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Original Article

Assessment of the Climate Change Impact on Broiler Chickens in Northern Tunisia

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ABSTRACT

Climate change continues to influence global ecosystems, raising concerns for livestock. This study assesses the impacts of climate change on broiler chickens in northern Tunisia, focusing on well-being and mortality rates during summer. Historical data from the NRMCM5.1 and MPIESM1.2 models, were utilized, covering 1970 to 1997. Projections for 2041-2070 under the RCP4.5 and RCP8.5 emissions scenarios were examined, providing insight into future challenges. The Temperature-Humidity Index (THI) and Temperature-Humidity-Velocity Index (THVI) served as thermal comfort indicators. The research utilized temperature and relative air humidity data from two models and scenarios (RCP4.5 and RCP8.5) as inputs for the DCP system, thus evaluating comfort parameters (THI and THVI). The analysis involved calculating annual temperature and humidity averages at the system's output for each grid and region. Historical and projected data were employed to assess mortality levels by identifying heatwave periods, which had an average duration of 2.7 consecutive days with THI exceeding 30.6°C. The analysis showed significant increases in THI and THVI in the RCP8.5 pessimistic scenario, indicating a risk of heat stress. Mortality rates were used as a measure of the vulnerability of the poultry industry to climate change, and the projections showed substantial average increases of 2.2°C for THI and 1.5°C for THVI.. The RCP4.5 and RCP8.5 scenarios predicted an increase in mortality for the period 2041-2070, with averages increasing from 0.8 to 1.3 for RCP8.5 and from 0.6 to 1.1 for RCP4.5, highlighting the need for adaptation strategies to ensure sustainability in poultry farming.

INTRODUCTION

The increase in the global population has caused a growing demand for food, particularly animal protein. Over the past decade, global poultry meat production has increased in 25%, reaching 109 million tons per year FAO (2019). In Tunisia, traditional local poultry breeding is widely practiced in both rural and urban areas. It amounts to approximately 9% of poultry meat production and nearly 7% of egg consumption in the country. Traditional poultry farming has significant economic importance in Tunisia and plays a crucial social role. It provides income for disadvantaged rural families and serves as a means of exchange in local markets. Over the past fifteen years, the Tunisian poultry sector has experienced notable growth; especially in poultry meat production, with a remarkable growth rate of 5.9%. This expansion can be attributed to significant infrastructure improvements and the enhanced quality of poultry products. Furthermore, the decrease in demand for red meat and seafood, primarily due to their higher prices relative to consumers' purchasing power, has also contributed to the development of the poultry industry in Tunisia. To meet this increasing demand healthily and efficiently, ensuring optimal environmental conditions in poultry houses is essential. However, the methods used to achieve high production performance and feed efficiency render broiler chickens more sensitive to thermal stress, leading to undesirable consequences such as reductions in the growth rate and feed efficiency (Guimarães et al., 2003; Lin et al., 2006). Heat stress has a significant impact on the immune system of animals, including poultry, leading to an increased disease frequency (Dohms *et al.*, 1991). In many regions of the world, including Tunisia, heat stress adversely affects the efficiency of poultry production, resulting in substantial economic losses (Teeter *et al.,* 1996; Quinteiro-Filho *et al.*, 2010). Adult broiler chickens exposed to high temperatures show reduced feed consumption, growth rate, feed efficiency, and survival rate (Teeter *et al.*, 1996). The summer months are particularly critical, as the temperature inside poultry houses rises due to external conditions and solar radiation, causing heat stress and resulting in decreased feed intake and increased mortality (Dohms *et al.,* 1991; Guimarães *et al.*, 2003). Climate change has direct impacts on poultry production, such as reductions in growth, egg production, and overall animal health due to extreme weather conditions. Birds must adapt to intense heat by using resources to regulate their body temperature, leading to a decrease in their productive performance (Al-Saffar *et al.,* 2002; Karaca *et al.*, 2002; Rozenboim *et al.*, 2007; Ayo *et al* 2011; Calefi *et al.*, 2017). Additionally, climate change has indirect impacts, including changes in the availability and quality of feed ingredients, a decrease in the quantity and quality of water, and disruptions in the spread of diseases and pest infestations. These factors negatively affect poultry productivity, resulting in increased losses and production costs (Mustafa *et al.,* 2010; Alemayehu *et al.,* 2017). Similarly to North Africa as a whole, Tunisia is recognized as a"hotspot" for climate change (Giorgi 2006), making it one of the top ten countries most susceptible to the adverse effects of climate change. Specifically, global warming will reduce the efficiency of air conditioning systems and the well-being of poultry. According to studies by (Chepete *et al.*, 2005; Marchini *et al,* 2007; Abreu *et al.,* 2012) and (Kumar *et al.,* 2021) poultry production systems are exposed to future risks due to favorable conditions for heat stress. Heat waves are meteorological events characterized by extremely high temperatures that can significantly affect chicken production. The frequency of these events has increased due to the influence of climate change. Notably, the European Union's Committee on Agriculture reported substantial economic losses of 15-30% in poultry production as a result of a heat wave that struck Europe in 2003. Similarly, a study conducted by (St-Pierre *et al.*, 2003) in the United States revealed production losses amounting to a staggering 128, million, dollars when environmental conditions deviated from the optimal thermal comfort zone. Research on cooling systems for broiler chickens has led to various solutions, making controlled air conditioning crucial for optimal conditions. Direct Pad Cooling (DPC)s, either used alone or in combination with nozzles, have been extensively investigated (Xuan *et al.,* 2012; Mehere *et al.,* Rogdakis *et al.*, 2014; 2014; Anisimov *et al.*, 2016; Cuce *et al.*, 2016; Arun *et al.*, 2020). Direct pad, indirect pad, and Maisotsenkocycle pad cooling systems (respectively DEC, IPC and MEC) have demonstrated superior energy efficiency and the ability to provide suitable environmental conditions. Direct pad cooling systems (DPC) are widely adopted for summer cooling highly valued by Tunisian poultry farmers, as they efficiently dissipate the heat generated by broiler chickens and ensure comfortable temperatures. Thermal comfort indices have been developed to measure thermal comfort zones for various animal species, including poultry. These indices include the wet bulb globe temperature (WBGT), wind chill factor, temperature humidity index (THI), temperature humidity velocity index (THVI), apparent equivalent temperature (AET), and the mortality rate (Xin *et al.,* 1992; Brown-Brandl *et al.*, 1997; Carvalho *et al.*, 2009; Rocha *et al.,* 2010; Purswell *et al.,* 2012). Among these indices, the THI stands out as the most widely used thermal comfort index. It provides a single value that combines the impacts of air temperature and humidity, offering a measure of the level of heat stress. The THI is frequently employed to assess the degree of heat stress experienced by broilers in different locations. (Dikmen *et al.,* 2009; Marai *et al.,* 2010) have investigated the THI as a valuable tool for evaluating livestock productivity in various climatic conditions, since it considers both air temperature and relative humidity and takes into account factors tailored to specific animal species (Hahn *et al.*, 2009). Moreover, this measurement demonstrates the impact of external factors on the animals, which ultimately influence their body temperature relative to the set point (2009). THI thresholds have been widely employed by extension services in the United States to alert livestock farmers of potential heat stress risks associated with meteorological conditions (Whittier *et al.*, 1993; Eirich *et al.*, 2015). Hahn *et al.* (2009) reported the following stress ranges based on the THI for ruminants: normal ≤ 74; moderate 75–78; severe 79–83; very severe (emergency) ≥ 84. For non-sweating animals such as broilers and pigs, the corresponding values are: normal < 27.8, moderate 27.8–28.8, severe 28.9–29.9, and very severe (emergency) ≥ 30.6 (Marai *et al.*, 2001; Robinson., 2001; Nienaber *et al.*, 2004; Vale *et al.*, 2010). Moreover, increasing air circulation around broiler chickens has been proven to be an effective approach to enhance their performance and well-being, especially when temperatures exceed the thermoneutral zone. This method promotes increased convective heat loss while reducing bird panting (Drury,1966; Simmons *et al.,* 1997; Lott *et al.*, 1998). However, it is essential to note that while the effect of air velocity can be beneficial at high temperatures, it may also be detrimental at lower temperatures if causing excessive heat loss. To assess the impact of air velocity on the regulation of body temperature in broiler chickens, it is necessary to integrate this variable into the THI (Tao *et al.*, 2003b). Given the non-linear nature of air velocity, an asymptotic function should be considered (Tao *et al.*, 2003a). The management of broiler chickens' environment, nutrition, vitamin and mineral supplementation, addition of dietary fats, and the implementation of genetic strategies have been extensively researched as means to enhance comfort conditions and maximize production. These research endeavors have led to numerous studies aimed at optimizing these various aspects to ensure the well-being and productivity of broiler chickens (Chen *et al.*, 2005; De Smit *et al.*, 2005; Lin *et al.*, 2006; Daghir, 2008; Biswal *et al.,* 2022; Hoffmann, 2010; Shini *et al.*, 2010;). The studies mentioned earlier have primarily focused on determining the performance of cooling and production systems, as well as assessing the impact of both the environment and nutrition on the well-being of broiler chickens. However, few studies focus on the impact of the weather on chicken mortality (Vale *et al.*, 2008, 2010). It is therefore crucial to assess the future impact of climate change on chicken cooling systems and their impact on animal well-being, especially in hot climate regions such as Tunisia. The evaluation of these impacts is a crucial question that requires urgent attention from poultry farmers to better understand and anticipate the challenges posed by climate change for the poultry industry. Climate models are extensively utilized tools for forecasting the effects of climate change on variables such as temperature, relative humidity, and various aspects of the natural environment. Current climate models are based on mathematical and physical equations and use volumetric grid discretization to represent the atmosphere and oceans. However, this approach has limitations, as it fails to fully capture the strong interactions that occur at various spatial and temporal scales within these complex systems, mainly due to their spatial resolution, which is typically greater than 1° (Giorgi, 2010). Consequently, this leads to uncertainties in regional and local-scale predictions. These uncertainties can have a significant impact on the accuracy of comfort and production parameters for broiler chickens, as well as on the strategic adaptation decisions in the poultry sector within agricultural regions. To tackle this issue, researchers use downscaling techniques, such as the Coordinated Regional Climate Downscaling Experiment (CORDEX). The objective of this study is to evaluate the influence of climate change on the well-being of broiler chickens in the northern regions of Tunisia for the projected period of 2041-2070. This assessment will utilize a direct pad cooling system (DPC) and will also encompass an examination of the frequencies of high mortality rates for the same projection period.

MATERIALS AND METHODS

Climate change projections and study area

This study focuses on evaluating the impact of climate change on the comfort parameters of broiler chickens through the implementation of direct pad cooling systems (DEC). To conduct this assessment, two General Circulation Models (GCMs) were selected: GCM1 (MPI-ESM1.2) and GCM2 (CNRMCM5.1) (Séférian *et al.*, 2013; Eyring *et al.*, 2016). Additionally, two Representative Concentration Pathways (RCPs), namely RCP4.5 and RCP8.5, were considered. The variables utilized for evaluation are the near-surface air temperature (TAS) and near-surface relative humidity (HURS), which were obtained from the CORDEX portal (www.cordex.org/data-access/esgf/). The research team assessed the potential future impact of climate change on comfort conditions and mortality rates for broiler chickens within nine natural regions located in northern Tunisia. These regions are recognized as the primary broiler chicken production areas in the country and are close to the main cities that represent the key consumption areas. The climate models MPI-ESM1.2 and CNRMCM5.1 were applied at a spatial resolution of 0.11° and a temporal resolution of 3 hours downscaled to 1 hours using linear interpolation, resulting in 199 grid cells encompassing the northern Tunisia regions. The geographic coordinates (latitude, longitude) and the number of grid cells used for simulation in each region are provided in Table 1 and Figure1.

The time frame was from 2041 to 2070, representing a medium-term climate projection. To ensure accurate results, systematic errors in TAS forecasts of both models were addressed using a linear adjustment technique (Teutschbein *et al.,* 2012; Dieng *et al.*, 2022; Kim *et al.*, 2023). Additionally, the historical climate projections of both models (MPI-ESM1.2 and CNRMCM5.1) for the period from 1970 to 1997 were compared to those observed in the nine regions in northern Tunisia, where observations were available with less than 10% missing data. Subsequently, bias correction was applied to TAS projections for the period from 2041 to 2070, as explained in (El Melki *et al.*, 2023). The observed climate data were collected from the National Institute of Meteorology (INM) for the period from 1970 to 1997, serving as the reference period for the adjustment of the climate models regarding temperature within the study area.

Table 1 – Natural régions information.

Natural Region	Region Number	Latitude	Longitude	Number of cells
Khemirs' Mountains	1	36.54 to 37.05	8.11 to 9.07	21
Mogods' Mountains	2	36.76 to 37.21	9.14 to 9.57	13
North East Tell	3	36.91 to 37.35	9.67 to 10.22	14
High Medjerda	4	36.6 to 36.43	8.43 to 8.96	07
Middle Medjerda	5	36.64 to 36.75	9.47 to 9.90	05
Lower Medjerda	6	36.67 to 37.03	9.87 to 10.00	06
Mountainous Tell	7	35.92 to 36.65	8.71 to 10.73	60
Maritime Tell	8	36.24 to 36.97	8.66 to 10.69	21
Dorsal Northwestern Side	9	37.27 to 35.07	10.79 to 8.02	52
Total				199

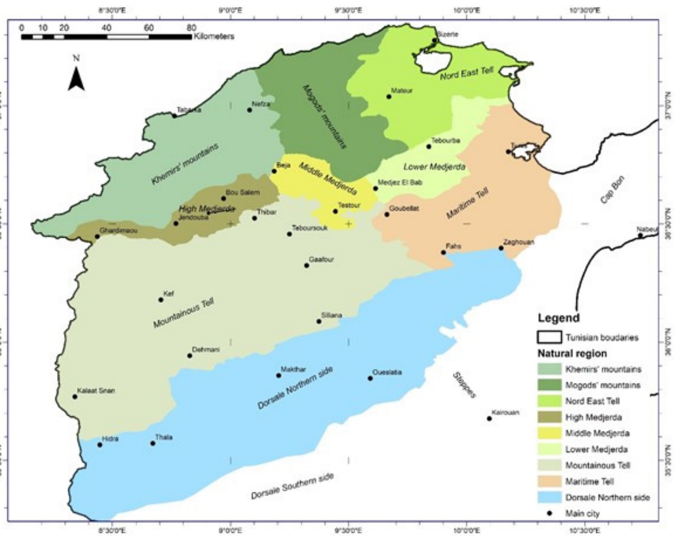

Figure 1 – Natural regions of the study area (Northern Tunisia).

Conceptual flow chart

To evaluate the impact of climate change on the comfort, well-being, and mortality levels (normal mortality, high mortality) of broiler chickens during the critical summer period from June 1st to September 30th, covering 132 days (3168 hours) of monitoring, two types of analyses were conducted in this study. The first analysis aimed to calculate the indicators of comfort and well-being for broiler chickens, encompassing both the historical period (1970-1997) and the future period (2041-2070). The second analysis focused on the evaluation of the mortality level by analyzing the occurrence and frequency of heat waves for both historical and future periods.

Comfort and well-being parameters

The inputs for the DCP system were the historical hourly data of temperature and relative humidity of the air (TAS and HURS) predicted by the MPI-ESM1.2 and CNRMCM5.1 models for the period 1970-1997, and the projected data for the period 2041-2070 under the two projection scenarios RCP4.5 and RCP8.5. The CoolProp software libraries were associated with Matlab R2015a, incorporating the characteristics of the DCP system, such as length, width, air velocity, water flow rate, and saturation efficiency (Figure 3). The dry temperatures and hourly relative humidity of the air at the outlet of the DCP were used for evaluating historical (1970-1997) and projected (2041-2070) comfort parameters, THI and THV. The annual averages of temperatures and relative humidity of the air at the outlet of the air conditioning system (DCP) for each cell in the northern regions of Tunisia were calculated using equations 1 and 2. Similarly,

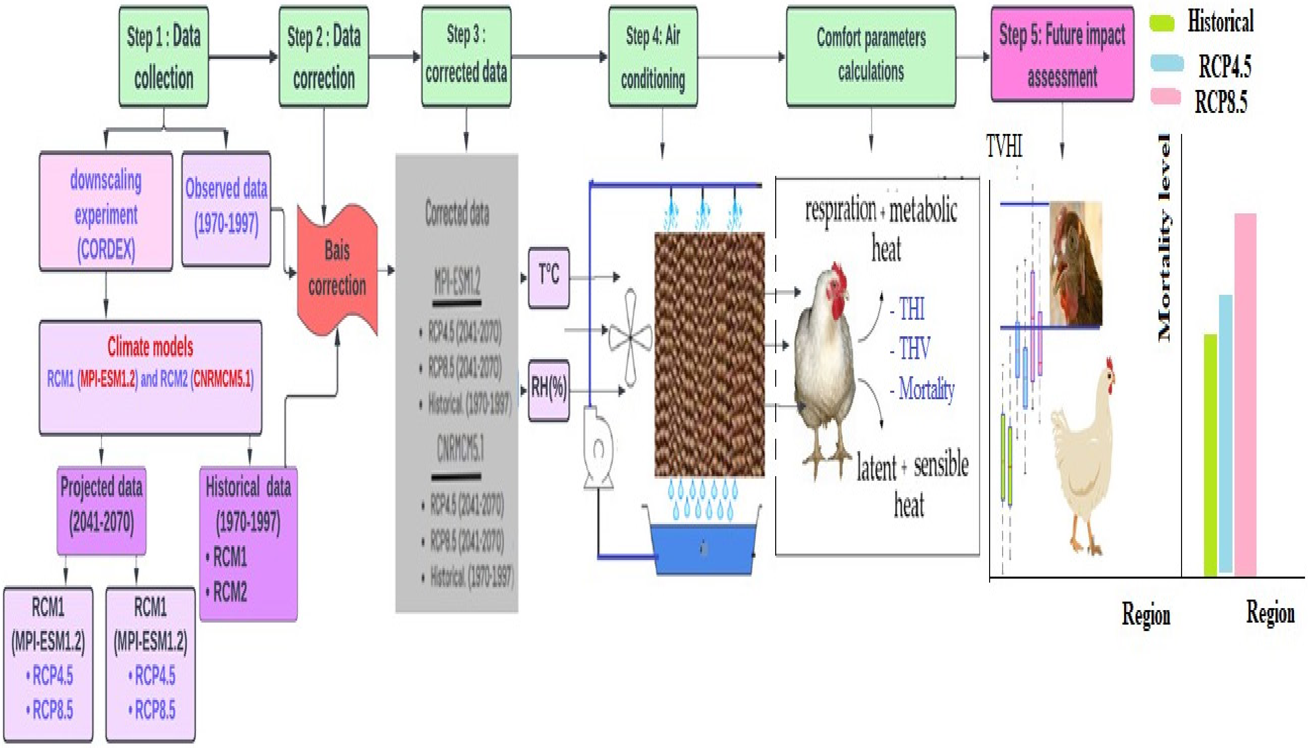

Figure 2 – Conceptual flowchart illustrating the methodology adopted for the evaluation of historical and future comfort conditions, as well mortality levels of broiler chickens when adopting a DCP system.

equations 3 and 4 were used to calculate each natural region's annual temperatures and relative humidity rates.

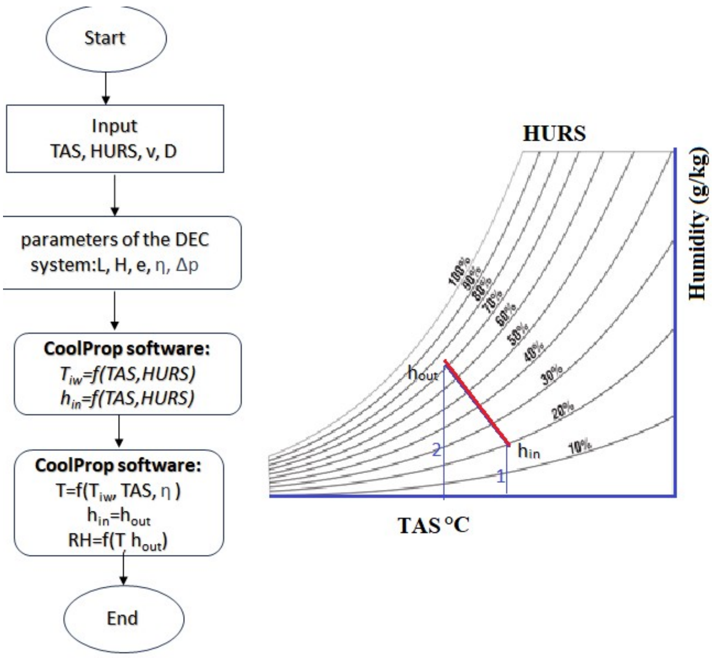

Figure 3 – Direct cooling pad in the psychrometric chart and flowchart of simulation parameters.

In equations 1, 2, 3, and 4, MAT represents the annual mean temperature in °C, MARH represents the annual mean relative humidity of the air in %, k corresponds to the number of hours during the study period (from June 1st to September 30th), and *p* represents the number of grid cells per natural region.

$$\text{MAT/cell} = \frac{1}{3864}\sum_{k=1}^{3864} T_K \quad (1)$$

$$\text{MARH/cell} = \frac{1}{3864}\sum_{k=1}^{3864} RH_K \quad (2)$$

$$\text{MAT / natural region} = \frac{1}{p}\sum_{p=1}^{n} \text{MAT / grid cell} \quad (3)$$

$$\text{MARH / natural region} = \frac{1}{p}\sum_{p=1}^{n} \text{MAT / grid cell} \quad (4)$$

Mortality level evaluation

According to (Robinson, 2001; Nienaber *et al.*, 2004; Vale *et al.*, 2010), for broiler chickens aged between 30 and 50 days, a period is classified as a heatwave if it lasts between one and five consecutive days, or if its average duration is 2.7 days, with a THI (Temperature-Humidity Index) exceeding 30.6 °C. In this study, the selection of heatwave periods and the calculation of their annual frequency for the 132 days of the monitored period (from June 1st to September 30th) were based on an average duration of 2.7 days. A Matlab code was developed to calculate heatwaves and their annual frequency for the 199 projection cells in the northern regions of Tunisia. The data used for these calculations come from historical temperature and relative humidity predictions from the NRMCM5.1 and MPI-ESM1.2 models for the period 1990-1997, as well as projection data related to the RCP4.5 and RCP8.5 scenarios for the period 2041 - 2070. These data were initially used as input parameters for the Matlab code to determine the hourly values of the Temperature-Humidity Index (THI) for each year during the 30 years of the historical period and the 30 years of the projection period, specifically for the control period (from June 1st to September 30th). The THIS is calculated using Equation 6, which is specified below. Heatwaves were defined as 64.8 consecutive hours (equivalent to 2.7 days) during which the THI was greater than or equal to 30.6. Each year, the output of the Matlab code provided the number of recorded heatwave events for the 199 cells in the northern regions of Tunisia. The annual number of heatwaves per natural region was calculated using equation 5.

$$f_p = \frac{1}{p}\sum_{k=1}^{p} n_p, (THI \geq 30.6°C) \quad (5)$$

In equation 5, p is the number of cells per natural region, and n_p is the number of heatwaves per cell.

Temperature-humidity index (THI) model

The thermal environment plays a crucial role in the metabolism and energy exchanges of animals. Managing thermal stress, whether due to heat or cold, is essential for improving animal health, well-being, and productivity. Thermal comfort indices have been used to assess the impact of climate change on the regulation of body temperature in broiler chickens at the 2041-2070 period as compared to the historical period (1970-1997) (Chepete *et al.*, 2005; Purswell *et al.*, 2012). The THI, a particularly common index, is derived from a linear combination of dry-bulb and wet-bulb air temperatures. It allows for an evaluation of the effect of the thermal environment on the temperature regulation of broiler chickens. This parameter is a valuable tool for assessing broiler chickens' responses to their thermal environment, allowing for the improvement of their comfort and overall performance. The THI can be calculated using equation 6.

$$THI = 0.85T_{db} + 0.15T_{wb} \quad (6)$$

Where Tdb is the dry-bulb temperature of the air and Twb is the wet-bulb temperature of the air. While air properties and the psychrometric chart are commonly used to calculate the wet-bulb temperature, humidity sensors can also be utilized to obtain accurate results. The empirical model proposed by (Stull, 2011), described by equation 7, is highly predictive of the wet-bulb temperature in poultry farming facilities. This model has a mean error of 0.0052 °C, median error of 0.026 °C, mean absolute error of 0.28 °C, and coefficient of determination (R^2) of 99.95%, making it a reliable method for analyzing the comfort conditions of broiler chickens in a farming environment (Bruno., 2011; Cole *et al.*, 2014; Doˇgramacı *et al.*, 2020; Raza *et al.*, 2020); C¸ aylı *et al.*, 2021).

$$T_{wb} = \tan^{-1}\left(1 + 0.5\sqrt{RH + 8.313659}\right) + \tan^{-1}(T + RH) + \tan^{-1}(RH - 1.676331) + 0.00391838(RH)^{\frac{3}{2}}\tan^{-1}(0.023101RH) - 4.68603 \quad (7)$$

Where T_{wb} represents the wet-bulb temperature (°C), *T* is the dry-bulb temperature (°C), and *RH* is the relative humidity (%).

Temperature-humidity-velocity index model

In this study, we utilized the temperature-humidity-velocity index (THVI) to evaluate the effect of air velocity on the well-being of broiler chickens while adopting a DCP system both in the past (1970-1997) and the future (2041-2070). The THVI was calculated using equation 8, developed by (Tao *et al.*, 2003b).

$$THVI = V^{0.058}THI \quad (8)$$

According to (Yahav *et al.*, 2001), air velocities ranging from 1.5 to 2.0 m/s are considered optimal for maintaining excellent performance in broiler chickens during rigorous summer periods. Likewise, a research conducted by Czarick & Fairchild (2008). has demonstrated that air velocities up to 3 m/s contribute to optimal weight gain and significantly improve feed conversion ratios during hot periods. In this study, specific air velocities of 1, 1.5, 2, 2.5, and 3 m/s were chosen to establish a range from minimum to maximum values, with the purpose of analyzing the future impact of climate change on the comfort of broiler chickens.

Statistical Analysis

In order to assess the future impacts of climate change on the comfort conditions of broiler chickens, an analysis of variance (ANOVA) was conducted to evaluate the variability of the Temperature-Humidity Index (THI). The annual averages of historical temperature-humidity indices over a 30-year period

Table 2 – Analysis of Variance of THI in terms of the Historical Models (RCP4.5 and RCP8.5), Natural Regions of Tunisia, and Their Interaction.

Source	Sum of Squares	df	Mean Square	F	Prob
RCP/Historical	3311.691	2	1655.845	854.808	0.000
Natural regions	199.686	8	24.961	12.886	0.000
RCP x Natural regions	0.972	16	0.061	0.031	1.000
Error	3085.793	1593	1.937		
Total	6598.141	1619			

(1970-1997), obtained from the NRMCM5.1 and MPI-ESM1.2 models, as well as the projected indices for the future period (1941-1970) derived from the same models under the RCP4.5 and RCP8.5 scenarios, were considered for the 9 natural regions of Tunisia. The results of this analysis are interpreted with a significance level of 0.05. The Wilcoxon test at the 5% significance level was used to compare historical mortality levels with projected ones, taking into account the reference scenarios RCP4.5 and RCP8.5 from the NRMCM5.1 and MPI-ESM1.2 models.

RESULTS

Temperature-Humidity Index (THI) analysis

The ANOVA analysis applied to the THI indicates a significant difference between the northern regions of Tunisia as well as climatic scenarios for evaluating the comfort of broiler chickens in the context of climate change. The two historical climate scenarios RCP4.5 and RCP8.5, for both the NRMCM5.1 and MPI-ESM1.2 models, historical data from the same models, and the nine natural regions have all been identified as significant to the THI. The RCP factor (RCP4.5 and RCP8.5), representing different trajectories of gas emissions, exhibited a notable impact on the THI with a substantial F-statistic of 854.8. This value suggests that future gas emissions and climate warming will exert a significant influence on the thermal comfort and well-being of broiler chickens. Similarly, the pronounced influence of historical data underscores the importance of prior conditions in understanding and anticipating future comfort conditions. The THI averages during the historical period were respectively 23.24 and 24.05 for the NRMCM5.1 and MPI-ESM1.2 models. Meanwhile, projections for the 2041-2070 period under the RCP4.5 and RCP8.5 scenarios were 26.44 and 27.10, high- lighting a trend towards an increase by the 2100 horizon. Furthermore, the natural regions exhibited a significant influence (F = 12.886), shedding light on the impact of the geographic location of poultry farms on the comfort conditions of broiler chickens. Hahn *et al* (2009) defined different stress ranges based on the THI for ruminants, while the corresponding values for non-sweating animals such as poultry and pigs are as follows: normal THI <=27.8, moderate THI between 27.8 and 28.8°C, severe THI between 28.9 and 29.9°C, and very severe THI (emergency) 30°C (Marai *et al.,* 2001). As for the historical simulation for the period (1970-1997), THI ranged from 23.46°C to 25.35°C for the NRMCM5.1 model (Figure 4), and a from 23°C to 24.35°C for the RCM2 model, offering normal average THI values (Figure 4). However, future projections obtained by the NRMCM5.1 and MPI-ESM1.2 models for the period 2041-2070 indicate a moderate average THI higher than or equal to 26°C for the RCP4.5 scenario. Similarly, the RCP8.5 scenario shows a severe THI average, ranging from 27 to 29°C.

Temperature-Humidity-Velocity - Index (THI) analysis

Table 3 and Figures 4 to 8 present the predicted values of the Temperature- Humidity- Velocity Index (THVI) for different air velocities (1, 1.5, 2, 2.5, and 3 m/s) in the 9 natural regions of northern Tunisia,

Table 3 – THVI Index Variation in Northern Tunisia.

Model	Scenario	1.0	1.5	2.0	2.5	3.0
NRMCM5.1	Historical	23.17 - 24.35	22.63 - 23.78	22.85 - 23.39	21.97 - 23.00	21.74 - 22.84
	RCP4.5	23.21 - 26.43	25.81 - 27.07	26.31 - 27.50	27.14 - 25.97	24.79 - 26.00
	RCP8.5	27.39 - 28.62	26.75 - 27.96	26.31 - 27.50	27.14 - 25.97	26.86 - 25.70
MPI-ESM1.2	Historical	23.60 - 24.49	23.05 - 23.92	22.67 - 23.52	22.38 - 23.22	22.15 - 23.97
	RCP4.5	25.79 - 26.65	25.19 - 26.03	24.78 - 25.60	24.46 - 25.27	25.01 - 24.20
	RCP8.5	26.70 - 27.72	26.08 - 27.08	26.63 - 25.65	25.32 - 26.29	25.05 - 26.01

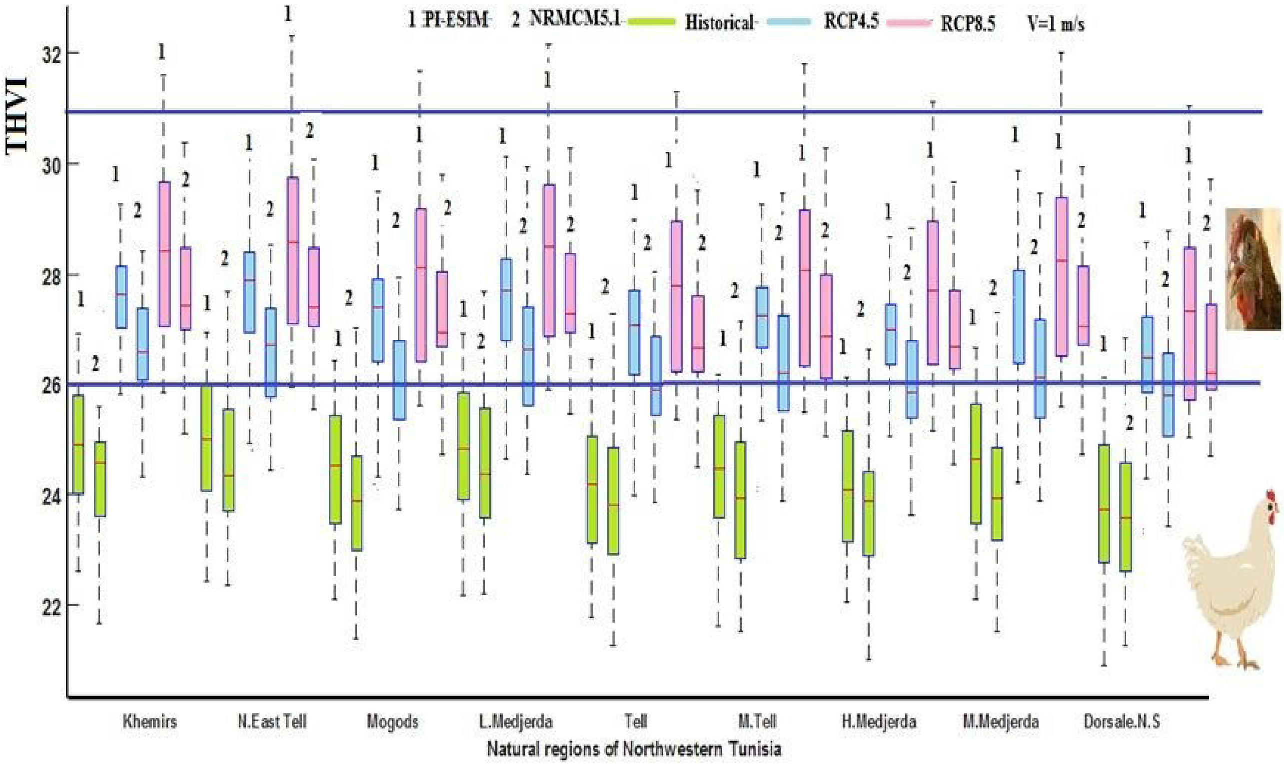

Figure 4 – Historical and projected temperature-humidity-velocity index (THVI) data predicted by the NRMCM5.1 and MPI ESM1.2 models for the northern regions of Tunisia from June 1st to September 30th for air velocity of 1m/s.

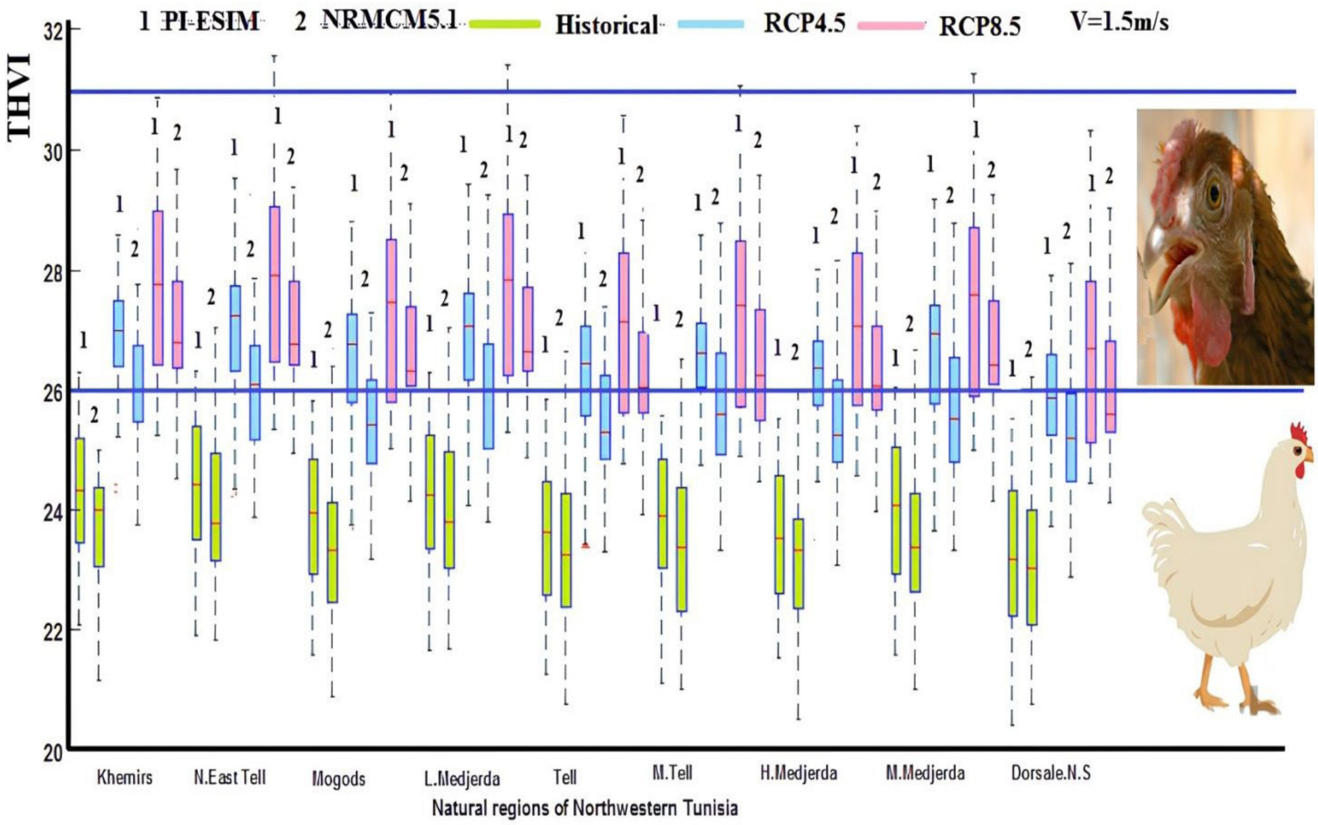

Figure 5 – Historical and projected temperature-humidity-velocity index (THVI) data predicted by the NRMCM5.1 and MPI-ESM1.2 models for the northern regions of Tunisia from June 1st to September 30th for air velocity of 1.5m/s.

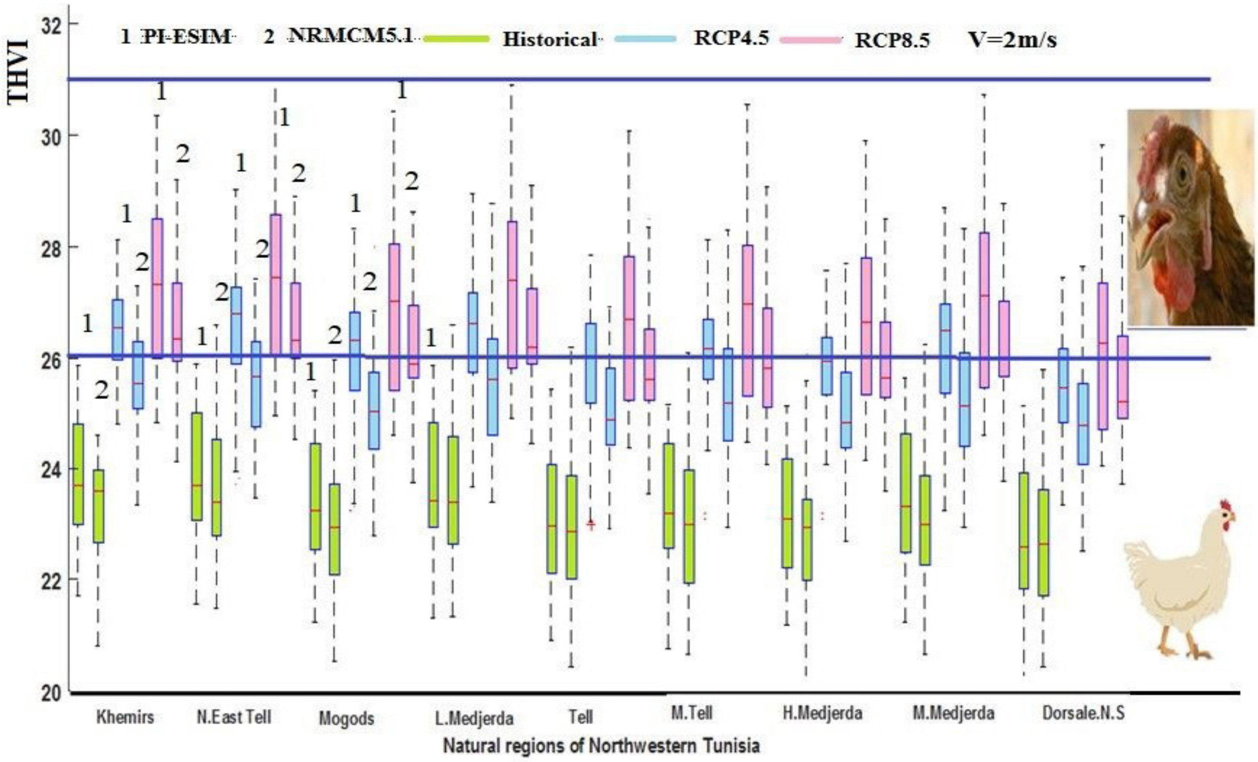

Figure 6 – Historical and projected temperature-humidity-velocity index (THVI) data predicted by the NRMCM5.1 and MPI-ESM1.2 models for the northern regions of Tunisia from June 1st to September 30th for air velocity of 2m/s.

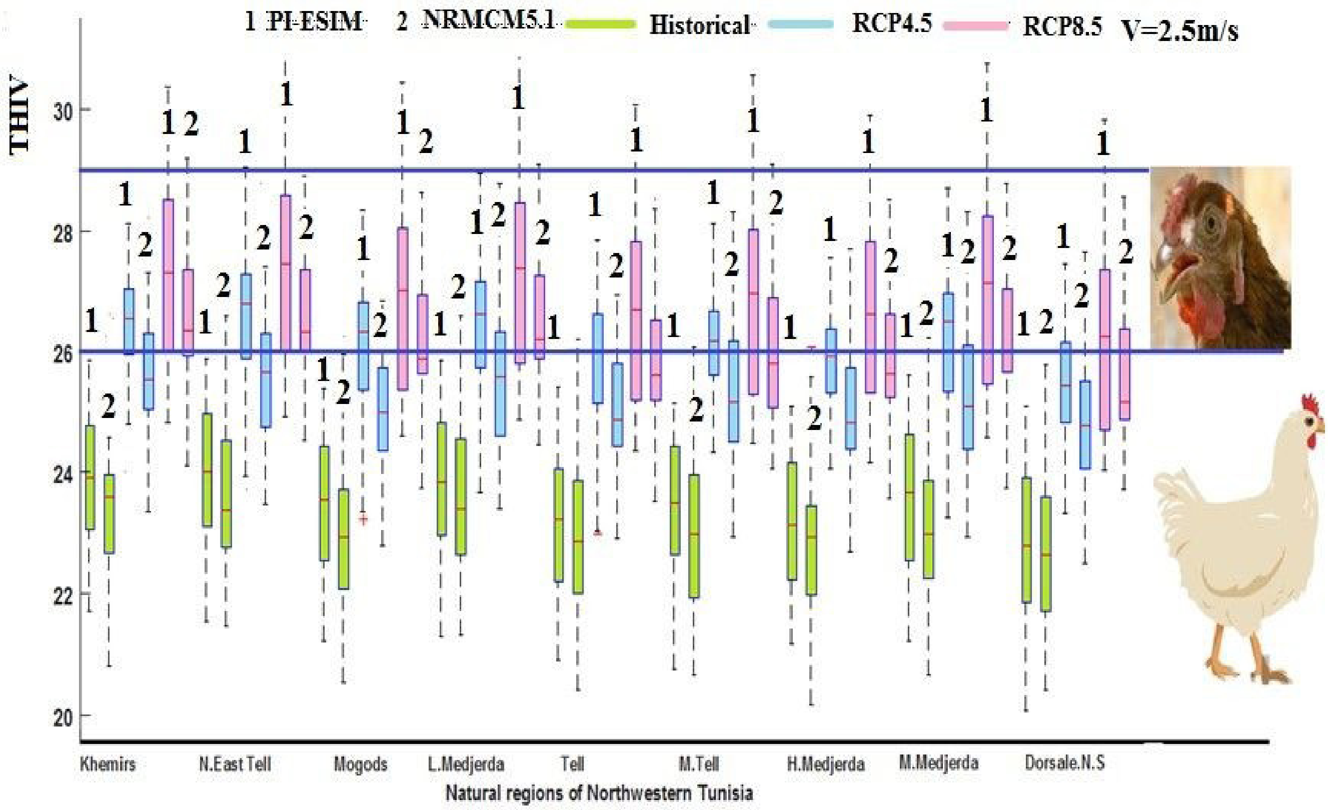

Figure 7 – Historical and projected temperature-humidity-velocity index (THVI) data predicted by the NRMCM5.1 and MPI-ESM1.2 models for the northern regions of Tunisia from June 1st to September 30th for air velocity of 2.5m/s.

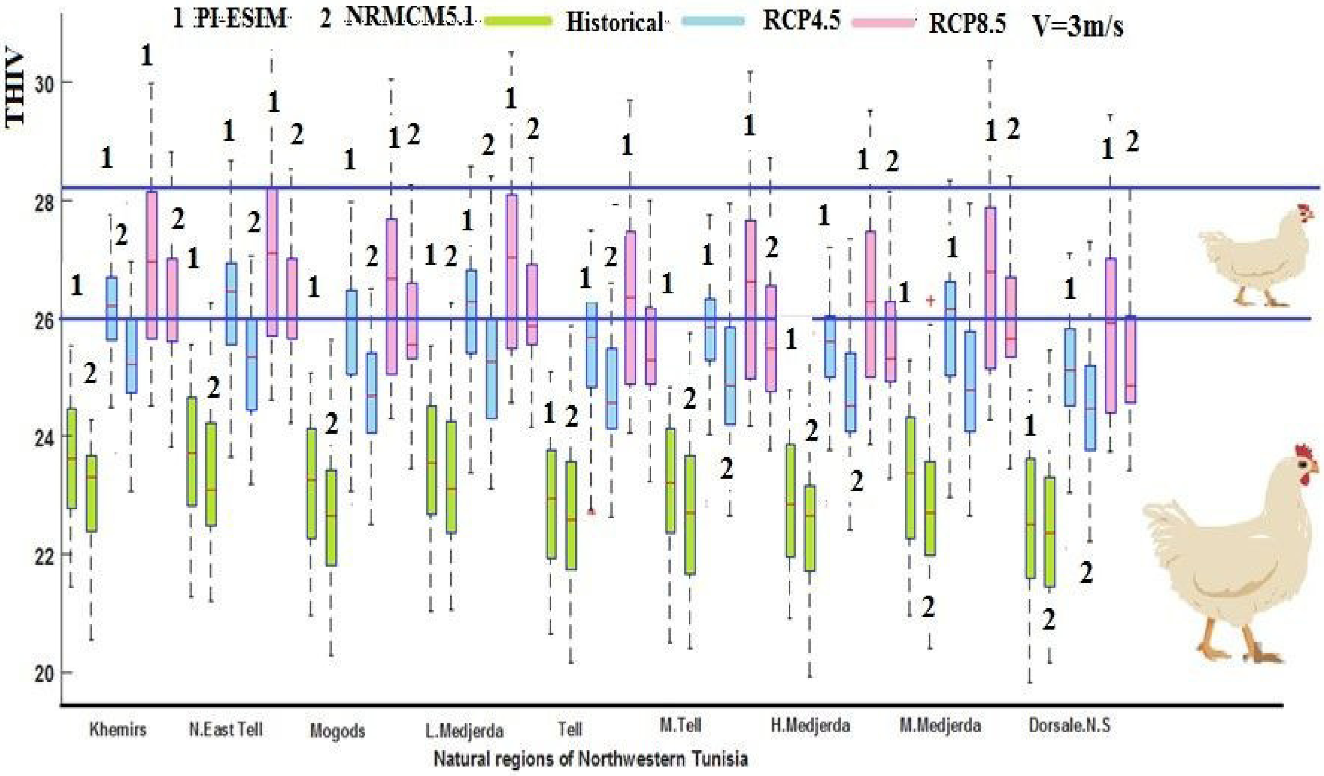

Figure 8 – Historical and projected temperature-humidity-velocity index (THVI) data predicted by the NRMCM5.1 and MPI-ESM1.2 models for the northern regions of Tunisia from June 1st to September 30th for air velocity of 3m/s.

according to the NRMCM5.1 and MPI-ESM1.2 models. The results from historical predictions (1970-1997) and projections for the RCP4.5 251 and RCP8.5 scenarios by both models (NRMCM5.1 and MPI-ESM1.2) indicate a decrease in THVI with an increase in air velocity at the exit of the DPC system, suggesting an improvement in the comfort and well-being conditions of broiler chickens. Air velocities between 2 and 3 m/s may contribute to better aeration of the poultry washing areas and less stressful climatic conditions for broiler chickens, thereby reducing the risk of thermal stress. During the historical period (1970-1997), the predictions from the NRMCM5.1 and MPI-ESM1.2 models show moderate THVI values, ranging from 21.74 to 24.49 for different air velocities. However, future projections obtained from the NRMCM5.1 and MPI-ESM1.2 models, as well as the RCP4.5 and RCP8.5 scenarios for the period 2041-2070, indicate a trend towards hotter and potentially more hazardous conditions for broiler chickens. THVI values increase significantly for both scenarios, reaching up to 28.62 for RCP8.5 at an air velocity of 1m/s.

Impact of climate change on mortality levels

The table reveals a significant and striking distinction between the projected mortality levels (high, normal) of the historical period (1970-1997) and those of the future projections (2041-2070) obtained using the NRMCM5.1 and MPI-ESM1.2 models. The Wilcoxon analysis compellingly highlights the potential impact of climate change on mortality levels across all regions of northern Tunisia. Furthermore, figure 9 shows the annual average frequency of high mortality for the reference period of June 1st to September 30th, which stays below or equal to 1 during the historical period (1970-1997) for both projection models.

However, it is noteworthy that future projections in both projection models (NRMCM5.1 and MPI-ESM1.2) reveal elevated high mortality frequencies, ranging from 1.2 to 1.6 for the optimistic scenario (RCP4.5) and from 1.3 to 2.2 for the pessimistic scenario (RCP8.5). Considering both models, the results indicate an increase in mortality when comparing historical and projected scenarios.

DISCUSSION

In order to assess the impact of climate change on the well-being and mortality rates of broiler chickens during the critical summer period for the timeframe of 2041-2070, we applied the projected temperature and relative humidity from the NRMCM5.1 and MPI-ESM1.2 models. These models were selected due

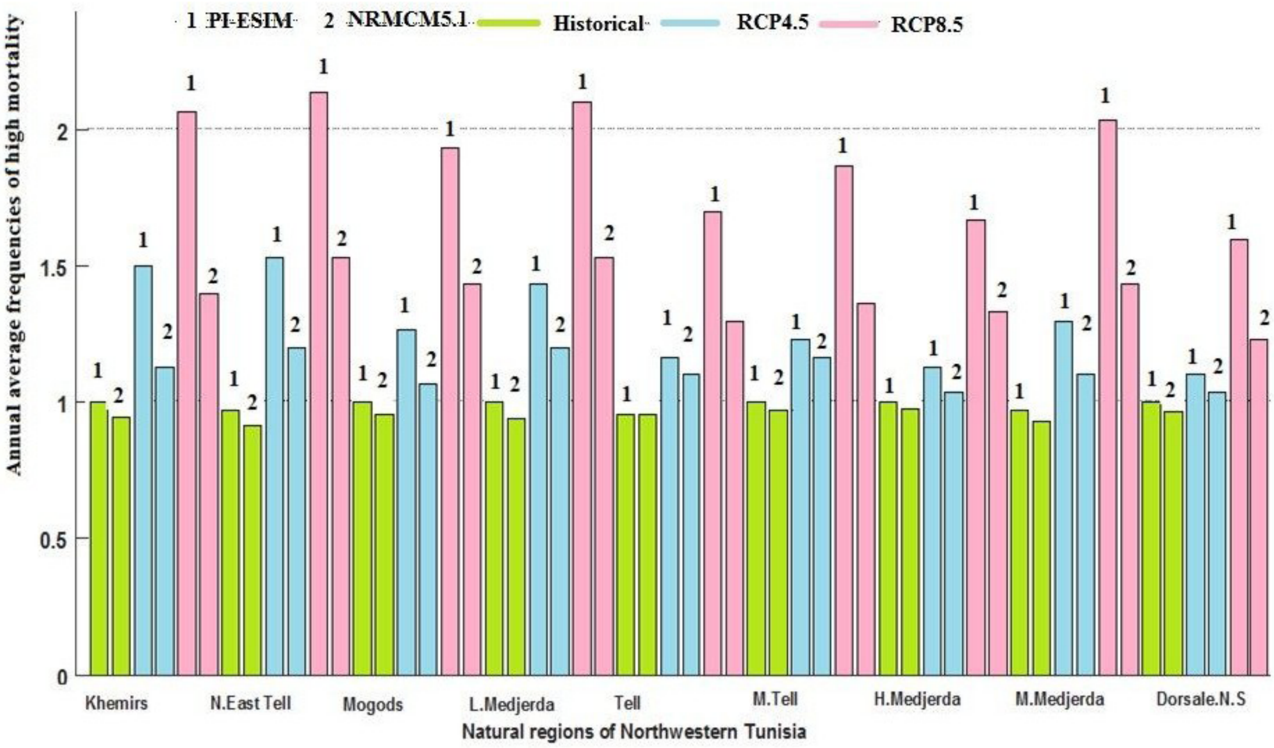

Figure 9 – Historical and projected data of the annual level of high mortality predicted by the NRMCM5.1 and MPI-ESM1.2 models for the northern regions of Tunisia from June 1st to September 30th.

to their relevance in evaluating historical comfort conditions and observed mortality rates from 1970 to 1997, as well as projecting future scenarios (2041-2070) under RCP4.5 and RCP8.5 conditions.

The findings derived from these models, in conjunction with those from the direct evaporative cooling system, reveal alarming trends for the comfort of broiler chickens across the nine regions of northern Tunisia. Future projections indicate a significant increase in THI and THVI, suggesting a potentially heightened risk of thermal stress. Specifically, the projections indicate an average THI increase of 2.2°C and an average THVI elevation of 1.5°C under the pessimistic scenario (RCP8.5), which is a substantial impact projection.

With regard to future mortality (2041-2070), the analysis reveals a noteworthy surge in mortality rates under both the RCP4.5 and RCP8.5 scenarios. Average mortality rates could escalate from 0.8 to 1.3 in the pessimistic scenario (RCP8.5) and from 0.6 to 1.1 in the optimistic scenario (RCP4.5). These findings starkly underscore the potentially devastating effect of climate change on the poultry industry in 2041-2070. Confronted with these pivotal challenges, the assessment of the impact of climate change on well-being conditions and mortality rates becomes an urgent imperative for Tunisian farmers. Nevertheless, it is crucial to recognize the prevalence of research focusing on strategies aimed at optimizing dietary intake to enhance the availability of metabolizable energy for peak performance. While innovative approaches are being explored, such as increasing the proportion of energy derived from fats in the diet, it is imperative to consider the potential hazards associated with fat rancidity.

Furthermore, achieving a balanced intake of amino acids, particularly methionine and lysine, takes on critical importance to address potential deficiencies stemming from inadequate protein consumption. Additionally, low-protein diets could be recommended to reduce heat production induced by protein digestion, which generates more heat compared to the digestion of other nutrients. Moreover, the incorporation of antioxidant vitamins such as Vitamins A, C, and E could enhance the performance of broiler chickens by mitigating the detrimental impacts of oxidative stress during heat periods.

The adoption of a wet feeding approach has shown promise in optimizing the final weight and weight gain of chickens in hot environments. Previous studies have demonstrated that this method could stimulate increased water consumption, thereby facilitating adequate evaporation through panting and contributing to the thermal regulation of chickens. This approach could prove particularly advantageous during periodsof intense heat (Awojobi *et al.*, 2009; Dei *et al.*, 2011; Syafwan *et al.*,2011), thereby strengthening the resilience of poultry farms in face of mounting climate challenges.

Nonetheless, despite these adaptations, it is crucial to note that modern broiler chicken breeds, selectively bred for heightened feed efficiency and rapid growth, are increasingly susceptible to the ramifications of climate change. Rapid growth demands that housing systems consistently maintain an optimal thermal environment year-round to protect chickens from extreme weather conditions. This, in turn, entails heightened energy consumption for heating, cooling, and ventilation systems (Bell *et al.*, 2001).

Many current studies often focus on specific aspects such as enhancing cooling systems, optimizing breeds, and devising feeding strategies to mitigate heat stress resulting from climate change (Liang *et al.*, 2014; Izar-Tenorio *et al.*,2020; Çayli *et al.*, 2021; de Carvalho Curi *et al.,* 2022). However, in summary, a comprehensive approach is crucial to comprehend the complex impacts of climate change on broiler chicken performance. It is vital to meticulously examine the consequences of projected climate models, optimized feeding strategies, and adaptable housing practices to ensure the resilience and sustainability of the poultry industry in the face of escalating climate challenges. To better understand and manage the multifaceted repercussions of climate change on poultry farming, adopting an integrated approach is imperative. An integrative optimization study could provide valuable insights by simultaneously considering ongoing climate changes, the genetic influence on animal performance, cooling system efficiency, and economic factors related to costs and production duration. By seamlessly integrating these diverse components, such a study could guide the development of more comprehensive and effective adaptation strategies, aiming to ensure both the economic viability and environmental sustainability of poultry farming in the face of impending climate challenges. To assess the impact of climate change on the well-being and mortality rates of broiler chickens during the critical summer period and the period 2041-2070, we employed temperature and relative humidity projections from the NRMCM5.1 and MPI-ESM1.2 models. These models were chosen for their relevance in assessing historical comfort conditions and observed mortality rates from 1970 to 1997, as well as for projecting future scenarios (2041-2070) under the RCP4.5 and RCP8.5 conditions. Results derived from these models, combined with the direct cooling pad system, reveal concerning trends regarding the comfort of broiler chickens in the nine northern regions of Tunisia. Future projections indicate a significant increase in THI (Temperature-Humidity Index) and THVI (Temperature-Humidity-Vapor Pressure Index), suggesting a potentially heightened risk of thermal stress. Specifically, the pro- ejections indicate an average THI increase of 2.2°C and an average THVI increase of 1.5°C in the pessimistic scenario (RCP8.5), highlighting the considerable magnitude of the projected impact.

Regarding future mortality (2041-2070), the analysis reveals a notable increase in mortality rates under both the RCP4.5 and RCP8.5 scenarios. Average mortality rates could increase from 0.8 to 1.3 in the pessimistic scenario (RCP8.5) and from

0.6 to 1.1 in the optimistic scenario (RCP4.5). These results strikingly underscore the potentially devastating effect of climate change on the poultry industry by 2041-2070. Faced with these crucial challenges, the assessment of climate change impact on well-being and mortality rates becomes an urgent imperative for Tunisian farmers. Nevertheless, it is crucial to recognize the dominant prevalence of research focused onstrategies aimed at optimizing feed intake to enhance metabolizable energy availability for optimal performance. While innovative approaches like increasing the proportionof fat-derived energy in the diet are being studied, it's imperative to consider the potential risks associated with fat rancidity.

Furthermore, achieving a balanced intake of amino acids, especially methionine and lysine, holds crucial importance to address potential deficiencies resulting from inadequate protein consumption. Advocating for low-protein diets might be recommended to reduce heat production induced by protein digestion, which generates more heat compared to the digestion of other nutrients. Incorporating antioxidant vitamins such as vitamins A, C, and E could also enhance broiler performance by mitigating the adverse effects of oxidative stress during heat periods.

The adoption of a wet feeding approach has shown promise in optimizing final weight and weight gain of chickens in hot environments. Previous studies have demonstrated that this method could stimulate increased water consumption, thereby facilitating adequate evaporation through panting and contributing to chicken thermoregulation. This approach could be particularly advantageous during periods of intense heat, enhancing the resilience of poultry farms against growing climate challenges.

However, despite these adaptations, it is essential to note that modern broiler breeds, selectively bred for increased feed efficiency and rapid growth, are becoming increasingly sensitive to the ramifications of climate change. Rapid growth demands constant maintenance of optimal thermal environments throughout the year to protect chickens from extreme weather conditions. This, in turn, leads to increased energy consumption for heating, cooling, and ventilation systems.

Numerous current studies focus on specific aspects such as improving cooling systems, optimizing breeds, and designing feeding strategies to alleviate thermal stress resulting from climate change. However, studies on housing, stocking density, and adiabatic cooling have revealed varying results. For instance, Sartori *et al.* (2001) found thatpad cooling systems coupled with ventilation improved weight gains, feed conversion, and reduced mortality. In contrast, Bueno *et al.* (2006) observed below-standard performances in terms of daily weight gain in conventional and high-density housing systems. Studies on different ventilation systems have not shown significant differences in terms of poultry performance, mortality, and foot injuries (Bueno *et al.,* 2006). Semi-intensive rearing systems have positively influenced bird welfare and performance, as demonstrated by Silva *et al.* (2003). However, de Souza *et al.* (2010) observed better bird performance in non-automated shelters during winter and spring, highlighting the impact of various factors on poultry performance. Similarly, the natural management of thermal regulation represents an additional alternative to improve the comfort conditions of broiler chickens. Indeed, without resorting to sophisticated mechanical devices, this approach involves the meticulous selection of the building's location, its orientation, the judicious choice of effective natural ventilation, and the use of materials with high heat capacity to withstand temperature variations, such as roof thermal insulators. According to Tinoco (1995), the use of materials with high heat capacity is a less costly alternative compared to the use of artificial thermal regulation systems. The roof plays a crucial role in receiving solar radiation and transmitting it inside the facility. The amount of radiation reaching the birds depends on the type of roofing material used, and the possible presence of thermal insulation below. According to Nääs (1994), thermal insulation is generally the most effective and economical solution to improve the environmental conditions of buildings in general. The use of a ceiling under the roof is one of the most commonly adopted methods of thermal insulation, contributing to increasing the comfort of birds by reducing thermal transmission and increasing their inertia. Another crucial aspect related to thermal transmission is the reduction of thermal amplitude in the poultry house, which, if too significant, can cause harm to the birds (Nääs, 1995). According to McFerran (1993), poultry facilities with quality thermal insulation offer better economic returns and limit the occurrence of dermatitis related to excessive moisture in the litter. This author also emphasizes that the most detrimental consequences of excessively humid litter result in the deterioration of bird feed conversion. A comprehensive approach is essential to grasp the complex impacts of climate change on broiler chicken performance. It is crucial to analyze the consequences of cli mate projections, optimal feeding strategies, and adaptable housing practices to ensurethe resilience and sustainability of the poultry industry against increasing climate-related challenges. Adopting an integrated approach is imperative to better manage the multiple repercussions of climate change on poultry farming. An integrative optimization study could provide valuable insights by simultaneously considering ongoing climate changes, the influence of genetics on broiler chicken performance, cooling system efficiency, and economic factors related to costs and production duration. By transparently incorporating these different elements, such a study could guide the development of more comprehensive and effective adaptation strategies, aiming to ensure the economic and environmental viability of poultry farming against upcoming climate challenges.

CONCLUSION

This study sheds light on the critical implications of climate change for broiler chicken welfare and mortality rates in the northern regions of Tunisia. The findings underscore the pressing need for proactive adaptation strategies within the poultry industry to mitigate the potentially devastating impacts of rising temperatures and altered humidity levels. The projected increases in Temperature-Humidity Index (THI) and Temperature-Humidity-Velocity Index (THVI) under the pessimistic RCP8.5 scenario reveal a significant elevation in the risk of thermal stress. Additionally, the projected rise in mortality rates, particularly under the RCP8.5 scenario, further highlights the urgency of addressing climate change's impact on poultry farming. The integration of historical data and future projections from advanced climate models provides valuable insights into the potential challenges that lie ahead. The adoption of comprehensive mitigation and adaptation strategies, encompassing genetic selection, dietary optimization, and innovative housing approaches, becomes imperative to safeguard the sustainability and profitability of poultry farming in the face of changing climatic conditions. The complexities presented by climate change require a holistic and interdisciplinary approach, engaging stakeholders across the poultry industry, scientific community, and policy-making spheres. As global temperatures continue to rise, the collaboration between these different stakeholders becomes paramount in developing resilient strategies that ensure the well-being of broiler chickens and the economic stability of poultry farming.

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