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Experiments on Energy-Efficient Evaporative Cooling Systems for Poultry Farm Application in Multan (Pakistan)

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Citation: Shahzad, K.; Sultan, M.; Bilal, M.; Ashraf, H.; Farooq, M.; Miyazaki, T.; Sajjad, U.; Ali, I.; Hussain, M.I. Experiments on Energy-Efficient Evaporative Cooling Systems for Poultry Farm Application in Multan (Pakistan). *Sustainability* **2021**, *13*, 2836. https://doi.org/10.3390/su13052836

Academic Editors: Muhammad Sultan, Yuguang Zhou, Redmond R. Shamshiri and Aitazaz A. Farooque

Received: 17 January 2021
Accepted: 25 February 2021
Published: 5 March 2021

Abstract: Poultry are one of the most vulnerable species of its kind once the temperature-humidity nexus is explored. This is so because the broilers lack sweat glands as compared to humans and undergo panting process to mitigate their latent heat (moisture produced in the body) in the air. As a result, moisture production inside poultry house needs to be maintained to avoid any serious health and welfare complications. Several strategies such as compressor-based air-conditioning systems have been implemented worldwide to attenuate the heat stress in poultry, but these are not economical. Therefore, this study focuses on the development of low-cost and environmentally friendly improved evaporative cooling systems (DEC, IEC, MEC) from the viewpoint of heat stress in poultry houses. Thermodynamic analysis of these systems was carried out for the climatic conditions of Multan, Pakistan. The results appreciably controlled the environmental conditions which showed that for the months of April, May, and June, the decrease in temperature by direct evaporative cooling (DEC), indirect evaporative cooling (IEC), and Maisotsenko-Cycle evaporative cooling (MEC) systems is 7–10 °C, 5–6.5 °C, and 9.5–12 °C, respectively. In case of July, August, and September, the decrease in temperature by DEC, IEC, and MEC systems is 5.5–7 °C, 3.5–4.5 °C, and 7–7.5 °C, respectively. In addition, drop in temperature-humidity index (THI) values by DEC, IEC, and MEC is 3.5–9 °C, 3–7 °C, and 5.5–10 °C, respectively for all months. Optimum temperature and relative humidity conditions are determined for poultry birds and thereby, systems' performance is thermodynamically evaluated for poultry farms from the viewpoint of THI, temperature-humidity-velocity index (THVI), and thermal exposure time (ET). From the analysis, it is concluded that MEC system performed relatively better than others due to its ability of dew-point cooling and achieved THI threshold limit with reasonable temperature and humidity indexes.

Keywords: poultry farms; air-conditioning; evaporative cooling systems; temperature-humidity index; temperature-humidity-velocity index

1. Introduction

1.1. Background

The agriculture sector of Pakistan contributes to about 21% of the gross domestic product (GDP) and absorbs 45.5% of the total labor strength [1]. The total share of livestock sector in agriculture covers about 11.4% of the agriculture gross domestic product and 53.25% of the value-added products [2]. Among the livestock sector, poultry contributed about 1.4% in overall gross domestic product (GDP) during (2017–18) [3]. It also employs directly/indirectly 1.5 million people [4]. Furthermore, the poultry meat production amounted to total 1.43 million tons in 2017–2018 which represented the 32.76% of the total meat production in the country. Keeping in view the economic importance of poultry, it is desirable to monitor the environmental condition for their control sheds where several flocks are brought up on yearly basis. A huge amount of capital is invested to raise the controlled structures. Therefore, minor risks either by labor or machine are vulnerable to poultry. Pakistan is recognized as a tropical country being along the equator on globe.

Climate change causes an increase in frequency, duration, and magnitude of heat events [5,6]. Tropical countries are susceptible to hot and humid weather conditions [7]. In Pakistan, there is a cycle of four seasons giving temporal variations. Summer and winter reach the intense weather conditions. Over this course of time, temperature hits above 40 °C and the corresponding mark of relative humidity drops below 20% in plain areas during summer. Poultry birds are susceptible to environmental conditions. It is advisory to control these factors that adversely affect the production and welfare of broiler chickens. Heat stress is the major contributory force to affect the fate of these broilers. Poultry birds are homoiothermic in nature and have the ability to control the body temperature throughout the year whereas, the thermoregulatory mechanisms are efficient only in the range of thermo-neutral zones (27.5–37.7 °C) [8,9]. The current study consists of the applicability of evaporative cooling systems in the ambient conditions of Multan, Pakistan. To maintain the thermal comfort in a poultry farm, air-conditioning is necessary [10,11]. Figure 1a,b shows the dry-bulb temperature (DBT) and relative humidity (RH) variation for Multan (Pakistan) throughout the year. It is found from the literature that the temperature higher than 25 °C causes heat stress in poultry [12]. This study comprises the poultry thermal comfort under the ambient conditions of Multan, Pakistan. The suitable relative humidity ranges from the efficiency of the poultry farms and the chickens get affected by this temperature-humidity index (THI) [13]. Once these situations reach poorly managed controlled houses for poultry, the mortality rate per flock increases.

Pursuing this trend, growth of chickens is depressed, and heavy economic loss is incurred. High temperatures can be absorbed by the poultry birds to some extent but may go negatively when summer conditions turn severely warm with low humidity in ambient air.

1.2. Heat Stress and Poultry Air-Conditioning

Heat stress is a key problem affecting both the health and performance of the poultry [14]. The chickens try to maintain their body temperature in between the thermo-neutral zone but it is a condition where chickens are unable to maintain the balance between the heat production and heat loss [15]. If the controlled temperature exceeds this zone, heat must be lost in some way by poultry birds. Chickens have no sweat glands. Naturally, a human body has pores on the skin through which moisture loss occurs by specific glands balancing the ambient weather conditions. Unlike humans, chickens are deprived of such sweat glands. Weight gain in chickens gradually goes on with increasing age. During summer, the body heat of poultry birds is also exalted causing raised temperature [16]. At this point, there are two ways: either reduce feed intake by bird or provide optimal weather conditions inside controlled sheds. At 29.4 °C (85 °F), chickens start panting [17]. Figure 2a shows the temperature/humidity heat stress index for chickens which combines the air temperature with the relative humidity to analyze that how increasing humidity affects the thermal comfort zone. Panting is a natural process for heat dissipation in bodies of poultry birds. Analogous to humans, this process maintains metabolic heat balance for chickens. As a result of this phenomenon, water intake is increased to avoid dehydration. Figure 2b illustrates the temperature zones of poultry birds which states that the optimum poultry bird's growth can be obtained by maintaining the desired temperature and humidity zones inside the poultry house. During panting, high values of temperature and humidity pose a serious problem. As the chickens lose moisture heat of the body to their surroundings for attaining thermal comfort. But high humidity in ambient hot air hinders the functioning of this process [18]. It also affects the productive and reproductive performance as well as the economic traits and the welfare of poultry [19,20].

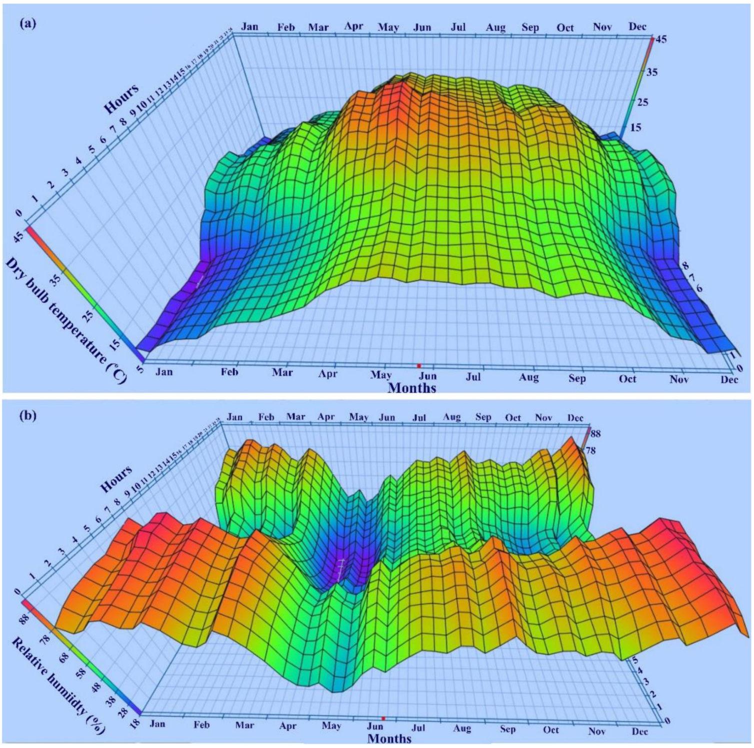

Figure 1. Illustration of (**a**) dry-bulb temperature, and (**b**) relative humidity variation (on hourly basis) for the ambient conditions of Multan, Pakistan.

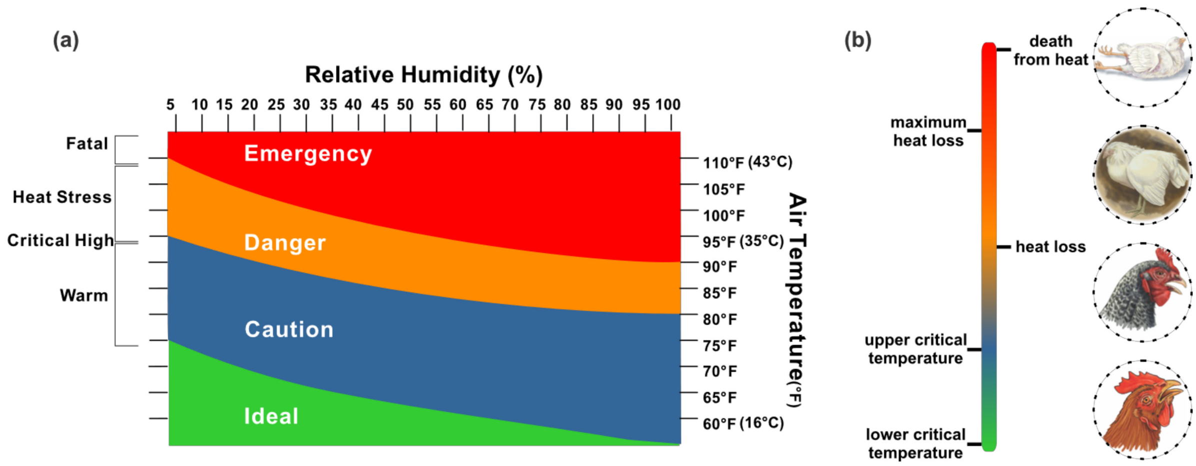

Figure 2. Heat stress effects on poultry birds. (**a**) Illustration of temperature-humidity index (THI) for chickens, reproduced from [21,22], and (**b**) diagram of temperature zones for broiler chickens representing lower, upper, and maximum temperature, reproduced from [23].

The activity and position of broiler chickens in broiler houses if monitored and controlled could potentially lead to ameliorate conditions for health, energy consumption, and welfare of these birds [14]. This research focused on controlling chamber environment for broilers on micro-scale to understand their attributes. Broiler chickens transmit heat flow from their body surface to maintain thermal equilibrium with the environment. The surface temperature of birds can be directly related to the flow of blood in their body. Any change in ambient temperature can be felt through the blood flow in birds near the skin. Climate in poultry houses is a combination of dry air and humidity. Poultry litter is affected when moisture and relative humidity is increased above 70% in room/poultry house. In a result, ammonia (above 70 ppm) production increases which affects bird's health and reduces growth [24–26].

The optimum control of these two parameters guarantees the safety and welfare of broiler chickens. Broiler chickens maintain their body temperatures through sensible (change in body surface temperature) and latent (release of moisture from body in while exhaling) heat emissions. It is suggested that the comprehensive study of metabolic functions be conducted to understand the heat production in poultry birds. Figure 3 illustrates the effects of heat stress on behavioral changes. Chickens under heat stress conditions spend less time in feeding and more in drinking, wings are lifted and less moving. The panting signs are also observed [15]. Physiological changes include the oxidative stress, acid base imbalance, respiratory alkalosis, and changes in cecal microbial profile. Heat stress is correlated with the cellular oxidative stress which causes severe health disorders, lower growth rates and economic losses [16,17]. The heat stress causes production changes by increasing the weight of the chickens and decreasing the quality and quantity of eggs. The mortality rate also increases due to heat stress [18].

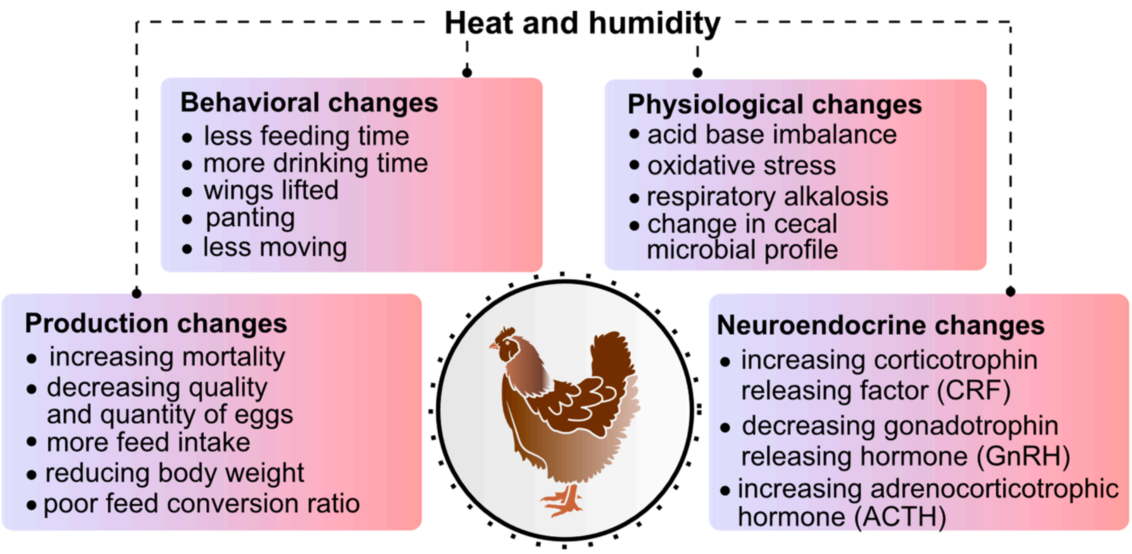

Figure 3. Heat stress effects on the poultry behavioral, physiological, production and neuroendocrine changes, reproduced from [18].

With the increasing ambient temperature, the mortality rate increases. The high levels of temperature not only affect the production performance but also hinders the immune function in poultry [27,28]. To achieve the desired conditions for poultry, many cooling systems have been developed and thus controlled air-conditioning has become necessary. Air conditioning systems specifically evaporative cooling pads alone, or in combination with nozzles are studied in literature [19,20,29,30]. Figure 4 illustrates the schematic of a typical EC-based poultry air-conditioning.

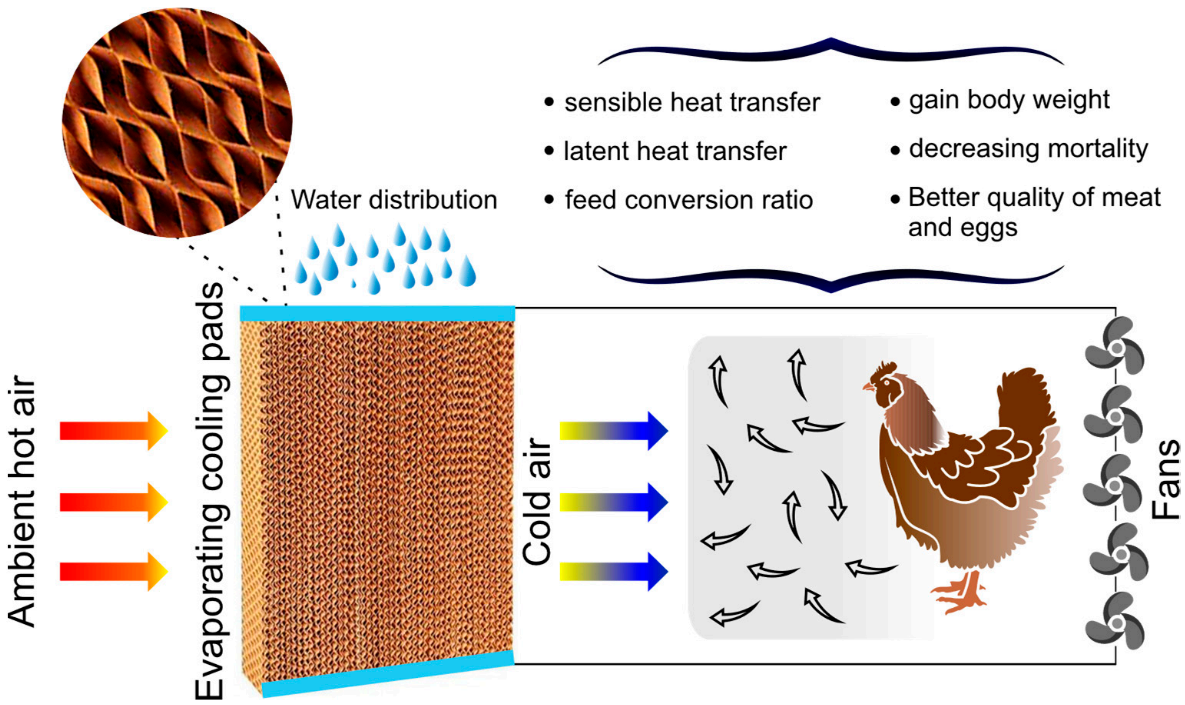

Figure 4. Schematic diagram of typical poultry air-conditioning for thermal comfort.

Air-conditioning happens to be an integrated process which transports the ambient air into the conditioned space with optimal parameters of thermal environment for the occupants [19,20,29,31]. In this way, it controls and maintains the temperature, relative humidity, and air movement, in the conditioned space within the predetermined limits either for thermal comfort or product processing. For poultry birds, thermal environment is of prime significance. The optimal mixture of temperature and relative humidity gives birth to temperature-humidity-index (THI). It is the thermal comfort that enhances health of occupants in any conditioned space [32–34]. DEC, IEC, and MEC systems are performing better as compared to vapor compression systems in terms of saving primary energy and providing desired environmental conditions. Poultry control sheds employ direct evaporative coolers for summer cooling. Evaporative cooling systems are developed and installed to meet air-conditioning requirement in poultry houses. The efficiency of these systems makes them cost effective and acceptable to user end. Poultry control sheds are chambers which are conditioned on the principle of direct evaporative cooling system. Heat production by poultry birds is ejected out of the system with reduction in temperature.

The objectives of this study include the understanding of poultry air-conditioning requirements for poultry birds based on heat and moisture production, calculating heat stress per bird and THI index to assess the desired evaporative cooling systems under the climatic conditions of Multan, understanding the effects of sensible and as well as the latent heat production in poultry birds and evaluation of evaporative cooling systems i.e., direct evaporative cooling (DEC), indirect evaporative cooling (IEC), Maisotsenko-Cycle evaporative cooling (MEC) for the poultry environment in terms of THI and THVI.

2. Evaporative Cooling Systems

Many types of cooling systems are available to provide cool air for commercial or domestic purpose. Since the ancient times, evaporative cooling systems (EC) are used for cooling the ambient air by evaporating water droplets into the air. Evaporation of water is a process in which heat of the ambient air is absorbed and water vapors are imparted to it. In this process, only the latent load is achieved by providing humidity into the ambient air. Whereas the total heat (enthalpy) gets negligible change. Evaporative cooling generally lies on the conversion of sensible heat into the latent one. The main work is accomplished by the water in EC systems. The heat and mass transfer in EC systems occurs on account of temperature and vapor pressure deficits. On the other hand, vapor compression air-conditioning (VCAC) systems employs CFCs or HCFCs which are environmentally harmful being the major exploiters of ozone layer depletion [10,31]. In this regard, increasing research efforts have been made in designing low cost and environmental friendly technologies; specifically EC techniques have been demonstrated effectively [35–37]. Energy consumption is also lower in EC systems as compared to the VCAC [38]. When ambient air is passed through any water steam directly or indirectly, it gets cooled with the effect of water evaporation into the air [20,31,39]. EC system is generally employed in hot and relatively dry climates [7]. On the contrary, humid environment is not suitable for evaporating cooling systems as air is already saturated. The evaporating cooling system can be categorized into DEC and IEC with respect to the interaction of water with air. A new system called M-cycle evaporative cooling (MEC) has also been introduced to get a cool fresh air. Figure 5 shows the laboratory-scale models for DEC, IEC, and MEC systems, respectively. These systems were developed in Agricultural Engineering Department Bahauddin Zakariya University Multan, Pakistan. The experimental setup uses 6.5 L/min water pump for all three developed systems and a standard anemometer for air flow rate (i.e., average 1.7m/s). Standard temperature and moisture sensor (H2) with an experimental uncertainty of ±1 °C temperature and ±2% RH was used in the experimental setup. Experimental data were collected for a time span of a typical meteorological year and thermodynamic analyses were carried out for poultry air-conditioning. Under the climatic conditions of Multan city, these systems can be employed to achieve certain results which were further optimized to obtain THI and THVI values. Figure 6 illustrates the schematics of typical evaporative cooling with DEC, IEC, and MEC. EC system is an environment friendly and energy saving technology [40]. In terms of thermal comfort, this system can be a suitable option in hot and arid climates as the relative humidity lies in between the 60 and 70%. This system altogether meets the thermal comfort needs of the occupant, being environmentally friendly [41]. The effectiveness of EC system is indicated by wet-bulb and dew-point effectiveness [31]. In this system, ambient air is directly brought in contact with water stream to lower down the temperature and increase relative humidity [19,20,29,31,42].

2.1. *Direct Evaporative Cooling (DEC)*

It is the easiest and oldest type of EC system in which ambient air is brought in direct contact with air stream to reduce the temperature [38]. The continuous evaporation of water vapors (adiabatic process) causes a cooling effect up to a saturation point in which enthalpy of air remains same, whereas the humidity ratio increases throughout the process [31,44]. These water streams are brought from metal or plastic tubes commonly known as "pads" as their boundary walls. The ambient air is showered with water and thus, it gets cooled and humidified. The water stream is injected with the help of motor and from the top of the wall water droplets are drawn downward with the gravity force and capillary action. The ambient temperature is potentially reduced to its wet bulb temperature at wet-bulb effectiveness of 75–95% [31,45]. Figure 6 shows the working principle of DEC system. In dry climates, DEC system works with 80% efficiency as reported in [38].

2.2. *Indirect Evaporative Cooling (IEC)*

It is a system in which heat and mass transfer phenomenon takes place without the addition of moisture and works on the principle of sensible cooling [44]. In this system, cooling effect is produced by isenthalpic cooling in the wet channel and sensible heat transfer in the dry channel [44]. In IEC systems, product air passes over the dry side while the working air passes over the wet side. In case of DEC, the conditioned air is obtained but with an increased relative humidity level [46]. To achieve the constant absolute humidity, the IEC systems are desired. Figure 6 shows the working principle of an IEC system. IEC system can reduce the temperature up to the wet-bulb temperature at wet-bulb effectiveness of 50–65% [47]. The humidity ratio of the inlet and outlet air remains same while the enthalpy of the outlet air decreases in an IEC system [44].

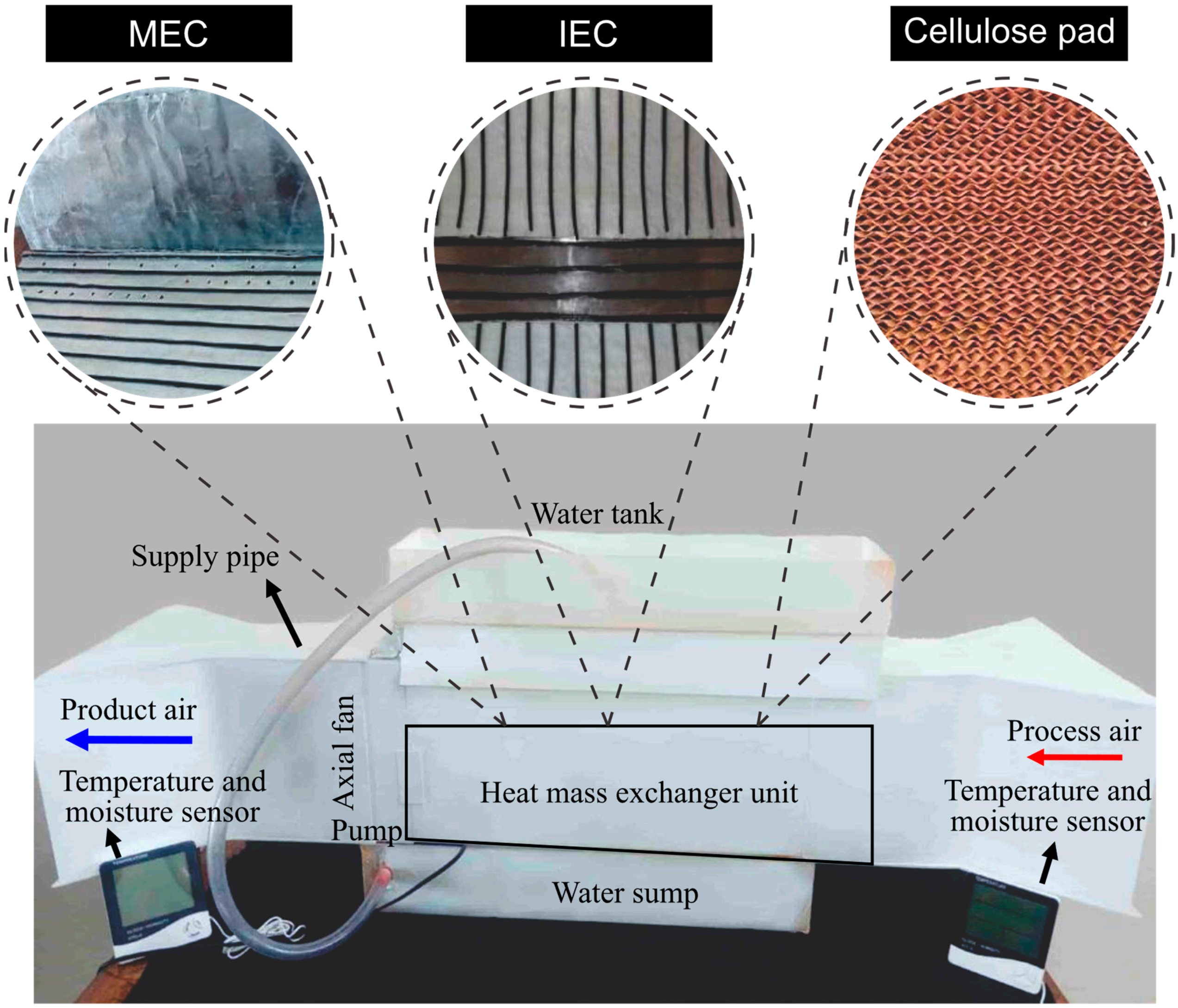

Figure 5. Laboratory-scale models for direct evaporative cooling (DEC), indirect evaporative cooling (IEC), and Maisotsenko-Cycle evaporative cooling (MEC) systems, reproduced from author's work [43].

2.3. M-Cycle Evaporative Cooling (MEC)

Maisotsenko-Cycle (M-Cycle) evaporative cooling technique is an advanced method for achieving the dew point temperature as compared to the other two traditional systems where cooling limit touches the wet bulb temperature [44,48]. In this system, the cooling effect is produced by evaporative cooling and heat transfer where dew-point temperature is achieved instead of wet-bulb temperature [49,50]. Figure 6 illustrates the working principle of MEC system. This system comprises of three channels in which wet channel is sandwiched in between the two dry channels. The ambient air cools down due to the convective heat transfer between the dry and wet channels when it passes through the dry channel [51]. In this system, the humidity ratio of the inlet and outlet air remains same while the enthalpy decreases [45,52]. The studied experimental systems have been developed at lab-scale and analyzed for poultry air-conditioning. However, when developed at large scale, factors like pressure drop, fan power, availability of fresh water for evaporative coolers, availability of the evaporative media, direction of the system installation in the poultry shed, and the energy consumption should be taken into consideration.

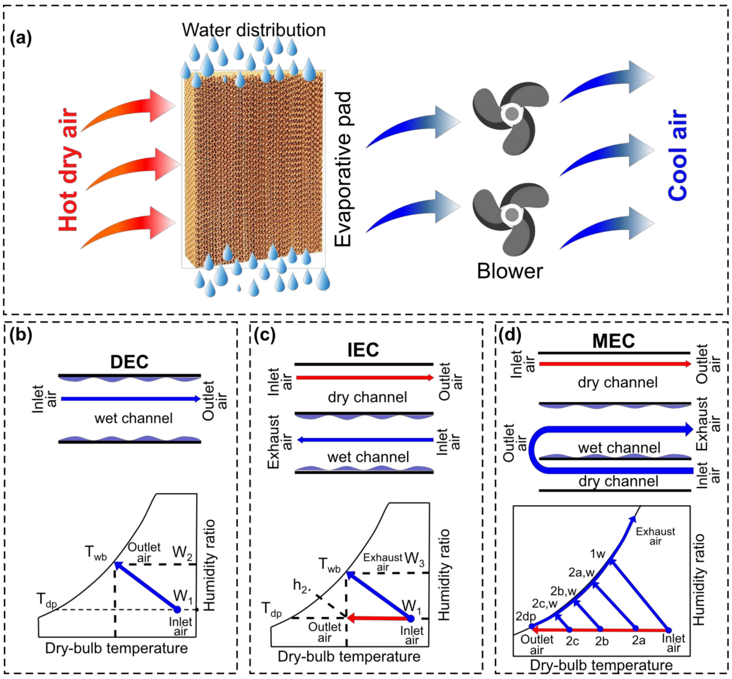

Figure 6. Illustration of evaporative cooling phenomenon. (**a**) Typical evaporative cooling phenomenon using evaporative pads. (**b**–**d**) DEC, IEC, and MEC systems phenomenon along with air transformations on psychrometric chart.

3. Materials and Methods

Mathematical Models for Poultry Heat Generation

Heat production in poultry birds changes with their body weight and muscle growth due to the consumption of more energy produced from the feed intake [21,22]. Heat production in poultry birds based on live weight is governed by Equation(4) given in literature [15].

$$Q = 60.65 + 0.04W \tag{1}$$

where, Q is the heat production (W/kg) and W is the live weight (kg). Sensible heat production (SHP), and latent heat production (LHP) based on broiler age at various temperatures were calculated using gates model Equations (5)–(12) given in literature [53]. The set of Equations (5)–(12) were replicated from [53] using the self-defined chicken age, and specific temperature ranges (presented below) to investigate the performance of the developed EC systems.

All brooding temperature relations encompass the broiler chickens of age below 15 days. Whereas the rest of relations (i.e., for brooding temperature 15.6 °C, 21.1 °C, and 26.7 °C) are concerned with heat and moisture production of broilers above 15 days and below 48 days.

For all brooding temperatures:

$$SHP = K\exp\left(-6.5194 + 2.9186x - 0.24162x^2\right) \tag{2}$$

$SE = 0.284$ K; $3 \leq x \leq 5$

$$LHP = K\left(-42.961 + 27.415x - 2.84344x^2\right) \tag{3}$$

$SE = 0.296$ K; $2 \leq x \leq 5$

For temperature (t = 15.6 °C):

$$SHP = K\left(38.612 - 2.6224x - 0.072047x^2 - 0.00066x^3\right) \tag{4}$$

SE = 0.045; $20 \leq x \leq 41$

$$\text{LHP} = \text{K}\left(22.285 - 0.78279\text{x} + 0.011503\text{x}^2 - 0.000038\text{x}^3\right) \tag{5}$$

SE = 0.192 K; $20 \leq x \leq 43$

For temperature (t = 21.1 °C):

$$\text{SHP} = \text{K}\left(36,070 - 2.1307\text{x} - 0.058862\text{x}^2 - 0.00051\text{x}^3\right) \tag{6}$$

SE = 0.110 K; $20 \leq x \leq 39$

$$\text{LHP} = \text{K}\left(11.221 + 0.40495\text{x} - 0.02727\text{x}^2 - 0.000353\text{x}^3\right) \tag{7}$$

SE = 0.069 K; $20 \leq x \leq 43$

For temperature (t = 26.7 °C):

$$\text{SHP} = \text{Kexp}(5.3611 - 0.16177\text{x}) \tag{8}$$

SE = 0.052 $20 \leq x \leq 23$

$$\text{LHP} = \text{K}\left(20.094 - 0.70318\text{x} + 0.015182\text{x}^2 - 0.000108\text{x}^3\right) \tag{9}$$

SE = 0.022 K; $20 \leq x \leq 42$

Where SHP, LHP represent the specific sensible, and latent heat production (W/kg), x represents bird age (days) and SE denotes the standard error of regression.

Temperature-humidity index (THI) is a direct combination of DBT and WBT. The further insights of THI for broilers and layers is given below in Equations (10) and (11) given in literature [54,55].

$$\text{THI}_{\text{broilers}} = 0.85\text{t}_{\text{db}} + 0.15\text{t}_{\text{wb}} \tag{10}$$

$$\text{THI}_{\text{layers}} = 0.60\text{t}_{\text{db}} + 0.40\text{t}_{\text{wb}} \tag{11}$$

where, t_{db}, t_{wb} represent dry-bulb and wet-bulb temperatures (°C) respectively and THI represents temperature-humidity index.

Temperature-humidity-velocity index (THVI) is used to analyze the ability to maintain an internal condition constant by including velocity as one of the factors. The further insights of THVI and ET can be seen in Equations (12)–(15) with normal, alert, danger, and emergency regions of homeostasis for the broilers given in the literature [56].

$$\text{THVI} = \text{THI} \times \text{V}^{-0.058} \quad (0.2 \leq \text{V} \leq 1.2) \tag{12}$$

For 1 °C temperature rise

$$\text{ET} = \left(2 \times 10^{29}\right) \times \text{THVI}^{-17.68} \tag{13}$$

For 2.5 °C temperature rise

$$\text{ET} = \left(4 \times 10^{13}\right) \times \text{THVI}^{-7.38} \tag{14}$$

For 4 °C temperature rise

$$\text{ET} = \left(3 \times 10^{11}\right) \times \text{THVI}^{-5.91} \tag{15}$$

where, THVI represents temperature-humidity-velocity index, and ET stands for exposure time in minutes. Wet-bulb temperature is calculated by Equation (16), as given in literature [57,58].

$$T_{wb} = T_{db} \tan^{-1}\left[0.151977 + (RH + 8.313659)^{\frac{1}{2}}_{2}\right] + \tan^{-1}(T_{db} + RH) - \tan^{-1}(RH - 1.676331) + 0.00391838\, RH^{\frac{3}{2}}_{2} \tan^{-1}(0.023101RH) - 4.686035 \quad (16)$$

4. Results and Discussion

Climate control strategy starts with the estimation of ambient weather details for a region. Such kind of analysis makes it visible that what kind of changes occur in the ratio of DBT and RH in a day. Evaporative cooling systems (DEC, IEC, and MEC) were evaluated in the laboratory under summer conditions in Multan. These systems appreciably reduced the ambient temperature and increased relative humidity to meet the threshold THI limit for poultry birds. Figures 7 and 8 show the experimental analysis of DEC, IEC, and MEC systems for the climatic conditions of Multan. Table 1 shows the summary of performance profile of the experimental DEC, IEC, and MEC under the climatic conditions of Multan (Pakistan) for poultry air-conditioning.

Table 1. Summary of performance profile of the experimental DEC, IEC, and MEC under the climatic conditions of Multan (Pakistan) for poultry air-conditioning.

Month	Ambient Temperature	Ambient RH	DEC			IEC			MEC		
			ΔT	ΔRH	ΔTHI	ΔT	ΔRH	ΔTHI	ΔT	ΔRH	ΔTHI
	(°C)	(%)	(°C)	%	(°C)	(°C)	%	(°C)	(°C)	%	(°C)
Apr	36.5	39.5	10	48.5	9	6.5	23	6.5	12	37.5	10
May	37.5	36	10	49	8.5	6.5	20.5	5	11.5	42	9.5
Jun	38	44	7	48	8.5	5	19.5	7	9.5	39	10
Jul	37.5	66	5.5	21	3.5	4.5	12.5	3	7	30.5	5.5
Aug	38.5	62	7	26	4.5	4.5	15.5	3	7.5	31.5	5.5
Sep	35	55	6.5	36	5	3.5	16.5	3.5	7	34.5	6

Δ denotes the gradient/difference in ambient the supply air-conditions.

Broiler heat production increases as its weight increases. It is directly proportional to the physiological growth of birds being grown up under healthy conditions. Broilers need optimal environmental conditions to thrive in tropical regions. In these dry and humid regions, broilers need evaporative cooling effect in hot conditions to maintain their body heat and moisture loss. These birds are sensitive to the slight change in temperature and humidity values and become accustomed to high mortality rates. In Figure 9, it is mentioned through graphical representation that with the increase in broiler age, their body weight keeps on increasing. The way this body weight increases, the need for encountering heat and moisture production arises.

For this purpose, an optimal air-conditioning and ventilation technique needs to be devised. The heat from the broiler started increasing from 60 till 155 W/m^2 with the corresponding increase in the weight up to 2700 g. Sensible and latent heat production of broilers is studied with respect to its weight under different temperatures according to Gates model. A set of regression equations were developed to study the heat production patterns in broilers. This situation is graphically presented in Figures 10–13, to understand the effects of high temperature and difference in heat production on the overall welfare of poultry birds. These models made it clear that broilers with growing age attain physiological maturity and meanwhile, their sensible and latent heat production is dependent on ambient temperature. These graphs also illustrate that total heat production with varying temperatures increase initially and comes to rest. On the other hand, sensible and latent heat production makes narrower gap at lower temperatures while this gap gets wider at higher temperatures.

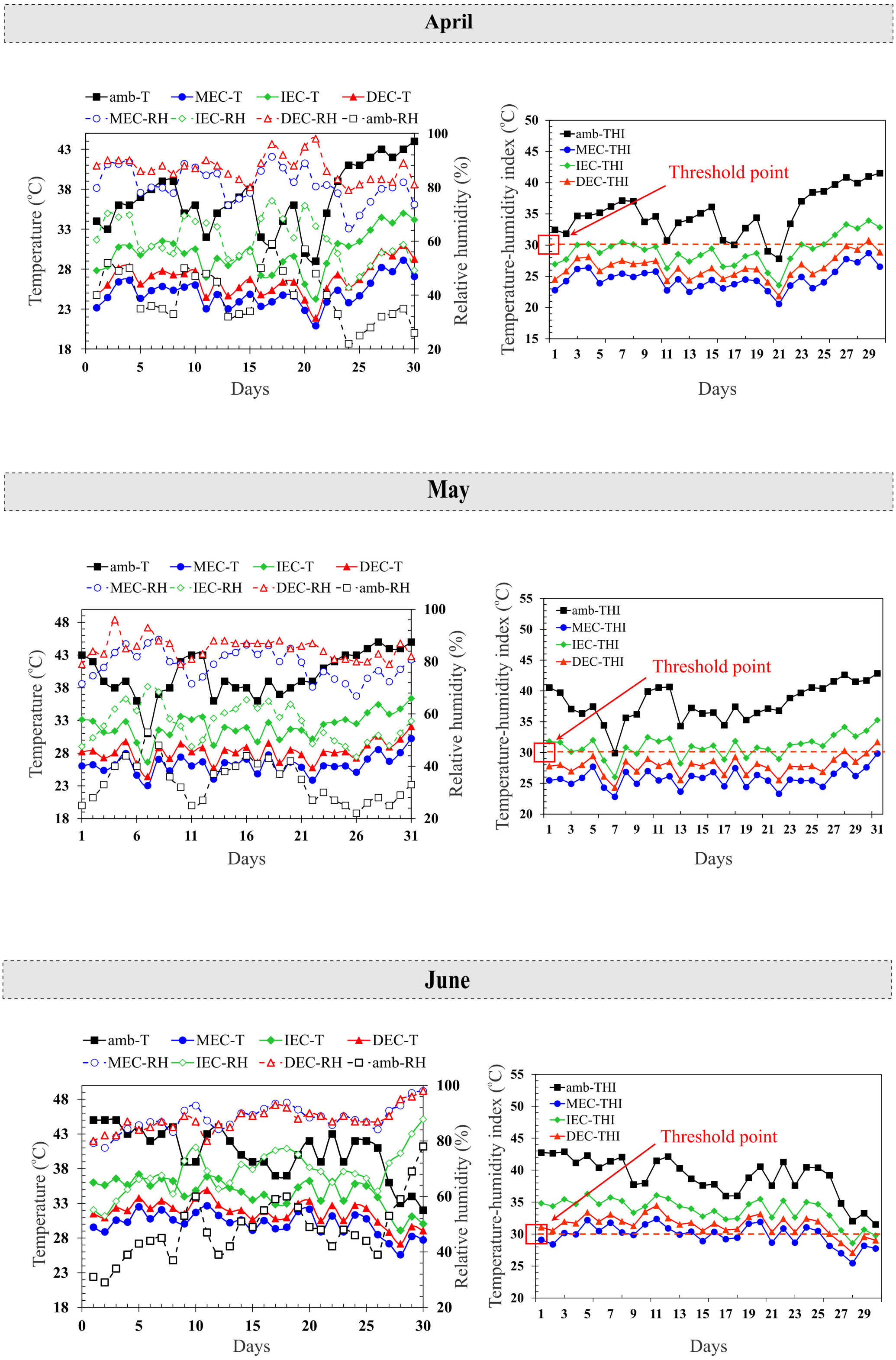

Figure 7. Experimental analysis of DEC, IEC, and MEC systems in the months of April, May, and June for ambient conditions of Multan, Pakistan.

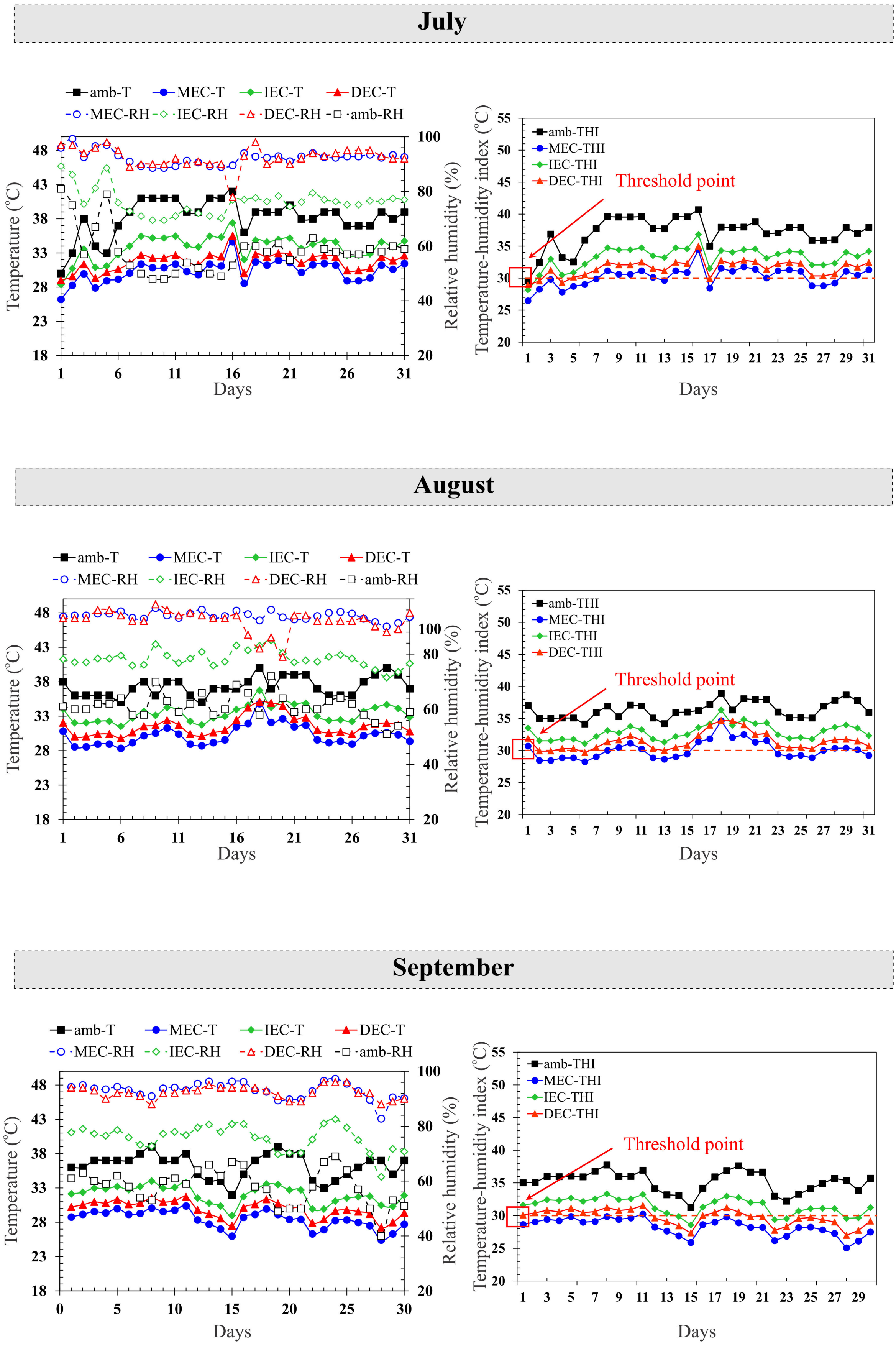

Figure 8. Experimental analysis of DEC, IEC, and MEC systems in the months of July, August, and September for ambient conditions of Multan, Pakistan.

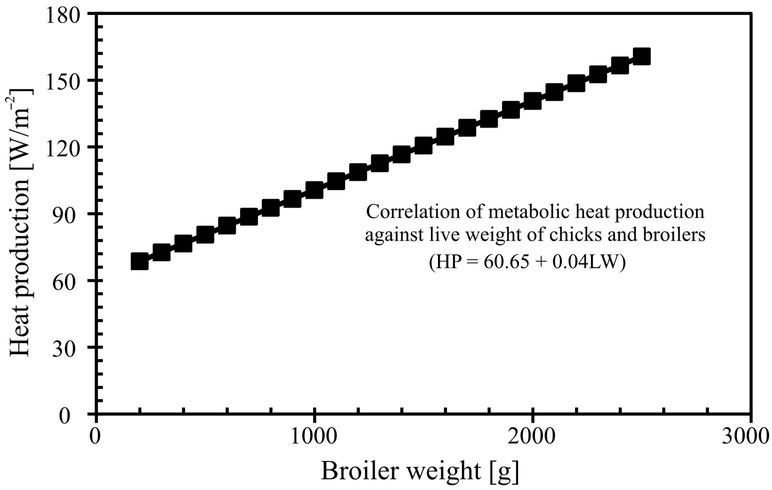

Figure 9. Relationship of broiler weight and heat production of chickens and broilers.

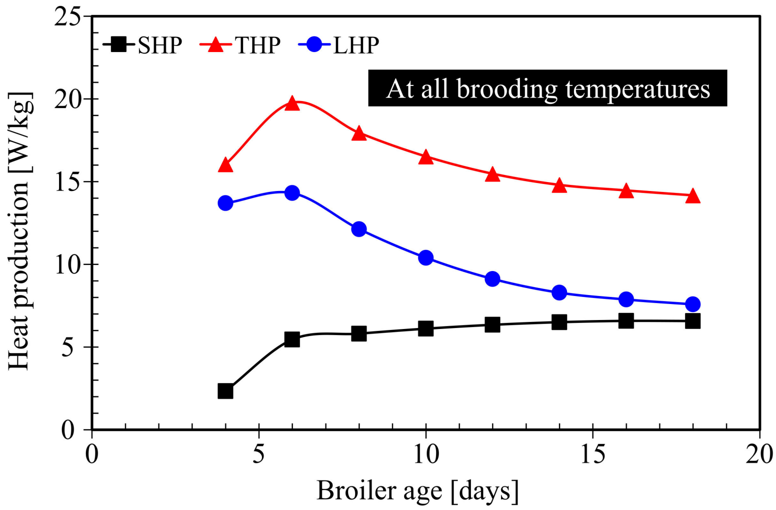

Figure 10. Representation of Broiler age [days] as the function of sensible, latent, and total heat production at all brooding temperatures.

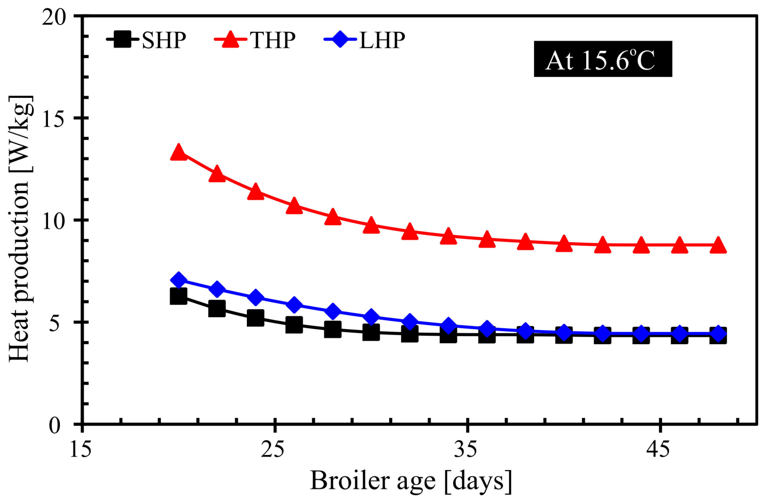

Figure 11. Representation of Broiler age [days] as the function of sensible, latent, and total heat production at 15.6 °C temperature.

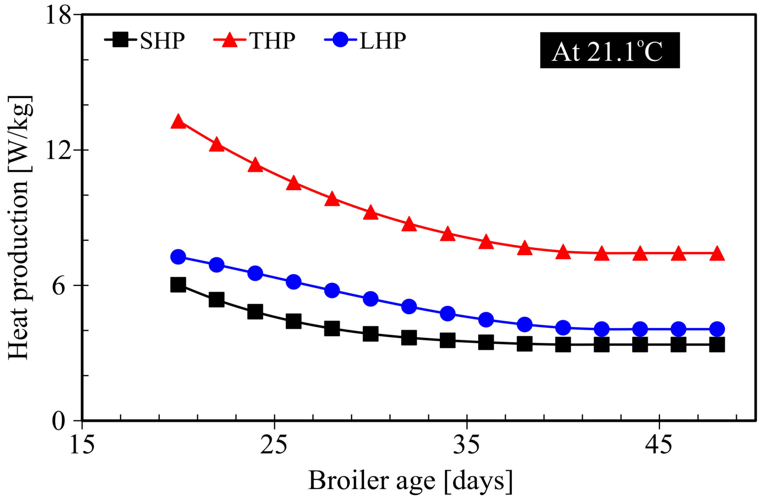

Figure 12. Representation of Broiler age [days] as the function of sensible, latent, and total heat production at 21.1 °C temperature.

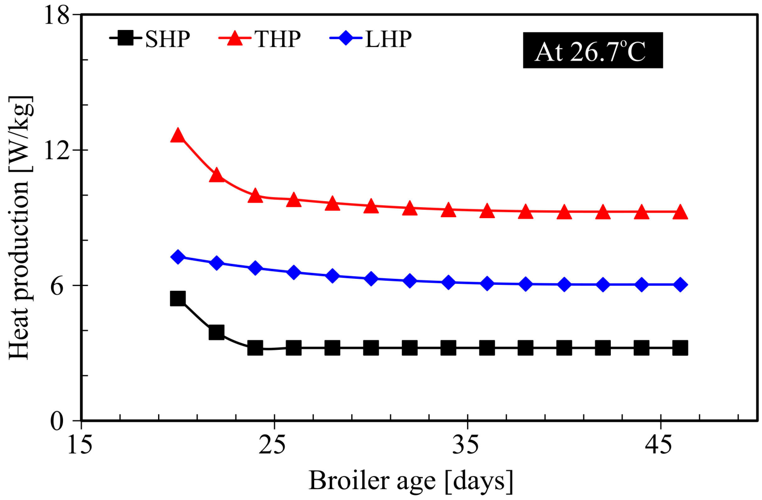

Figure 13. Representation of Broiler age [days] as the function of sensible, latent, and total heat production at 26.7 °C temperature.

This can be controlled with the help of management guide designed for broilers where THI values can resolve this deficiency. The difference between sensible and latent heat production is seriously important to get a know how about the assimilative capacity inside the poultry environment. The wider the gap is, poorer is the resilience of the environment surrounding the poultry birds.

The sustenance capacity of poultry birds to survive heat stress increases with the increasing velocities as depicted in different layouts of THVI with thermal exposure time (ET) in Figure 14. Figure 14 was reproduced from published literature using the tabular data in a research conducted by Tao et al. [56]. These figures categorize exposure time of broiler chickens with THVI and state that it is the air movement that tells the story other way round if not checked properly.

In these figures, it is shown that increasing velocity to some extent makes it easier to achieve thermal comfort zone for poultry birds. THI is the summation of different percentage compositions of dry- and wet-bulb temperatures. Dry-bulb temperature is measured by simple thermometer while wet-bulb temperature is measured with soaked wet cloth wrapped over the measuring segment of the thermometer. In Figure 15a,b, it is stated that there is correlation between T_{ab} and THI to describe the increasing trend from the daily data of weather for broilers from daily weather conditions to calculate THI which is a function of T_{db} and RH.

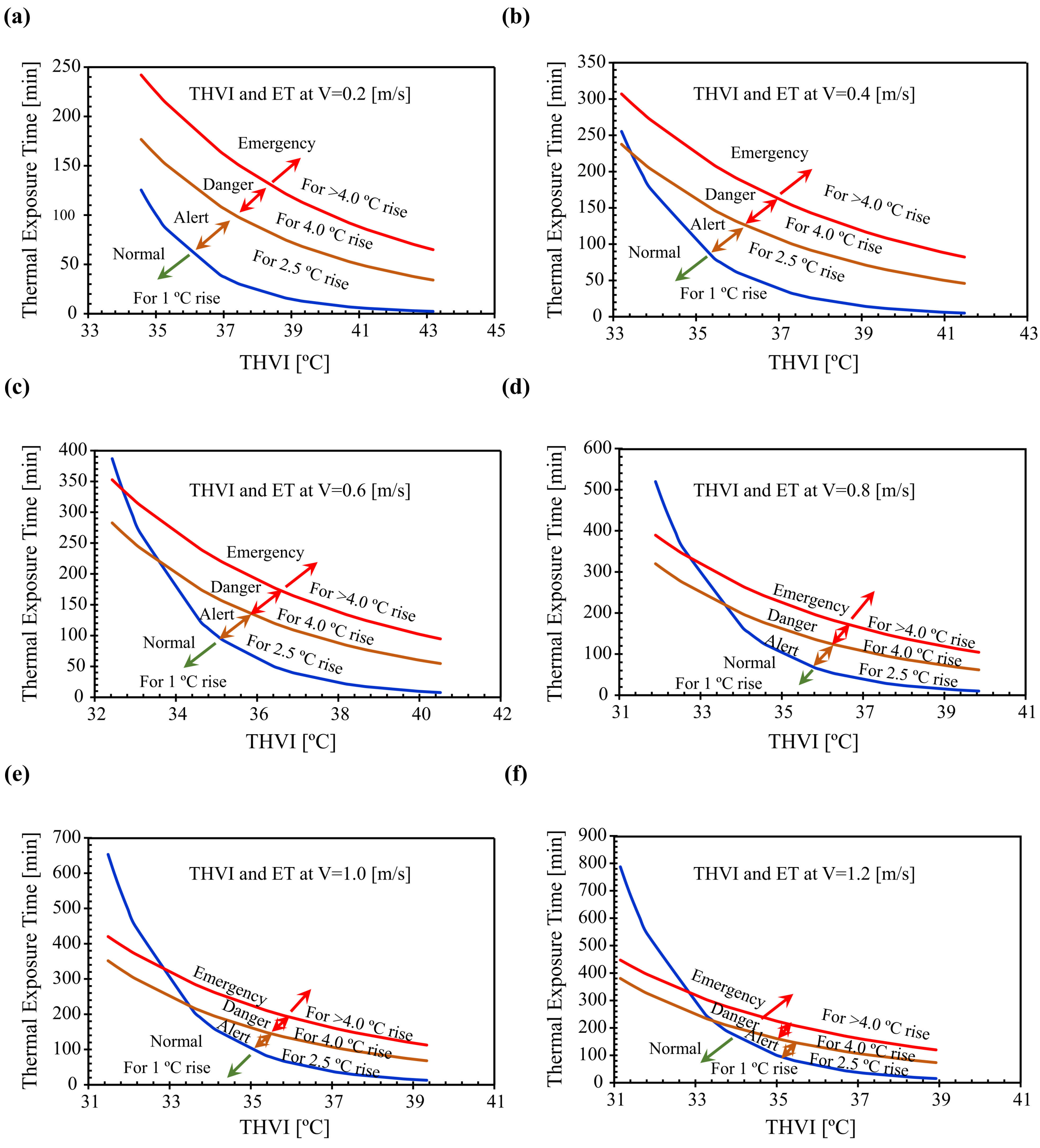

Figure 14. Thermal comfort zone for poultry birds with respect to THVI [°C] and ET [min] at (**a**) 0.2 m/s, (**b**) 0.4 m/s, (**c**) 0.6 m/s, (**d**) 0.8 m/s, (**e**) 1.0 m/s, (**f**) 1.2 m/s velocities, respectively, reproduced from tabular data published by [56].

From Figure 15, an empirical equation is obtained with appreciable R^2 value. Figure 15 concludes that the range of THI variation is less in broiler chickens (Figure 15a) as compared to relatively higher range of THI variation in egg-laying chickens (Figure 15b). This also explains the assimilative capacity of natural environment to resist heat stress to some extent in both cases of broilers and layers, respectively. Figure 16a,b proposes a THI pyramid (i.e., amalgamation of THI) based on daily wet-bulb temperature range. In Figure 16, the green, blue, and red color lines overlaid on top of the regression lines represent boundaries of different zones based on allowed THI of both broilers and egg-laying chickens. In Figure 16, chart area covered underneath the green line represents the threshold zone, chart area covered between green and blue line represents the alert zone, area covered between blue and red line represents the danger zone, and area covered above the red line shows the emergency zone based on the allowed/comfortable THI for both cases. The resilience of layers chicken is more in pyramid (i.e., amalgamation of THI as shown in Figure 16) as compared to broiler chicken with enlarged elliptical trend (in Figure 16). Figure 17a,b explains dry bulb representation with the RH and THI relationship for broilers and egg-laying chickens and states that this trend for broiler chickens was found to be more tolerant to the thermal stress (i.e., heat stress due to ambient air conditions) effectively as compared to layer chickens, which justifies the published literature against the thermal stresses of broilers and layers as shown in Equations (13)–(14). According to Figure 17a, the broiler chicken has higher range of temperature-humidity-index at a specified relative humidity indicating relatively more thermal resilience as compared to layer chicken (Figure 17b) at same relative humidity conditions. Feasibility calendar of EC (DEC, IEC, and MEC) systems for the ambient conditions of Multan (Pakistan) is presented in Figure 18. The ambient conditions of the study area were recorded for a year using standard temperature sensor and were later analyzed for poultry air-conditioning.

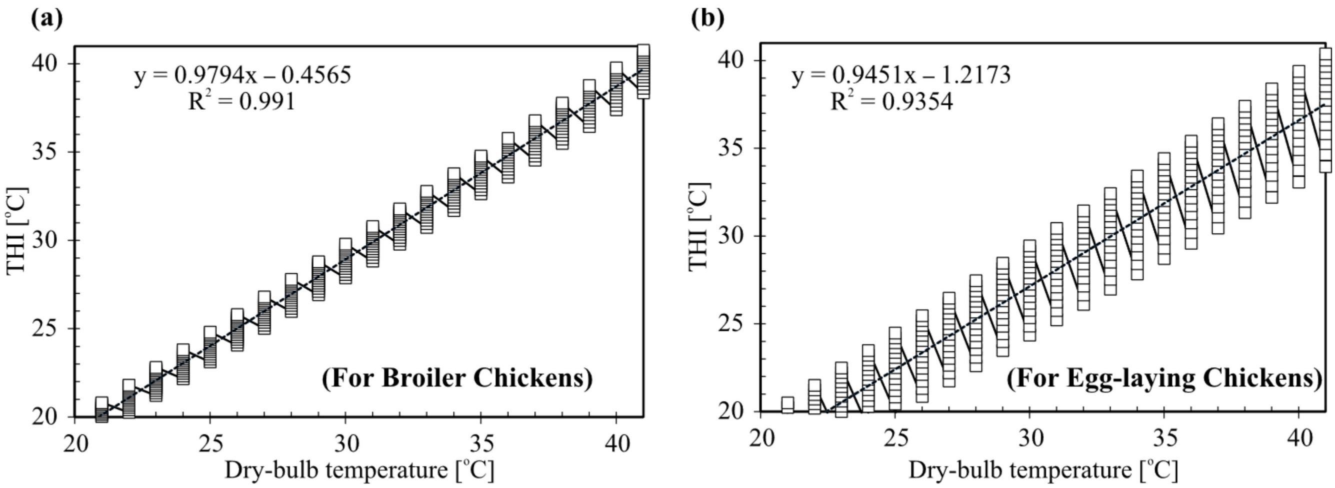

Figure 15. Representation of dry-bulb temperature and THI as a correlating factor for (**a**) broiler chickens, and (**b**) egg-laying chickens.

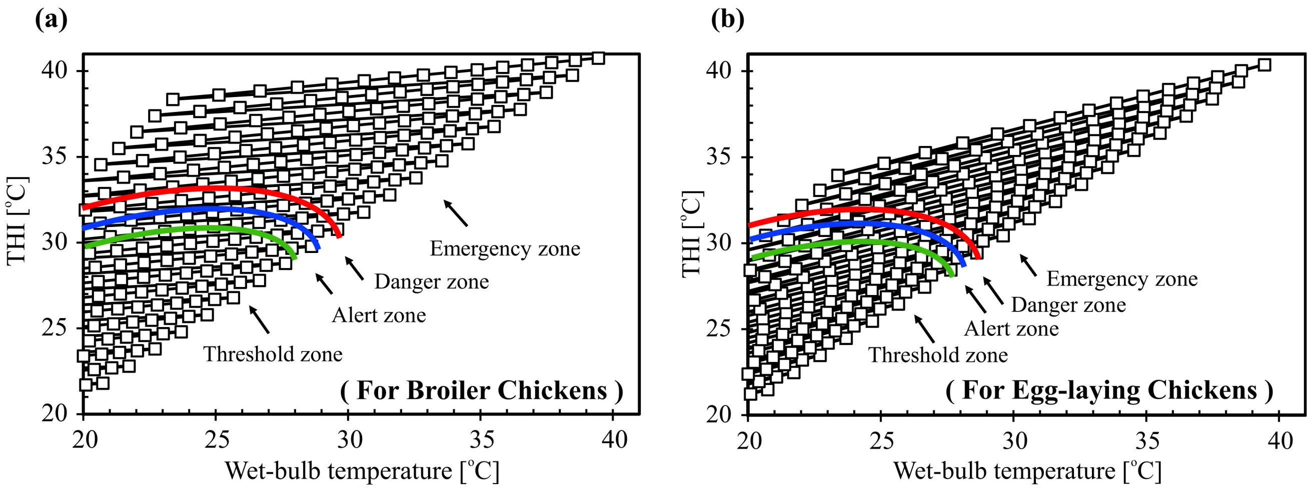

Figure 16. Representation of wet-bulb temperature and THI as correlating factor for (**a**) broiler chickens, and (**b**) egg-laying chickens.

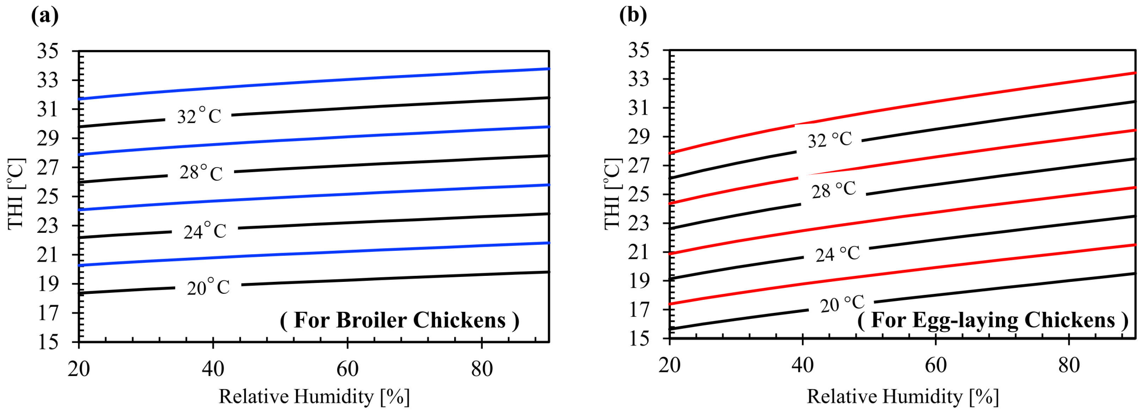

Figure 17. Representation of dry-bulb temperature as a function of relative humidity and THI for (**a**) broiler chickens, and (**b**) egg-laying chickens.

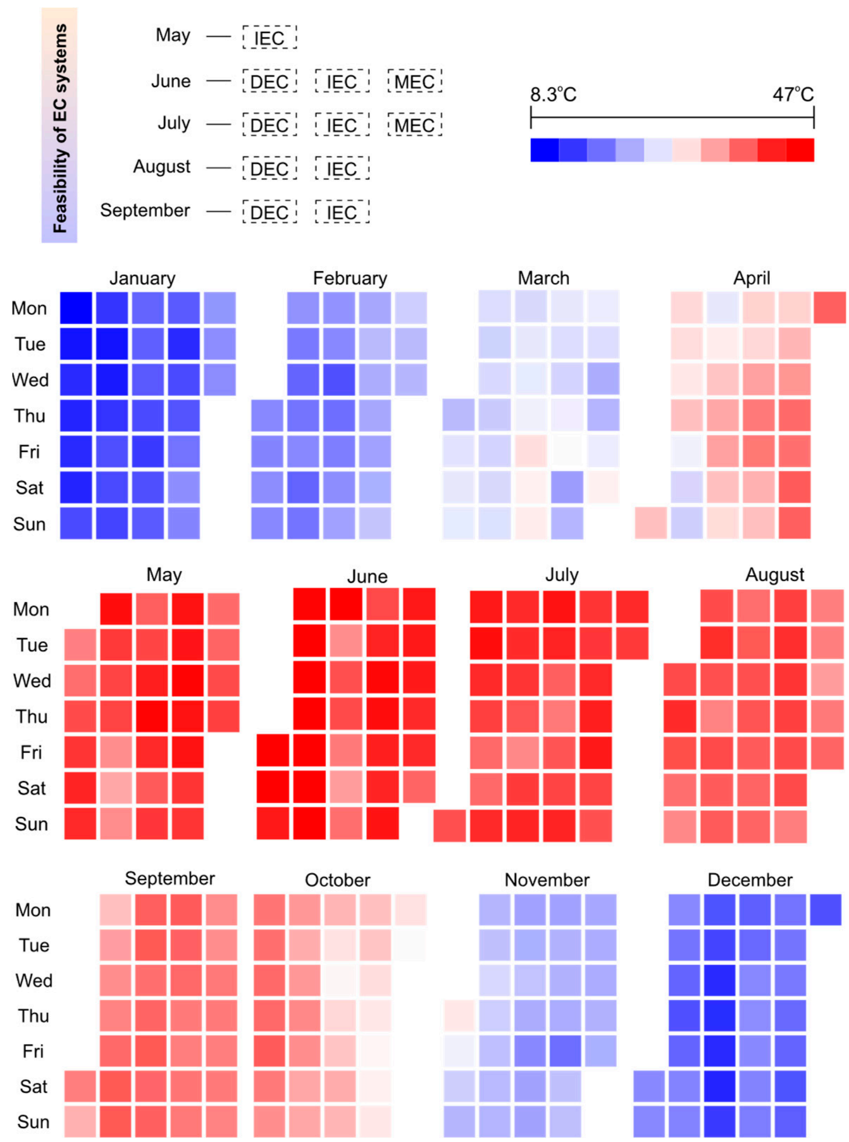

Figure 18. Feasible calendar showing the applicability of evaporative cooling systems for the ambient conditions of Multan, Pakistan.

5. Conclusions

Poultry industry is affected by (sensible/latent) heat stresses and results in substantial economic loss. Heat stress causes severe impacts on poultry health such as mortality rate and body weight increases. Economically, these birds are the cheapest source of proteins in South Asia. Furthermore, poultry farming is catching its momentum with millions of capital investment by many in a quest to gain much more in a short span of time. In view of presented work, the air-conditioning process for broiler chickens carries significant importance. The major issue revolves around is the optimal control of temperature and humidity such as THI. Any minor fluctuations of index wreak havoc for the investor and birds ultimately. For all this there was an open window for the current research to oversee an energy-efficient evaporative cooling system that could condition the air without raising humidity levels. In this regard, the EC systems (DEC, IEC, and MEC) were studied under the weather conditions of Multan in line with the regression equations from Gates model. In fact, the empirical relations of sensible and latent heat production minimized the need to erect a whole new setup to raise poultry birds for studying the heat and moisture production. Moreover, the experimental results of the studied EC systems conclude that the MEC system could be considered as a viable alternate option as compared to the traditional DEC systems used for poultry air-conditioning due to the psychrometric and climatic (i.e., monsoon season) limitations of the DEC system. However, all the studied standalone evaporative cooling systems are still limited by the ambient air conditions. This problem can be resolved by further research on experimental desiccant dehumidification-based evaporative cooling systems for poultry air-conditioning. Therefore, the present study concludes the MEC as the best alternate option to the traditional DEC system used for poultry air-conditioning in Multan, Pakistan.

Author Contributions: Conceptualization, K.S., M.B., and M.S.; data curation, K.S. and M.B.; formal analysis, K.S. and M.B.; funding acquisition, M.S.; investigation, K.S., M.B., H.A., M.F., T.M., U.S., I.A., and M.I.H.; methodology, K.S, M.S., M.B., M.F., and T.M.; project administration, M.S.; resources, M.S. and T.M.; supervision, M.S. and T.M.; validation, M.S. and T.M.; visualization, M.B., H.A., U.S., I.A., and M.I.H.; writing—original draft, K.S.; writing—review and editing, M.S., M.B., H.A., M.F., T.M., U.S., I.A., and M.I.H. All authors have read and agreed to the published version of the manuscript.

Funding: The Bahauddin Zakariya University, Multan-Pakistan funded this research under the Director Research/ORIC grant titled “Development and performance evaluation of prototypes of direct and indirect evaporative cooling-based air-conditioning systems.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: All this work is part of the Ph.D. research of Khawar Shahzad (1st Author). This research work has been carried out in the Department of Agricultural Engineering, Bahauddin Zakariya University, Multan-Pakistan. The Bahauddin Zakariya University, Multan-Pakistan funded this research under the Director Research/ORIC grant titled “Development and performance evaluation of prototypes of direct and indirect evaporative cooling-based air-conditioning systems,” awarded to Principal Investigator Muhammad Sultan.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

EC	evaporative cooling
GDP	gross domestic product
DBT	dry-bulb temperature
RH	relative humidity
THI	temperature-humidity index

THVI	temperature-humidity-velocity index
DEC	direct evaporative cooling
IEC	indirect evaporative cooling
MEC	M-cycle evaporative cooling
Q	heat produced (Q/kg)
W	Live weight (kg)
SHP	sensible heat production (W/kg)
LHP	latent heat production (W/kg)
x	bird's age (days)
SE	standard error of regression.
ET	thermal exposure time

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