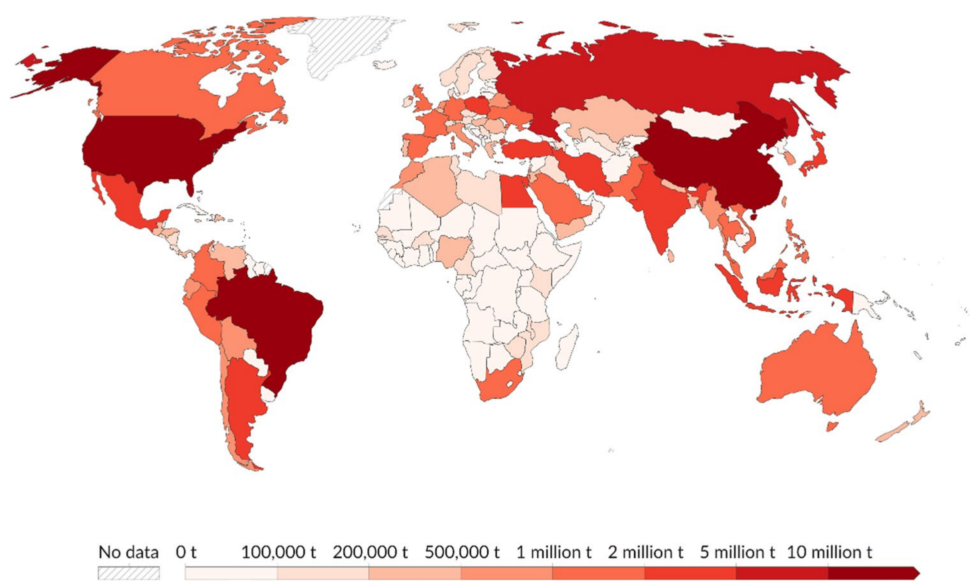


Fig. 1 Number of poultry birds worldwide in 2022. Source: Food and Agriculture Organization of the United Nations

Fig. 2 Production of chicken meat worldwide in 2022 (measured in tons annually). Source: Food and Agriculture Organization of the United Nations



urbanization and industrialization, investment in order to meet the demand for protein, extensive and vertically connected production systems, industrialization of the poultry industries into large enterprises, and the improved genetic potential of contemporary broilers.

Figure 1 (Global Chicken Population, 2022): The map illustrates the global distribution of chicken populations, with darker purple indicating higher numbers. Major chicken-producing countries include China, the United States, Brazil, and India, each with over 1 billion chickens. Other significant producers are spread across Asia, Latin America, and North America, while many African and European nations have smaller chicken populations.

Figure 2 (Global Broiler Meat Production, 2022): This map shows global broiler meat production, represented by shades of red, with the United States, Brazil, and China leading the world, producing over 10 million tons of broiler meat annually. Other countries like India, Mexico, and Russia also contribute significantly to the global broiler supply, producing between 2 and 5 million tons annually. Smaller producers are concentrated in Africa and Europe. Both figures highlight a strong correlation between regions with large chicken populations and high broiler meat production, emphasizing the significant role these regions play in global poultry supply.

1.5 Water scarcity

Water resources are under pressure because of the rapidly expanding global chicken meat industry because livestock production uses a lot of water. Roughly one-third of all water used in agricultural agriculture worldwide is used for animal production. the major use of water for producing livestock is growing feed [21]. A water metric measurement called "water footprint" (WF) has been used to precisely calculate the amount of water utilized in proportion to final products. Mekonnen and Hoekstra [22] state that 4300 L of water is needed for every kilogram of chicken meat. WF is, therefore, a useful instrument for animal production's sustainable freshwater management. The earth's temperature is rising by 0.2 °C every decade due to climate change, and there are notable variations in both the amount and the distribution of rainfall. Heat waves and water scarcity, thus, may have an impact on the health, welfare, and productivity of poultry in the future [23]. The amount of water that chickens need on a daily basis depends on a number of parameters, including performance level, housing circumstances (temperature, light intensity, schedule, etc.), and feeding-related aspects (type and components). A summary of some of the variables that may impact chicken water consumption may be found in Fig. 3. Particularly in dry and semi-arid areas, the effects of water shortages may pose a future threat to the growth of backyard and industrial chicken production. In certain parts of the world, limits or shortages of water may also make it more difficult to achieve food security. Chicken water consumption is influenced by several factors that are critical for maintaining health and productivity. Ambient temperature plays a significant role, with higher temperatures and heat stress leading to increased water intake for cooling. Production levels also affect consumption, as growing broilers and layers need more water to support growth and egg production. Diet composition, such as high-protein and sodium-rich feed, raises water needs, while dry feed requires more water for digestion. Housing conditions, including poor ventilation, overcrowding, and high humidity, increase water intake as birds struggle to regulate their temperature. Longer light schedules extend activity and water consumption, while clean, cool water encourages better intake compared to warm or poor-quality water. Additionally, heat-tolerant breeds may require less water to manage stress, making genetic factors another consideration. Managing these variables is essential to optimize poultry performance, particularly in the face of climate change.

The ratio of supply to demand determines how scarce water is in a certain area. Water shortage will probably become a more significant barrier to agricultural productivity in the future as human populations, incomes, and the demand for livestock products rise [24]. Water availability and utilization in animal production are expected to vary due to climate change [25]. Increased irrigation water demand per animal and land area, as well as higher temperatures, are predicted [26]. In the upcoming decades, livestock, crops, and non-agricultural uses will compete increasingly for the limited water

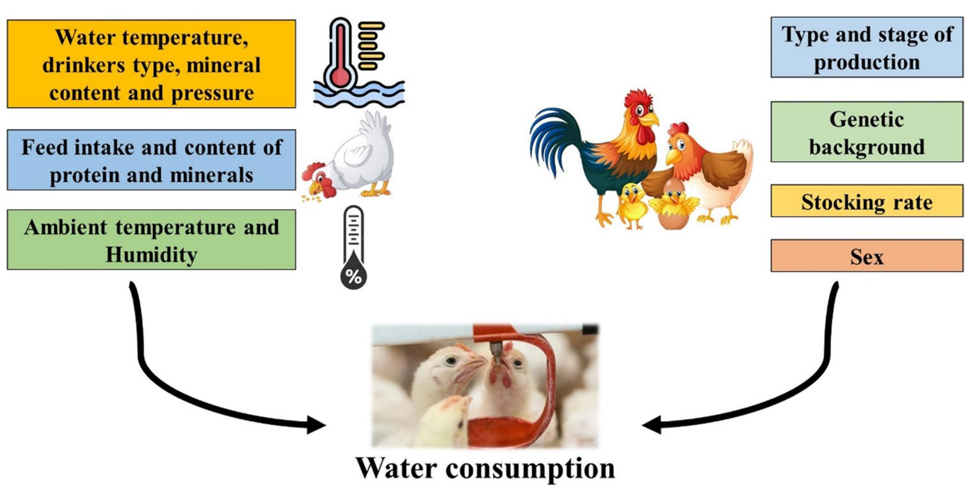


Fig. 3 Factors affecting water consumption in chickens

supply. As a result, more effective livestock production systems will be required to solve the issue of water scarcity [27]. Also, water scarcity won't be as much of an issue in some places as rising sea levels, flooding, or runoff. These consequences have the potential to lower water quality and harm the infrastructure that is used to deliver and transport water [28]. In addition, rising sea levels, saline water intrusion, and natural disasters such as cyclones, droughts, and floods can have negative effects on the economy, human lives lost, traditional lifestyles lost, biodiversity lost, disease outbreaks, and starvation [29].

1.6 Poultry industry victim or culprit

The livestock subsector was once thought of as a victim until it was discovered that it was a significant source of greenhouse gas (GHG) emissions, including CH_4 and CO_2. Because these gases trap heat in the earth's crust and prevent it from reflecting into space, they contribute to global warming. It is estimated that the production of chicken meat and eggs contributes 8% of the annual worldwide greenhouse gas emissions from the livestock industry or 606 million tons of CO_2 equivalent [30]. It is estimated that the average emission intensity for layers is 3.5 kg of CO_2 equivalent per kg of eggs. For broilers, it is 5.4 kg of CO_2 equivalent per kg of carcass weight [31].

Feed production (fertilization, machinery use, and transportation) was the primary source of emissions. About 57% of the emissions from the supply chains for chicken and eggs come from the production of feed [32], with the remaining 21.1% coming from the increase of soybean farming for meat and 12.7% from the egg industry. Broiler feeds are higher in protein and often contain a larger percentage of soybeans from land-use converted areas [33]. In eggs, manure emissions make up 20% of emissions, but in broilers, they only make up 6%. Because hen manure is typically managed in liquid systems with long-term pit storage, it differs from that of specialized meat production, where most of the manure is treated in dry, aerobic conditions [34]. In many countries, hen manure for egg production is not handled as a liquid. The use of liquid manure systems for laying hens needs to be discouraged. Dry manure has many advantages. It is easier to transport than liquid manure. This helps prevent over fertilization of the.

ground near big chicken houses. Dry manure systems also reduces water use [35].

1.7 Carbon footprints

The "carbon footprint" is the entire amount of greenhouse gases (GHGs) produced by human activity, which includes carbon dioxide [CO_2], methane [CH_4], and nitrous oxide [N_2O]. A given activity, sector, or enterprise's GHG emissions are measured by its "carbon footprint" [36]. Basically, feed production, energy use, and manure management are the three main contributors to greenhouse gas emissions from the chicken industry. Feed production, which includes transportation, fertilizer application, and land use modification, has an impact on the carbon footprint of broiler production [37]. The usage of energy for lighting, ventilation, and heating, which includes electricity and fossil fuels, increases emissions even more. The use of naturally ventilated buildings for broiler production can significantly reduce electricity consumption, particularly in areas where the electrical grid is unreliable. Such systems help eliminate the need for mechanical ventilation and cooling systems that rely heavily on electrical power, thus minimizing operational costs and the environmental impact from the use of fossil fuels required by generators. Naturally ventilated buildings, when properly designed with effective air circulation and thermal regulation, can maintain optimal temperature and air quality, reducing the risk of heat stress in broilers while enhancing sustainability. Studies have shown that implementing these designs can be effective in energy savings and reducing the overall carbon footprint of poultry production. This approach is particularly beneficial in rural and developing regions, where access to reliable electricity may be a challenge. Utilizing renewable energy, such as solar-powered climate control systems, can further enhance efficiency, as highlighted by Firfiris et al. [38], who reviewed passive cooling systems in livestock buildings for energy savings. Moreover, Gad et al. [39] demonstrated how solar energy and climate control systems can significantly improve poultry house productivity, offering a sustainable solution for reducing energy dependence in poultry farming.

Last but not least, the storage and disposal of manure results in the release of methane, a potent greenhouse gas [40]. When it comes to farm operations, methane, nitrous oxide, and carbon dioxide have been found to be the primary contributors to greenhouse gas emissions (GHG emissions). According to Chataut et al. [41] and Al Zahra et al. [42], bedding was the main source of nitrous oxide emissions in the industrial, contemporary chicken farm.

According to a study examining the effects of food items on the environment (Fig. 4), the production of chicken meat generated 9.87 kg CO_2 equivalent per kilogram, less than that of cattle (beef and dairy herd), lamb and mutton, and pig meat [43]. Chickens are predicted to provide 8% of the overall emissions from the animal industry or 0.6 Gt of

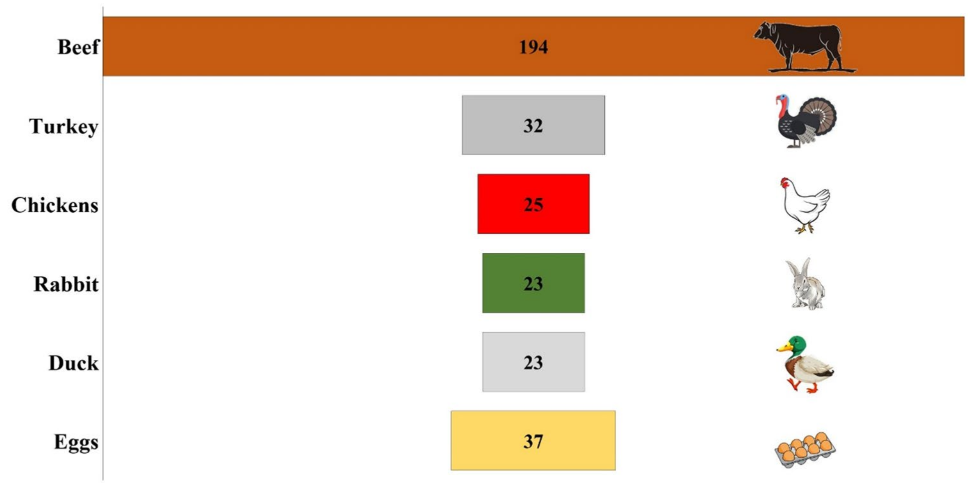


Fig. 4 Emissions of greenhouse gases per gram of food product (g CO_2eq/g protein). CO_2 equivalents were used to measure emissions

CO_2-equivalent emissions [19]. In particular, 78% of feed production, 8% of farm-level direct energy consumption, 7% of post-farm meat processing and transportation, and 6% of manure storage and processing are accountable for greenhouse gas emissions in the broiler industry [16]. Figure 4 shows the greenhouse gas emissions per gram of various food products, highlighting significant differences in environmental impact. Beef has the highest emissions at 194 g of CO_2 equivalents per gram of product, making it the most environmentally damaging protein source. Turkey produces 32 g of CO_2 equivalents per gram, while chicken is lower at 25 g. Rabbit and duck both contribute 23 g of CO_2 equivalents per gram, making them more eco-friendly options. Eggs, at 37 g of CO_2 equivalents per gram, fall between turkey and chicken in terms of emissions. This data emphasizes that choosing lower-emission proteins, such as poultry or rabbit, can help reduce the overall carbon footprint of food production, contributing to climate change mitigation efforts.

Numerous factors affect the impact of broiler production on carbon. The content and supply of feed are critical since the production and distribution of feed components contribute to emissions. Good nutrient use and feed conversion ratios can help reduce the carbon footprint by minimizing the amount of feed needed per unit of meat produced. Emissions can be significantly decreased by increasing the energy-efficient qualities of broiler housing and employing renewable energy sources. Moreover, methane can be extracted and utilized in composting and anaerobic digestion, two sustainable manure management methods. Thus, although broiler production has a lower carbon footprint than other livestock production systems, its environmental impact still needs to be considered. By implementing strategies to improve feed, boost energy efficiency, embrace sustainable manure management techniques, and employ genetic selection, the carbon footprint of chicken production can be significantly reduced. More research, creativity, and collaboration between the many poultry industry sectors will be needed to promote sustainable methods that lower greenhouse gas emissions and guarantee an ecologically friendly chicken production system [44].

1.8 Impact of climate change on poultry production

The physical, ecological, and health effects of living things may be impacted by changes in the climate, including the frequency of extreme weather events such as heatwaves, droughts, and floods [45]. The economy's cattle subsector is seeing a growing number of effects of climate change. The increase in ambient temperature that follows the rise in global temperatures is one of the main causes of concern. Poultry production is reported to have a relatively lesser carbon footprint per unit of product than ruminant production, despite the livestock subsector being acknowledged for generating 18% of worldwide emissions of greenhouse gases [46]. However, several studies have asserted that poultry species are more susceptible to the adverse effects of elevated temperatures than other animal species [47]. Numerous behavioral, physiological, and neuroendocrine changes brought on by heat stress (HS) in chickens affect their performance and general health (Fig. 5).

1.9 Consequences of heat stress on the physiological response of chickens

As Fig. 5 illustrates, rising temperatures have a detrimental effect on hens' physiological processes at every stage of life, which ultimately impacts how well they perform. The growth rate and the cost of production are influenced by

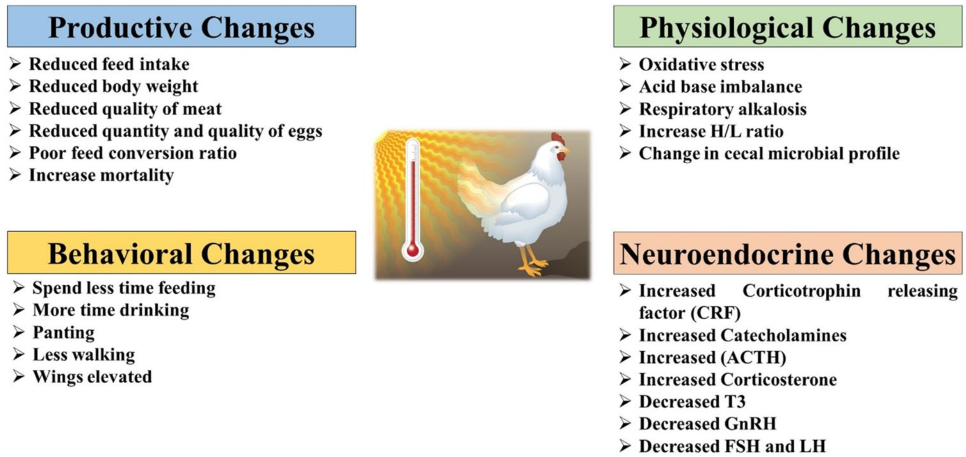


Fig. 5 Heat stress's impacts include physiological, neuroendocrine, behavioral, and production features

physiological behavior [48]. According to reports, chicks that are one day old have rapid metabolism and growth rates, which makes it challenging for them to adjust to the constant rise in ambient temperatures [49]. As was previously established, chickens are particularly vulnerable to HS because they lack sudoriferous glands [50]. The neurogenic system is activated in hens exposed to HS as part of their initial reaction [51]. The neurogenic system is activated under stress and causes an increase in blood sugar, respiration, muscular tone, and nerve sensitivity. This response and neurogenic system activation result in the release of two important hormones, which are regulated by norepinephrine and adrenaline. High heat waves influence the hypothalamic–pituitary–adrenal cortical system in addition to the neurogenic response, which leads to the release of corticotrophin-releasing factor [52]. According to Løtvedt et al. [52], this hormone functions as a messenger, signaling the pituitary gland to release adrenocorticotropic hormone (ACTH). When corticosteroid is secreted from the adrenal cortical tissue, ACTH is released from the pituitary. Elevated blood levels of corticosteroids can significantly impact multiple physiological processes, such as mineral metabolism and glucose synthesis. This can lead to hypercholesterolemia, immune system dysfunction, cardiovascular disorders, and gastrointestinal (GI) lesions [53]. Animals use a variety of methods, including conduction, convection, and evaporative heat loss that entail vasodilatation and sweating, to maintain homeostasis during hypoxia [54]. Chickens with HS have altered metabolic processes, which increases the synthesis of glucose to keep the organisms in the HS condition equilibrium. By increasing air circulation towards the body's surface throughout HS, the air sacs play a crucial part in enabling gaseous exchange, which leads to the evaporation of heat. It is significant to note that increased panting, a typical reaction of HS in chickens, results in increased carbon dioxide exhalation. Consequently, this leads to an increase in blood pH, which is referred to as respiratory alkalosis [23]. The availability of free calcium and bicarbonate, which are essential for the mineralization of the eggshell, is disrupted by these alterations in blood chemistry. Because the layer industry has to produce high-quality eggs, this phenomenon is significant [55].

1.10 Consequences of heat stress on chicken productive performance

Numerous investigations have revealed that HS has a detrimental impact on hens' immunological, physiological, and general health in addition to their ability to produce. Chickens choose survival over growth under high waves [56]. Extended heat stress (HSS) in broiler chickens can result in acid–base imbalance and activate lipid peroxidation, which can have negative impacts on muscle growth, fat metabolism, meat quality, and blood chemical profile. Furthermore, excessive heat waves cause chickens' protein content to drop and their fat deposits to rise [57].

Another study on broilers showed that by reducing protein digestibility by up to 9.7%, both continuous and CHS had a substantial impact on the growth rate [56]. In a 12-day trial, it was shown that HS reduced the daily feed consumption of chickens by 28.58 g and the amount of eggs laid by laying hens by 28.8% [58]. According to Mack et al. [59], the overall reduction of entire egg weight, eggshell thickness, just eggshell weight, and eggshell by HS was 3.24%, 2%, 9.93%, and 0.66%, respectively. Since the birds under HS ingested less feed than the control group, the notable weight loss may have resulted from reduced feed consumption. As a result, they discovered that production efficiency and egg quality were severely impacted by the reduction in feed intake and nutritional digestibility [60]. The length of HS, the intensity of the heat, the age of the bird, or the genetic and physiological state of the chickens could all be contributing factors to the variations [61].

1.11 Consequences of heat stress on gut health and immune response of chickens

The development of the immune system, water and electrolyte balance, and effective feed digestion and absorption all depend on gut health. HS has the potential to change the gut microbiota, which can result in dysbiosis of the gut and compromise the integrity of the gut barrier [62]. HS has been shown in numerous studies to have an impact on the composition of the gut microbiota and the health of birds [63]. According to a study, HS damaged the intestinal microbiota of Ross 308 broiler chickens. Between the ages of 21 and 42 days, the birds were subjected to repeated cycles of high temperatures (33 °C for 10 h each day). In their ceca, this HS increased harmful bacteria like *E. coli* and decreased beneficial bacteria like *Lactobacillus*.

Additionally, the HS compromised the integrity of their intestinal barrier and altered the anatomy of their intestines [64]. Arbor Acres broilers subjected to CHS (32 °C for 10 h/d) between the ages of 22 and 35 days were also shown to have altered gut microbiota profiles [65]. Researchers discovered that while bacteria including *Anaerofustis*, *Pseudonocardia*, *Rikenella*, and *Tyzzerella* were decreased in HS broilers, they identified an increase in *Parabacteroides*, *Saccharimonas*, *Romboutsia*, and *Weissella* in the ceca and deteriorated intestinal morphology [65].

The immunological condition of hens is also impacted by high temperatures [66]. The loosening of enterocytes and the entry of microorganisms from compromised gut health cause the onset of immunological inflammation. Thymus, spleen, bursa of Fabricius, liver, and lymphoid organ weights all drop in HS-affected chickens, along with immunological dysregulation. According to a study, broilers subjected to heat stress showed a drop in systemic humoral responses and a reduction in the ratio of circulating antibodies such as IgG and IgM [67]. Elevated outside temperatures have been shown to reduce laying hens' intraepithelial lymphocytes and IgA-secreting cells antibody titer. They also have a negative impact on broiler macrophage phagocytosis capability [68]. Moreover, HS lowers macrophage basal and oxidative bursts, as well as the macrophages' capacity to phagocytose in broilers. Furthermore, because there are more heterophils and fewer lymphocytes in the blood, a high temperature can change the ratio of circulating cells and raise the ratio of heterophils to lymphocytes [44].

1.12 Strategies to mitigate climate change in poultry production

Various approaches have been employed to mitigate the adverse effects of climate change on hens. These strategies include housing and environment, lower stocking density, thermal conditioning from an early age, genetic selection, nutritional modification, and Ovo administration of bioactive substances (Fig. 6). We go over each of these tactics below.

1.13 Environmental and housing strategies

Modernizing housing stock is a crucial adaptation strategy for tackling climate change's effects. The goal of contemporary chicken house design should be to optimize temperature management, airflow, and ventilation. In chicken production systems, ventilation and air movement are essential components of heat management, especially in tropical regions

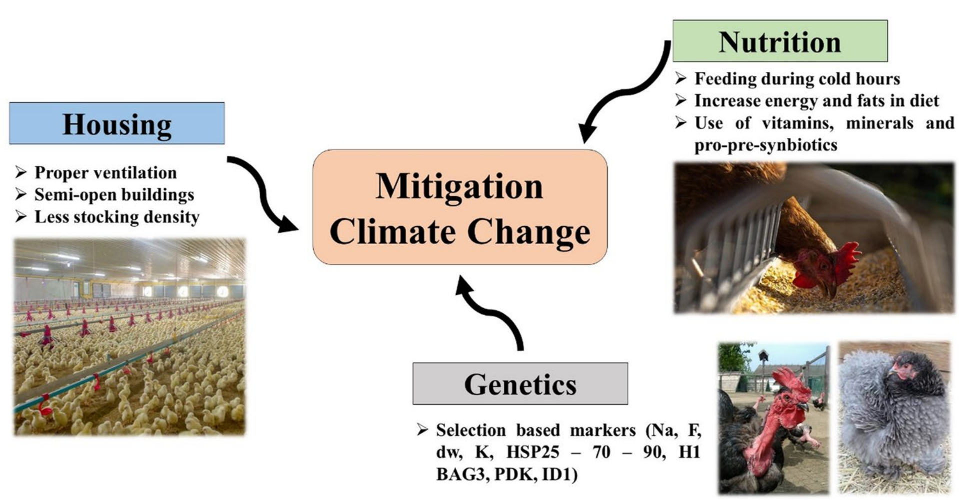


Fig. 6 Strategies to mitigate climate change in poultry production

where high temperatures and humidity are common [69]. In order to give the birds a more comfortable habitat, proper ventilation is crucial for eliminating excess heat, moisture, and airborne contaminants from the poultry house [70]. To guarantee the elimination of stale air and the flow of clean air through the poultry house, there must be adequate air movement. Heat, humidity, and dangerous gasses like carbon dioxide and ammonia can accumulate in stale air, which can negatively impact the health and productivity of chickens. In order to improve air quality and lower the heat load inside the building, efficient ventilation systems must be built to allow the interchange of stale air with outside fresh air [71].

Additionally, air movement and ventilation help to regulate the humidity levels in the chicken house. Elevated humidity levels can worsen the heat stress experienced by birds and foster an atmosphere that is conducive to the development of infections and the emergence of respiratory ailments. Ventilation systems help to lower humidity levels and provide a drier and more beneficial environment for the chickens by efficiently eliminating excess moisture from the housing [69].

Open-style houses with appropriate shading, sufficient air circulation, and a water intake are essential in hot and humid environments. The house should face east–west [72]. The width of such housing should not be more than 12 m, and the length of the building can be determined by convenience. Doors should be positioned 15–30 m apart in long buildings. Side-wall heights of at least 2.1 m and easily adjustable curtails are advised [73]. Adequate ventilation is crucial because the air movement helps remove moisture, ammonia, and carbon dioxide from the poultry sheds [74].

Additionally, having grass cover on the area around the chicken house will lessen the amount of light that reflects into the building. To guarantee air movement, vegetation should be regularly trimmed. It is best to plant shade trees in areas where they won't impede airflow [75]. In order to prevent heat build-up, it is important to take into account the state of the roofing. Poultry homes should have dust-free, spotless- roofs, white- or light-colored roofs. This will help keep a building cooler. Shiny roofs reflect solar radiation more effectively than rusty or dark roofs. Aluminum roofing or metallic zinc paint can be utilized to improve the roof's reflectivity. Poultry employs evaporative panels as a way to mitigate the adverse impacts of climate change (Oke et al., 2024). With the evaporation of water, these panels contribute to lowering the surrounding temperature, making it more comfortable for birds.

Additionally, a novel cooling technique called "evaporative cooling" of the ventral skin regions of laying hens has been developed. This technique involves moistening the skin and encouraging water evaporation, and it has the potential to mitigate the effects of climate change on poultry [76]. Poultry farmers are considering dark housing systems (DHS) as a way to increase bird productivity and health. Dark house systems, while improving broiler productivity through controlled light exposure, raise significant animal welfare concerns. These include restricted natural behaviors, increased stress, and physical health issues such as leg problems, poor bone development, and footpad dermatitis due to limited movement and poor ventilation. To address these concerns, it is essential to balance productivity with welfare by adjusting light management and improving ventilation and flooring. Adhering to animal welfare guidelines, such as those from the World Organisation for Animal Health (OIE), can help mitigate these issues. Studies, such as Firfiris et al. [38] and Gad et al. [39], highlight the importance of adopting systems that consider both productivity and animal welfare. These systems combine automated controls and specialized lighting to provide the ideal habitat for hens. Research indicates that when compared to birds housed in traditional housing, birds grown in DHS grow more quickly and require less nutrition. DHS sounds fantastic, but it's expensive to put up and run, particularly in underdeveloped nations. Thus, for the time being, other approaches, such as modifying chicken feed, maybe a preferable choice [23]. Automated control systems, though beneficial for optimizing poultry production, require specialized maintenance, which can be challenging in lower-income countries due to limited access to technical expertise and spare parts. Simpler, non-automated systems, such as naturally ventilated buildings, are easier to manage and maintain, making them more suitable for regions with fewer resources. These systems, though less advanced, can still effectively control the environment at lower costs. Gad et al. [39]suggest that simpler designs using renewable energy can enhance poultry house productivity without the need for complex maintenance.

1.14 Management strategies

There are a number of cooling techniques that poultry breeders can use to reduce heat stress. Misters, foggers, and sprinklers are examples of evaporative cooling systems that are frequently used in chicken houses to reduce temperature and raise humidity. As the water in these systems evaporates, a cooling effect is produced, making the birds' surroundings more comfortable. To further lessen heat stress, consider adding shady spaces inside your home or installing reflective roofing materials, which both aid in minimizing heat absorption from sunlight [77].

Effective bedding and litter control are essential for managing heat. It is possible to lower the humidity levels in the poultry house by selecting bedding materials that are suitable and have good moisture-absorbing qualities. By doing this, excessive moisture buildup is avoided, which may exacerbate heat stress. In order to keep the birds' habitat dry and pleasant and to avoid the buildup of heat-trapping ammonia, dirty litter must be routinely removed and replaced [78].

Thermal stress in chicken production systems can be considerably reduced by making management practice adjustments. By arranging feeding times during the cooler parts of the day, you can make sure that the chickens eat when the temperature is lower, which lowers the amount of heat they produce during digestion. Frequent health examinations guarantee the birds' well-being by enabling prompt detection and treatment of any heat-related problems [16].

1.15 Genetic strategies

Poultry that has been bred for disease resistance and heat tolerance will be more climatically adaptable. Programs for genetic selection can concentrate on characteristics that increase the birds' capacity to survive in hot climates. Maintaining genetic diversity within poultry species contributes to their ability to withstand environmental stresses. Poultry agriculture must be adapted to the changing climate by safeguarding and exploiting genetic resources [79]. Important genes that are thermotolerant, such as the chickens' dwarf, frizzle, and naked neck genes. It is believed that the genes for naked neck (Na) and frizzle (F) may be candidates for tolerance to temperature stress. They provide a realistic, long-lasting, and affordable response to the problem of heat stress [50]. It may be possible to improve a chicken's capacity for heat tolerance, development, and reproduction by using advantageous heat-resistant genes like frizzle (F) and bare neck (Na) [80]. It may be advantageous to breed for slower growth in order to produce plants that are more suited to warmer climates. Furthermore, research has to concentrate on identifying many potential genes, such as heat shock protein 70, which codes for thermotolerance, in order to guarantee sustainable livestock production in the face of climate change [81].

1.16 Climate change: nutritional strategies and dietary manipulation

1.16.1 Feeding strategies

Feed restriction is withholding feed from birds over some time, usually from 8 AM to 5 PM. This helps lower the metabolic rate of the birds, lower rectal temperature, reduce mortality, and reduce belly fat in heat-stressed broilers [82]. Another study found that feeding broilers 8 h a day during high heat waves improved feed efficiency and shortened tonic immobility [83]. Furthermore, feed restriction in broilers was found to reduce heat production by 23% [84]. Despite these benefits, the poultry industry does not commonly employ this practice because it slows down the growth rate and delays the marketing age of chickens [85].

Offering birds a diet high in protein in the cooler hours of the day and high in energy in the warmer hours is known as a dual feeding program [86]. According to studies, feeding heat-stressed broilers a meal high in protein from 4 PM to 9 AM and energy from 9 AM to 4 PM during high heat waves has been shown to lower body temperature and mortality [87]. Also, according to McGaw and Curtis [88], wet feeding improves digestion, increases nutrient absorption from the GI tract, and ensures that digestive enzymes function quickly on feed. When the outside temperature is high, chickens lose a lot of water. As a result, adding cool water to the feed promotes water intake, reduces intestinal viscosity, and speeds up feed passage. Wet feeding increased feed intake, body weight, and GI tract weight in broilers [89]. According to studies, giving laying chickens wet feed during HS boosted the number of eggs produced, their weight, and their intake of dry matter. This method has been shown to have beneficial benefits on chickens exposed to HS. Still, it is not widely used since it may encourage the growth of fungi in feed and ultimately lead to mycotoxicosis in chickens [89].

It has also been demonstrated that supplementing feed with fat helps birds deal with HS. Compared to protein and carbs, fat produces a smaller heat rise during metabolism [89]. By decreasing the rate of food consumption, adding fat to a bird's diet increases nutrient utilization in the GI tract [90]. However, research showed that adding more oil to a diet with a greater protein content mitigated the negative effects of CHS on the physiological and immunological characteristics, meat lipids, and broiler performance [91].

For chickens to withstand heat stress, a steady supply of clean water is essential [84]. It is important to have a sufficient supply of drinking water that is accessible to birds, as they tend to drink more in warmer weather to stay cool. Waterers need to be cleaned and maintained on a regular basis to maintain water quality and stop bacterial growth. Sufficient hydration maintains the birds' physiological processes and facilitates heat loss, enabling them to endure high temperatures [92].

1.17 Dietary vitamin, electrolyte, and phytochemical supplements

Vitamin E (VE) is a fat-soluble vitamin with antioxidant properties that aid in scavenging free radicals generated inside cells. According to studies, adding VE to the diet of laying hens raised under HS increased the number of eggs produced, their weight, the thickness of their eggshells, their specific gravity, and their Haugh unit [93]. According to reports, layers' diets supplemented with 250 mg VE/kg of feed were able to mitigate the harmful effects of HS [94]. Also, it was shown that adding vitamin A (6000 and 9000 IU/kg of diet) increased the egg weight of layer hens raised in hot environments [95]. Another study found that supplementing broilers exposed to HS with vitamin A (15,000/kg of feed) boosted body weight gain, improved feed efficiency, and decreased malonaldehyde (MDA) content [96]. As an antioxidant that is soluble in water, vitamin C works by scavenging reactive oxygen species to avoid oxidative damage. Vitamin C supplementation is, therefore, a useful tactic to lessen the adverse impacts of HS in poultry. Vitamin C supplementation (250 mg/kg of feed) enhanced heat-stressed birds' growth rate, nutritional application, production of eggs and quality, immunological response, and antioxidant status [93] In heat-stressed Japanese quail, dietary vitamin C supplementation decreased the serum concentrations of MDA, homocysteine, and adrenal corticotropin hormone [94].

The performance of heat-stressed quails during HS was enhanced by the addition of sodium selenite at 0.1 or 0.2 mg/kg of diet [97]. Additionally, it was discovered that adding 0.15 and 0.30 mg/kg of feed sodium selenite or selenomethionine supplementation during the high school (HS) stage improved feed efficiency and enhanced feed intake, body weight, and egg production [98]. Furthermore, prolonged panting under intense heat waves modifies the blood plasma's acid–base equilibrium and ultimately results in respiratory alkalosis. Electrolytes such as NH4Cl, $NaHCO_3$, and KCl can be supplemented to correct this acid–base imbalance. Birds excrete more bicarbonate ions from their kidneys to bring their blood pH back to normal during respiratory alkalosis. It has been proposed that a high dietary electrolyte balance of 200–300 mEq/kg can effectively mitigate the negative effects of HS in chickens [99]. Additionally, it has been discovered that supplementing heat-stressed laying hens with $NaHCO_3$ improves the quality of their eggshells [100].

Resveratrol is a naturally occurring bioactive polyphenol that is mostly present in turmeric, berries, peanuts, and grapes. Its ability to prevent HS in poultry has drawn attention in recent years. Resveratrol works in poultry physiology by boosting fatty acid oxidation, altering the immunological response, and eliciting the expression of heat shock protein and antioxidant mRNA. These activities support its capacity to reduce HS and preserve the physiological balance in chickens [101]. During HS, the broilers' antioxidant capacity was increased by supplementing them with 400 mg/kg of resveratrol in their feed [102]. In yellow-feather broilers under HS, resveratrol supplementation at 300 or 500 mg/kg of feed increased average daily growth, decreased rectal temperature, and lowered levels of corticosterone, adrenocorticotropin hormone, cholesterol, and MDA [102]. Egg production was increased in laying hens by supplementing their diet with 200 mg of resveratrol per kilogram of feed.

Moreover, turmeric contains a polyphenol called curcumin, which may be extracted and may help chickens with HS by lowering inflammation and oxidative stress, among other effects [103]. According to earlier findings, broiler chickens under heat stress perform better when fed feed containing curcumin (Zhang et al., 2018). Research has demonstrated that adding 100 mg/kg of curcumin to feed greatly increased the broiler's final body weight under high-stress conditions [58]. According to Liu et al. [65], adding 150 mg/kg of curcumin to laying hens' diet enhanced their immune system, antioxidant enzyme activity, laying performance, and egg quality. Green tea contains a polyphenol called epigallocatechin gallate (EGCG), which has strong anti-inflammatory and antioxidant qualities [65]. Luo et al. [104] reported that heat-stressed broiler chicks that received different dosages of EGCG in their diet (0, 300, and 600 mg/kg) showed increases in body weight, feed intake, serum total protein, glucose, and alkaline phosphatase levels. In female quails exposed to HS, adding 200 or 400 mg of EGCG/kg of diet enhanced intake, egg production, hepatic SOD, CAT, and GSH-Px activity, and the hepatic MDA level decreased linearly [94].

1.18 Probiotics, prebiotics, and synbiotics supplements

Probiotics, prebiotics, and synbiotics are essential for lowering stress-related inflammation and aberrant behaviors, as well as for modifying the microbiota-gut-brain axis and minimizing the negative effects of HS in chickens. Probiotics have also been linked to improvements in intestinal mucosal immunity, gut morphology, increased nutrient absorption, and egg production in laying hens kept under high stress [104]. Deng et al. [105]reported that adding probiotics (*Bacillus licheniformis* 0, 10^6, and 10^7 CFU) to the diets of laying hens exposed to high temperatures (HS) resulted in increased egg production and feed intake, improved intestinal health by restoring the structure of the weakened villus, and decreased the negative effects of HS. According to Hasan et al. [106], probiotics increase performance, body weight, feed intake, feed conversion ratio, and numerous blood parameters while reducing the detrimental effects of HS. Additionally, it has been discovered that adding 0.5% prebiotic (mannan oligosaccharide) and 1% probiotic (*Lactobacillus*) to the diet of broilers subjected to heat stress (35 °C) improved humoral immunity, increased thyroxine concentrations, decreased serum cortisol and cholesterol, and improved body weight, feed efficiency, villus length, and crypt depth [107]. According to Awad et al. [108], an additional study revealed that supplementing broiler diets exposed to high temperatures (35 °C) with 5% prebiotic (mannan oligosaccharides) and/or 1% probiotic would mitigate the adverse effects of HS, such as increased villus length in the ileum and jejunum, surface area, and crypt depth. According to a study of Abdel-Wareth et al. [109], adding synbiotics to the food at 1500 mg/kg for the starter diet and 750 mg/kg grower improved the growth performance and meat quality of broilers raised in high ambient temperatures.

1.19 Large climate change and its effects on poultry industry and sustainability

Climate change poses significant challenges to the poultry industry, affecting production efficiency, animal health, and sustainability. Rising temperatures lead to decreased feed efficiency, weight gain, egg production, and increased mortality rates in broilers. Water scarcity and poor water quality exacerbate health issues and reduce growth rates, while climate-induced diseases and reproductive health problems further hinder production. To mitigate these effects, sustainable practices such as improved ventilation, energy-efficient housing, water-efficient systems, and adjusted nutritional intake can enhance poultry resilience. Technological advancements like automated climate control, selective breeding for heat tolerance, and the adoption of renewable energy reduce the carbon footprint and improve farm sustainability. Climate variability also affects different regions uniquely, with extreme weather events and rising sea levels threatening poultry farms, especially those in coastal areas. Sustainable farm designs and waste management strategies are crucial for maintaining productivity and mitigating the economic impacts of climate change (see Table 1).

1.20 Economic impact

The economic drawback of climate change on the poultry industry should be thoroughly discussed, emphasizing the financial risks and costs associated with adaptation and mitigation. Some aspects to include are costs of adaptation: adaptation strategies, such as improved housing, ventilation, water management, and the use of heat-tolerant breeds, involve significant upfront costs. Reference studies like those from the World Bank or OECD that estimate adaptation costs for agricultural sectors, including poultry [110]. Economic Risks: climate-related risks, including loss of productivity, higher mortality rates, and increased disease prevalence, could lead to financial losses for poultry producers [111]. Economic assessments like those from IPCC's reports on climate change and food security would provide solid backing. Profitability and Market Access: the poultry industry's economic sustainability can be threatened by market access issues due to environmental regulations. This can be elaborated with data from FAO or World Bank regarding how smallholders and large poultry producers alike may face new market challenges in a climate-altered future [112–114].

1.21 Climate change and its effects on poultry gene expression

Climate change significantly impacts gene expression in poultry, leading to various physiological adaptations and challenges. Heat stress is a major factor, upregulating heat shock proteins, and genes related to oxidative stress while downregulating genes involved in growth, muscle development, and reproduction, thus impairing fertility and hatchability. Additionally, temperature fluctuations and prolonged heat exposure result in epigenetic modifications that cause heritable changes in gene regulation. Climate-induced stress also affects the immune system, reducing disease resistance while impacting organs like the lungs, heart, liver, and kidneys through altered gene expression. Water scarcity, cold stress, and high humidity further contribute to metabolic and hydration-related gene expression changes, affecting poultry's overall health and productivity. Molecular adaptations, including upregulation of stress-related and antioxidant enzyme genes, help mitigate the damage caused by climate stress, though long-term survival and performance may still be compromised (see Table 2).

Table 1 Large climate change and its effects on poultry industry and sustainability

Study	Findings	References
Impact of temperature rise on poultry production efficiency	Increased temperatures lead to reduced feed efficiency and egg production	[115]
Heat stress and its effect on broiler performance	Heat stress decreases weight gain and increases mortality rates in broilers	[116]
Water scarcity and its implications for poultry farming	Limited water availability affects growth rates and overall poultry health	[117]
Sustainability practices in poultry industry under climate change	Sustainable feed and water management mitigate adverse climate effects	[118]
Adaptation strategies to climate variability in poultry production	Improved ventilation and heat control systems can enhance resilience to climate variability	[119]
Impact of climate change on egg production and quality	Egg production decreases significantly with rising temperatures; shell quality is also affected	[120]
Energy-efficient housing in poultry production under climate change	Energy-efficient housing reduces heat stress and minimizes energy consumption	[121]
Nutritional adjustments to improve poultry resilience	Adjusted nutritional intake, such as higher antioxidant content, can mitigate climate stress in poultry	[121]
Water-efficient systems in poultry farming	Advanced water-efficient systems help mitigate the effects of water scarcity in poultry farming	[117]
Carbon footprint reduction in poultry farming	Adopting renewable energy practices reduces carbon footprint in poultry farming	[122]
Sustainable feed sources for poultry under climate stress	Exploring sustainable feed alternatives, such as insect-based protein, enhances resilience	[123]
Environmental stressors and poultry immune response	Environmental stress increases susceptibility to diseases, requiring improved management practices	[124]
Role of technology in adapting poultry farming to climate change	Technology-driven solutions, such as automated climate control, improve resilience	[125]
Genetic approaches to enhance heat tolerance in poultry	Selective breeding for heat-tolerant poultry shows promise in sustaining production	[126]
Impact of climate-induced diseases on poultry farming	Climate-induced diseases, such as avian influenza, are on the rise, requiring proactive measures	[127]
Global warming and poultry reproductive health	Rising temperatures negatively affect reproductive performance in poultry	[128]
Challenges of ventilation in poultry farms amid climate change	Ventilation systems are crucial in maintaining poultry health under climate stress	[129]
Poultry waste management and climate change	Proper waste management can reduce greenhouse gas emissions from poultry farms	[130]
Economic impacts of climate change on poultry industry	Climate change results in increased costs for cooling and water management in poultry farms	[131]
Heat stress management in poultry via automated systems	Automated climate control systems reduce heat stress and improve farm productivity	[132]
Feed conversion efficiency in heat-stressed poultry	Feed efficiency decreases in heat-stressed poultry, requiring dietary adjustments	[74]
Water quality challenges in poultry production during drought	Drought leads to reduced water quality, affecting poultry health and productivity	[133]
Role of shade and natural cooling systems in poultry farming	Natural cooling systems like shade and water sprinklers reduce heat stress in poultry	[134]
Impact of rising sea levels on coastal poultry farms	Coastal poultry farms face risks from flooding and rising sea levels	[135]
Weather variability and poultry farm output in different regions	Regional weather variability affects poultry production differently across geographies	[136]
Alternative energy use in poultry farms for climate mitigation	Using solar energy in poultry farms reduces reliance on non-renewable resources	[39]
Impact of extreme weather events on poultry mortality	Extreme weather events increase poultry mortality rates, impacting farm profitability	[137]
Sustainable poultry farm design for climate resilience	Sustainable farm designs incorporating natural cooling improve resilience to climate change	[138]
Poultry farmers' perception of climate change	Farmers in different regions perceive climate change and adapt to its effects in varying ways	[139]
Carbon sequestration strategies in poultry farming	Strategies like carbon sequestration can help offset emissions from poultry farming	[140]

Table 2 Climate change and its effects on poultry gene expression

Study	Findings	References
Climate-induced gene expression changes in poultry	Climate change alters expression of genes involved in metabolism and stress response in poultry	[115]
Heat stress and its impact on poultry gene expression	Heat stress significantly upregulates heat shock proteins and genes related to oxidative stress	[56]
Effects of temperature fluctuations on gene regulation in broilers	Temperature fluctuations lead to altered expression of genes regulating growth and development	[141]
Gene expression in layers exposed to heat stress conditions	In layers, heat stress reduces the expression of genes involved in egg production and fertility	[142]
Climate change and epigenetic modifications in poultry	Epigenetic changes in response to climate stress affect long-term gene expression in poultry	[143]
Role of heat shock proteins in poultry gene expression under stress	Heat shock proteins play a central role in protecting cells from stress-induced damage in poultry	[144]
Gene expression in poultry reproduction under heat stress	Heat stress impairs reproductive genes, reducing fertility and hatchability in poultry	[145]
Molecular adaptations in poultry to climate stress	Poultry show molecular adaptations through upregulation of stress-related genes under climate change	[146]
Gene expression related to immune response in poultry under climate change	Immune-related gene expression is altered, reducing disease resistance in heat-stressed poultry	[147]
Impact of heat stress on muscle development gene expression in poultry	Heat stress downregulates genes related to muscle growth and development in poultry	[148]
Oxidative stress-induced gene expression in heat-stressed poultry	Oxidative stress leads to upregulation of protective genes in poultry under extreme heat conditions	[149]
Cold stress and gene expression in poultry immune function	Cold stress triggers immune gene expression changes, reducing disease resistance in poultry	[150]
Water stress and its effect on poultry gene expression	Water deprivation alters genes related to metabolic and hydration regulation in poultry	[151]
Gene expression changes in poultry lungs under heat stress	Heat stress affects lung gene expression, impairing respiratory function in poultry	[56]
Stress-induced changes in poultry liver gene expression	Prolonged stress alters liver function through changes in gene expression in poultry	[152]
Epigenetic effects of prolonged climate stress on poultry	Epigenetic modifications due to climate stress led to heritable gene expression changes	[141]
Impact of climate variability on broiler gene expression	Broilers experience variable gene expression related to growth and metabolism under climate variability	[153]
Heat shock protein regulation in poultry gene expression	Heat shock proteins regulate protective gene expression in heat-stressed poultry	[154]
Gene expression in poultry neurons under climate stress	Climate stress affects gene expression in poultry neurons, influencing behavior and stress tolerance	[155]
Gene expression of poultry intestinal microbiota under heat stress	Heat stress alters gut microbiota gene expression, affecting digestion and nutrient absorption	[156]
Cold-induced changes in poultry muscle gene expression	Cold stress decreases expression of genes related to muscle function in poultry	[157]
Gene expression in heat-stressed poultry heart tissue	Heat stress affects cardiac gene expression, leading to potential heart dysfunction in poultry	[158]
Water scarcity and poultry gene expression adaptations	Water scarcity induces gene expression changes related to hydration and stress resistance	[159]
High humidity and its effects on poultry gene regulation	High humidity affects gene regulation, leading to increased susceptibility to infections in poultry	[160]
Gene expression in poultry skin during heat stress	Heat stress leads to changes in skin gene expression, affecting poultry heat dissipation	[150]
Gene expression of antioxidant enzymes in poultry under climate change	Antioxidant enzyme genes are upregulated in poultry to counteract oxidative damage from heat stress	[161]
Drought stress and its effect on poultry gene expression	Drought conditions alter gene expression related to water conservation and metabolism in poultry	[162]

Table 2 (continued)

Study	Findings	References
Gene expression in poultry kidneys during water stress	Kidney function is compromised through gene expression changes during water scarcity	[56]
Heat stress and epigenetic regulation of poultry genes	Epigenetic regulation is modified under heat stress, affecting gene expression across generations	[163]
Long-term heat exposure and gene expression adaptations in poultry	Long-term heat exposure leads to adaptive gene expression changes in poultry, enhancing survival	[77]

1.22 Future directions for poultry production and climate change

It is necessary to approach poultry production holistically, taking into account advancements in technology, research, and legislative frameworks. This study looks at practical ways to improve sustainable poultry production in relation to climate change, as well as the implications for policy. It also looks at industry's prospects in the future and makes recommendations for future research and innovation topics.

Governments have the authority to implement laws that encourage climate-conscious agricultural practices. Using renewable energy sources, establishing energy-efficient housing systems, and procuring feed sustainably are a few examples of these programs' incentives. Furthermore, carbon footprinting policies could be put in place to promote the industry's decrease in greenhouse gas emissions. Also, more environmental regulations may be implemented in order to monitor and control emissions from facilities that raise broilers. These limitations would encourage the adoption of environmentally friendly procedures and technologies in an effort to lessen the harmful effects of broiler farming on nature. Furthermore, services for research and extension It is imperative to allocate resources towards research and extension initiatives in order to provide poultry producers with up-to-date knowledge on strategies for adapting to climate change. Governments should support research institutes and extension activities to disseminate information on managing heat stress, dietary therapies, and illness prevention. The following are some possible areas for more study and technical developments: (a) Breeding and genetic selection studies are needed to create lines of poultry that can withstand high temperatures. The development of resilient broilers could be accelerated by the discovery of genetic markers linked to heat tolerance; (b) studies into climate-smart feed formulations could lead to diets that improve nutrient utilization and GHG emissions from feed production and promote sustainability in the broiler industry; and (c) intelligent monitoring and management technologies. Artificial intelligence-powered management tools and remote monitoring systems, for example, can optimize chicken production while reducing resource waste. These technologies allow for real-time monitoring of the feed intake, surroundings, and health state, allowing for prompt response as needed [16].

2 Conclusion

Through the adoption of cutting-edge technology and environmentally friendly techniques, the poultry sector can address many of its current challenges, particularly in hot, cold, low-income, and high-income countries. In hot climates, practical solutions such as heat-reducing paint for roofs can lower heat stress, while in cold climates, energy-efficient insulation and ventilation are key. In low-income countries, simpler, non-automated systems that are easy to maintain, like natural ventilation, are more effective than computerized buildings that may fail due to lack of spare parts. In high-income countries, advanced climate control systems and modern management techniques can optimize productivity and sustainability. In all situations, insect-based protein as feed offers a viable solution, promoting circular economy practices like waste recycling and reducing the sector's carbon footprint. Insect protein can replace traditional feed sources, lowering costs and environmental impact. Governments, academic institutions, and the private sector are collaborating to develop sustainable poultry farming technologies, but climate change's effects on poultry production necessitate well-designed policies and interventions to ensure the sector's resilience.

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