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Investigating Applicability of Evaporative Cooling Systems for Thermal Comfort of Poultry Birds in Pakistan

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Abstract: In the 21st century, the poultry sector is a vital concern for the developing economies including Pakistan. The summer conditions of the city of Multan (Pakistan) are not comfortable for poultry birds. Conventionally, swamp coolers are used in the poultry sheds/houses of the city, which are not efficient enough, whereas compressor-based systems are not economical. Therefore, this study is aimed to explore a low-cost air-conditioning (AC) option from the viewpoint of heat stress in poultry birds. In this regard, the study investigates the applicability of three evaporative cooling (EC) options, i.e., direct EC (DEC), indirect EC (IEC), and Maisotsenko-cycle EC (MEC). Performance of the EC systems is investigated using wet-bulb effectiveness (WBE) for the climatic conditions of Multan. Heat stress is investigated as a function of poultry weight. Thermal comfort of the poultry birds is calculated in terms of temperature-humidity index (THI) corresponding to the ambient and output conditions. The heat production from the poultry birds is calculated using the Pederson model (available in the literature) at various temperatures. The results indicate a maximum temperature gradient of 10.2 °C (MEC system), 9 °C (DEC system), and 6.5 °C (IEC systems) is achieved. However, in the monsoon/rainfall season, the performance of the EC systems is significantly reduced due to higher relative humidity in ambient air.

Keywords: evaporative cooling; poultry birds; heat production; temperature-humidity-index; Pakistan

1. Introduction

Air-conditioning (AC) is the process of controlling temperature and humidity of ambient air to achieve thermal comfort for a range of occupants [1,2]. It involves various processes to condition the

ambient air, which includes cooling, heating, humidification, dehumidification, and ventilation [3]. Applications of the AC are not only limited to humans' thermal comfort but also to agricultural products' storage and livestock applications [4]. Livestock sector as a part of agriculture sector is of prime importance for any growing economy [5]. It includes animal farming for meat and milk production as well as poultry farming for meat and egg production [6]. According to Pakistan Statistical Yearbook [7], the poultry sector under the agriculture sector contributed 1.4% in overall gross domestic product (GDP) of the country during economical year 2017–2018 [7]. Out of total meat production (i.e., 4.3 million tons), 1.47 million tons poultry meat is produced in the country, which highlighted the significance of the poultry sector in the economy [7].

In a poultry farm, cooling and ventilation of surrounding air are necessary for optimum growth of poultry birds [8]. These birds are highly susceptible to slight fluctuation in temperature and humidity of the surrounding air [8]. The poultry birds require an optimum temperature-humidity index (THI) throughout their growth up to the meat harvest stage. To achieve the required *THI* for the poultry birds, ambient air is conditioned. Several types of cooling systems are being used to attain thermal comfort of the poultry birds [3]. In Pakistan, pad type direct evaporative cooling (DEC) system is commonly preferred for cooling of air in poultry farms [9].

Typical hot and dry conditions of the country move to hot and humid conditions in the monsoon (i.e., heavy rainfall) season, which result in higher relative humidity in ambient air. This, therefore, limits the performance of a standalone DEC system [10]. Consequently, advanced evaporative cooling (EC) systems, namely the indirect evaporative cooling (IEC) system and the Maisotsenko-cycle based cooling (MEC) system, can be a better option for poultry farming in Pakistan [11]. EC systems are power-efficient when compared to conventional vapor compression air-conditioning systems in hot and dry climatic conditions [1,12]. The EC systems are simple in design (structure), energy efficient, and environmentally-friendly as compared to traditional vapor compression air-conditioning (VCAC) systems. The AC systems being traditionally used across the world consume a major share of primary energy and exhaust hydrochlorofluorocarbon-carbons (HCFCs)/hydro-fluorocarbons (HFCs)/chlorofluorocarbons (CFCs) [13–16]. Alternatively, HCFC, HFC, and CFC free refrigerants and desiccant unit based AC systems are also being studied [17,18]. Whereas, the EC systems have a very low carbon footprint when compared to the VCAC systems [19,20]. Objectives of this study include performance evaluation of three types of EC systems for the climatic conditions of Multan (Pakistan) and feasibility analysis of these EC systems for thermal comfort based on *THI* of poultry birds in poultry houses across Multan.

2. Thermal Comfort for Poultry Birds

Temperature and humidity control are necessary for every human and non-human's thermal comfort [4]. Additionally, the poultry birds also require an optimum temperature and relative humidity conditions for healthy growth [21]. Hence, seasonal variation in weather demands the need for AC. Figure 1 shows thermoneutral zones for poultry birds and represents the physical effect of heat stress on the poultry (broiler) birds [22]. Three different temperature zones are mentioned as thermoneutral, upper, and lower critical temperature zones. Optimum physiological growth in the birds increases with the optimum range of temperature and humidity inside the poultry house. Compared to the human body, the poultry birds lack sweat glands to dissipate body heat in a heat-stressed environment [21]. The birds transfer excess heat from their body into the environment by panting (i.e., heavy breathing) once the thermoneutral zone is crossed [21]. During the panting process, the birds transfer additional moisture into the environment, which leads to their suffocating conditions. Once the environment reaches a maximum heat point (i.e., dry-bulb temperature ≥ 47 °C [23]), the birds expire due to extreme stress heat. Figure 2 shows psychrometric representation of the required optimum temperature and relative humidity conditions for the birds (i.e., broilers) of varying age, and hourly climatic distribution of Multan. One-day-old chicks need relatively more temperature as compared to the elder chickens, as dictated by local practice of using heaters for one week. The optimum temperature slides down

from 34 to 32 °C, 32 to 28 °C, 28 to 26 °C, 26 to 24 °C, and 24 to 20 °C for one, two, three, four, and five week-old chickens, respectively [24,25]. At the same time, the relative humidity (RH) is maintained at 50–70% throughout the growth period [24,25]. In the poultry house, heat load is contributed by metabolism and respiration of the broiler, structure of the building (through convection), air change through doors, and sunlight through windows [26]. To satisfy the thermal comfort needs for poultry birds, a comprehensive AC system is needed to be installed in the poultry house, which has the potential to achieve the required heat loads. In this study, the working principle of different EC systems is explained and their respective performance for poultry air-conditioning is investigated including the effect of temperature, relative humidity, and velocity on the growth of poultry birds.

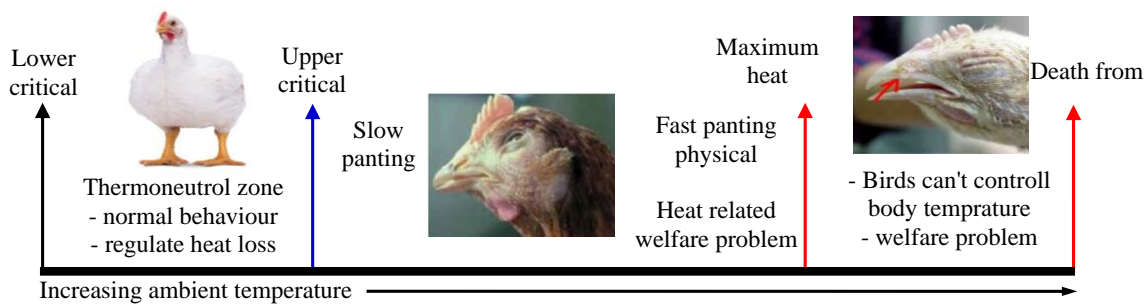


Figure 1. A simplified scheme showing thermoneutral zone of poultry birds.

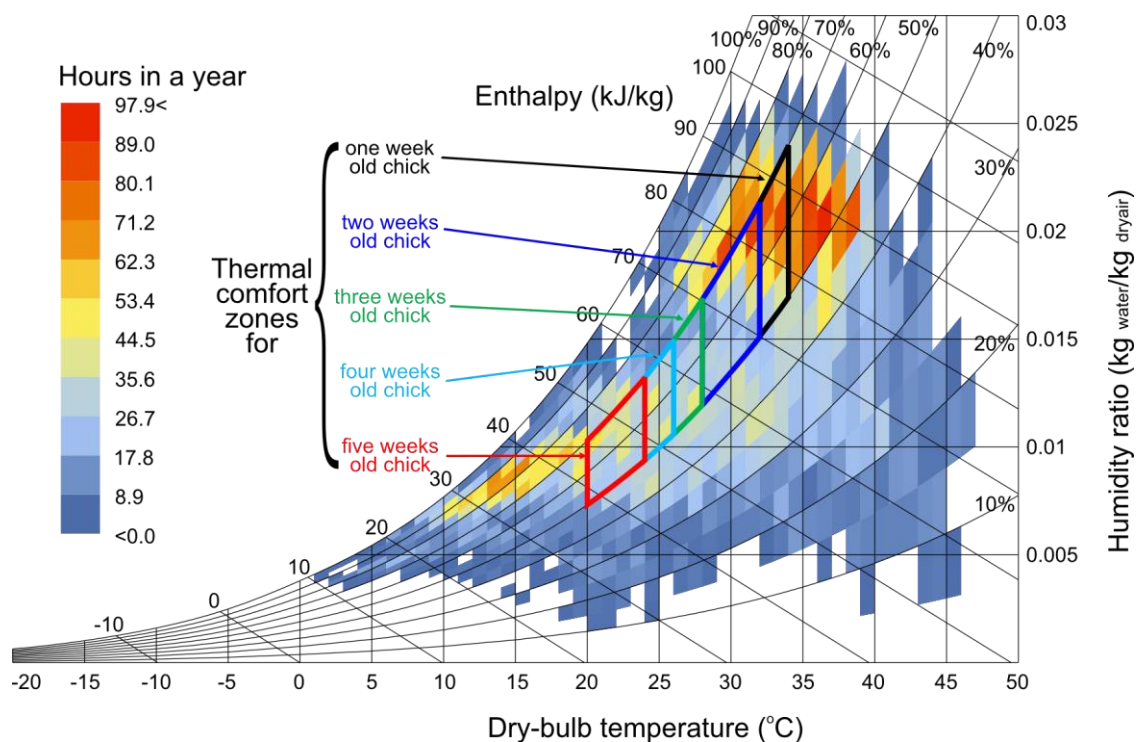


Figure 2. Psychrometric distribution of climatic conditions (hourly basis) of Multan associated with thermal comfort zones of poultry birds.

In order to achieve required temperature and humidity level inside poultry houses, the ventilation rate and air velocity are of paramount importance [27]. Ventilation generally mitigates the respiratory and humidity-related issues and replaces foul gases to increase the productivity of broilers. Factors to mark the productivity are feed intake, feed conversion ratio, and body weight gain [28]. Any slight variation in temperature, humidity, and air velocity results in poultry (health) welfare issues [29].

3. Materials and Methods

3.1. Evaporative Cooling (EC) Systems

Three kinds of lab-scale experimental EC systems were developed as shown in Figure 3. There was a similar housing assembly used for different heat mass exchangers (i.e., IEC and MEC channels) for experimentation. The direct (DEC), indirect (IEC), and M-cycle (MEC) evaporative cooling systems were operated for different conditions and the experimental data of temperature and relative humidity for the climatic conditions of Multan (Pakistan) was collected. Performance of the systems was evaluated in terms of the temperature gradient (i.e., difference between ambient and supply air temperature) and relative humidity (RH) level (of the ambient and supply air) to investigate the thermal comfort of poultry birds. In Figure 3, pictorial representations of the developed experimental systems along with MEC and IEC channels are presented. It consists of a fan, moisture sensor, temperature sensor, velocity sensor, and water storage tank. Additionally, experiments of the DEC system with cellulose cooling pads (or more commonly known as honeycomb pads) was used for this experiment instead of aspen wood fiber contained in a net (local name “khas”). The detailed scientific concept and thermodynamic fundamentals of these developed EC systems are described in the coming subheadings.

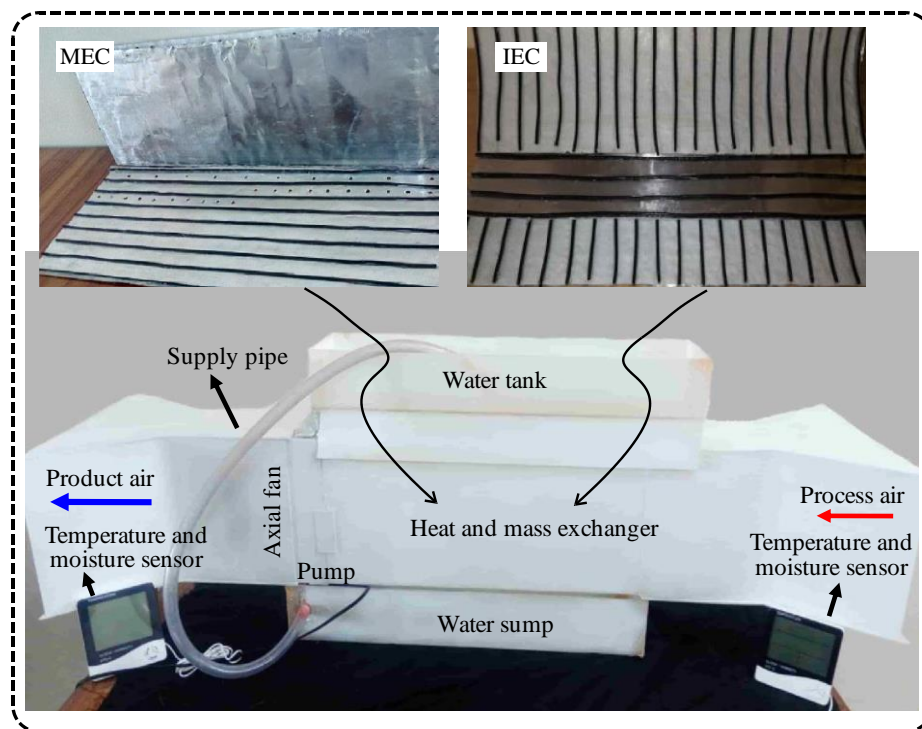


Figure 3. A pictorial representation of the experimental apparatus for MEC and IEC EC systems.

3.1.1. Direct EC (DEC) System

Direct evaporative cooling (DEC) system is the simplest and old type of EC system in which air comes directly in contact with the water surface to reduce its temperature [30,31]. Continuous evaporation of water (adiabatic process) vapors causes a cooling effect up to a saturation point of air [1,3,32]. Enthalpy (kJ/kg) of air at inlet and outlet conditions remains the same, whereas the humidity ratio (gram of water per kg of dry air i.e., g/kgDA) increases. The DEC system can potentially reduce the temperature of the inlet air up to its wet-bulb temperature with wet-bulb effectiveness (WBE) of 75–95% [3,33]. Schematic and psychrometric representation of the DEC system is shown in Figure 4a.

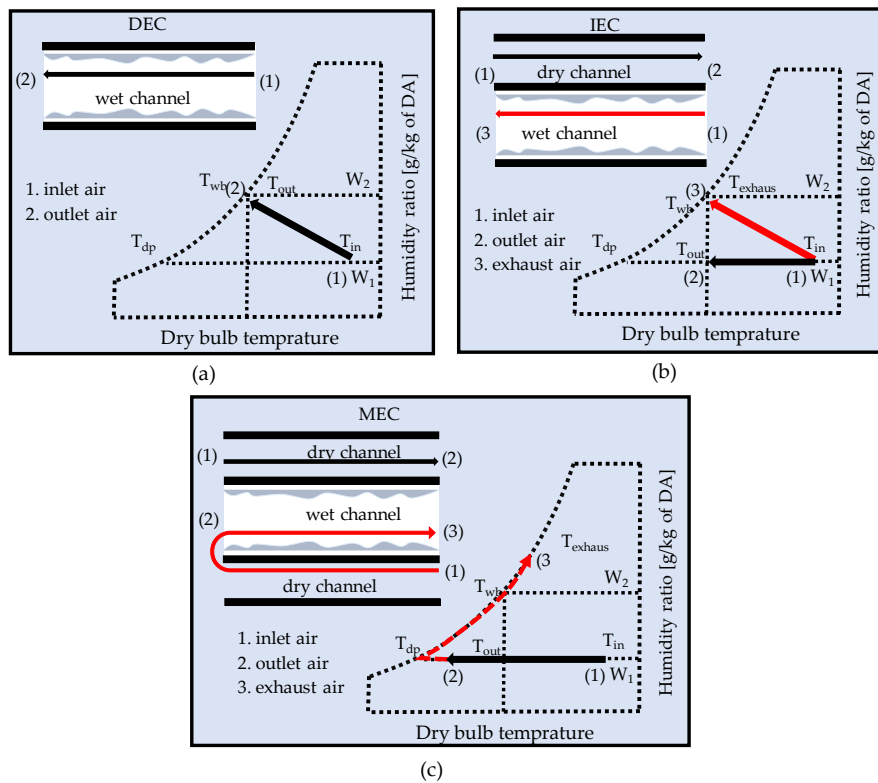


Figure 4. The schematic and psychrometric representations of the EC systems for (a) DEC, (b) IEC, and (c) MEC configurations.

Cooling effect in the DEC system is produced by utilizing latent heat of evaporation governed by Equation (1) given in the literature [3].

$$h_{outlet} = 1.006 T_{db} + w(2501 + 1.86T_{db}) \tag{1}$$

where h_{outlet} represents enthalpy of the outlet air (kJ/kg), T_{db} denotes dry-bulb temperature of the air ($^{\circ}\text{C}$), and w represents the humidity ratio of the outlet air (kg/kg). For further study on DEC, Equations (2) and (3) provide more insight [3].

$$(DBT)_{outlet} \geq (WBT)_{inlet} \tag{2}$$

$$(RH)_{outlet} > (RH)_{inlet} \tag{3}$$

where DBT denotes dry-bulb temperature air ($^{\circ}\text{C}$), RH denotes relative humidity of air (%), and subscripts outlet and inlet represent outlet and inlet air conditions, respectively.

3.1.2. Indirect EC (IEC) System

Indirect evaporative cooling (IEC) system is a system in which heat and mass transfer take place to reduce the temperature of primary/ambient air without the addition of moisture. It works on the basis of sensible cooling [1]. It consists of two channels named wet and dry channels [34]. Primary air passes through a dry channel and secondary/process air passes through a wet channel. In the IEC system, a cooling effect is produced by a two-way thermodynamic process: (1) isenthalpic cooling in the wet channel by water evaporation, and (2) sensible heat transfer in the dry channel [1,35]. It can reduce the temperature up to the wet-bulb temperature. Therefore, its WBE range is 50–65% [36,37]. In the IEC system, humidity (g/kg of dry air DA) of inlet air and outlet air remains the same. However, enthalpy (kJ/kg of dry air DA) of outlet air is decreased [1]. Schematic and psychrometric representation

of the IEC system is shown in Figure 4b. Further insights into the IEC system are governed by Equations (4)–(7) given in the literature [3].

$$(DBT)_{outlet} \geq (WBT)_{inlet} \quad (4)$$

$$(RH)_{outlet} > (RH)_{inlet} \quad (5)$$

$$w_{outlet} = w_{inlet} \quad (6)$$

$$h_{outlet} < h_{inlet} \quad (7)$$

where w and h represent the humidity ratio (kg/kg) and enthalpy of air (kJ/kg), and subscripts outlet and inlet represent outlet and inlet air conditions, respectively.

3.1.3. Maisotsenko-Cycle EC (MEC) System

Maisotsenko-cycle evaporative cooling (MEC) is the system in which ambient air undergoes a thermodynamic process in which psychrometric renewable energy available from the air is utilized to reduce the temperature of ambient air [1,38,39]. It is also called an advanced IEC system or regenerative evaporative cooling system [40]. In the MEC system, the cooling effect is produced by two thermodynamic processes: evaporative cooling and heat transfer [1,41] in which temperature of ambient air nearly reaches the dewpoint temperature instead of wet-bulb temperature [16,39,42]. It consists of three channels: one wet channel and two dry channels. The wet channel is sandwiched between two dry channels. When ambient air passes through the dry channel, it becomes cool due to convective heat transfer between wet and dry channels. In the MEC system, humidity (g/kg of dry air DA) of inlet air and outlet air remains the same. However, enthalpy (kJ/kg of dry air DA) of outlet air decreases [33,36]. Schematic and psychrometric representation of the MEC system is shown in Figure 4c. Further insights into the MEC system are governed by Equations (8)–(11) given in the literature [3].

$$(DPT)_{inlet} \leq (DBT)_{outlet} \leq (WBT)_{inlet} \quad (8)$$

$$(RH)_{outlet} > (RH)_{inlet} \quad (9)$$

$$w_{outlet} = w_{inlet} \quad (10)$$

$$h_{outlet} < h_{inlet} \quad (11)$$

where DPT, DBT, and WBT represent dewpoint, dry-bulb, and wet-bulb temperatures (°C), respectively, RH represents relative humidity (%), w and h represent the humidity ratio of air (kg/kg) and enthalpy of air (kJ/kg), respectively, and subscripts outlet and inlet represent outlet and inlet air conditions, respectively.

Performance of the EC systems can be assessed in terms of their effectiveness, i.e., wet-bulb effectiveness (WBE), given by Equation (12).

$$E_{WB} = \frac{DBT_{inlet} - DBT_{outlet}}{DBT_{inlet} - WBT_{inlet}} \quad (12)$$

where ε_{WB} , DBT, and WBT represent wet-bulb effectiveness (-), dry-bulb and wet-bulb temperatures of air (°C), respectively, and the subscripts inlet and outlet represent inlet and outlet air conditions, respectively.

3.2. Research Methodology

To determine the design cooling load for the AC system, heat produced (HP) by the birds and their THI is required. Pedersen (2000) [43,44] model is used to calculate the HP (sensible and latent) per bird for climatic conditions of Multan. Figure 5 represents an illustration of integration of EC systems into a poultry house and sensible and latent heat load generated by a poultry bird. Heat production in birds

changes with respect to their body weight [45]. The birds grow muscles over time due to consuming more energy produced from feed intake [46]. As a result, more heat is released. Heat production (*HP*) in poultry birds is governed by Equation (13) given in the literature [26].

$$HP = 60.64 + 0.04LW \tag{13}$$

where *HP* represents heat production from poultry birds (W/kg) and *LW* represents the live weight of poultry birds (g).

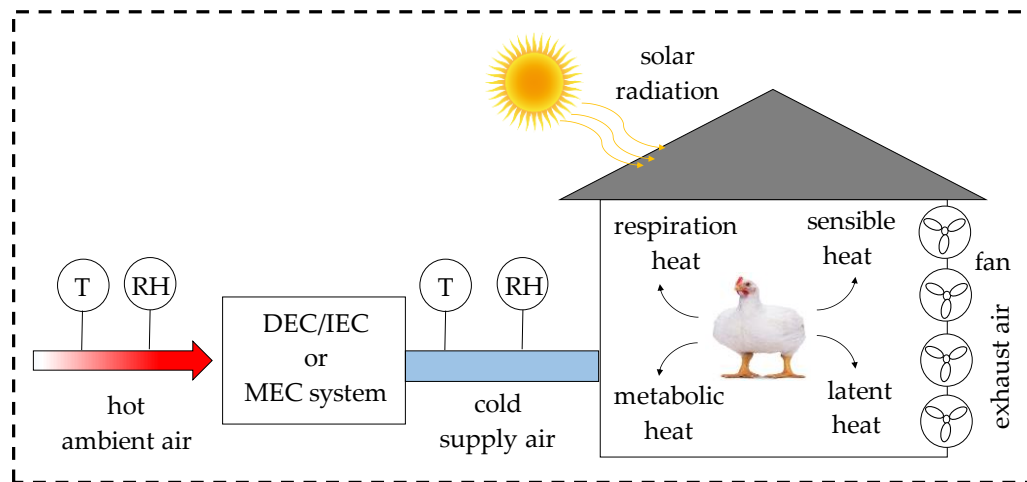


Figure 5. Scheme of temperature and humidity control system(s) in a typical poultry shed for maintaining the thermal comfort of poultry birds.

Sensible and latent heat production per bird is calculated using the Pedersen (2000) model given by Equations (14) and (15), respectively [43,44].

$$Q_t = 9.84m_a^3(4.10^{-5}(20 - T_{db})^3 + 1) \tag{14}$$

$$Q_s = 0.83Q_t(0.8 - 1.85e^{-7}(T_{db} + 10)^4) \tag{15}$$

where Q_t and Q_s represent total and sensible heat productions (J/s), respectively, and m_a represents the mass of live birds (kg) and T_{db} represents dry-bulb temperature (°C).

The temperature-humidity index (*THI*) is a linear combination of dry-bulb temperature and wet-bulb temperature. *THI* has been established to evaluate the effect of the thermal environment on thermoregulatory status of poultry birds [47]. Equation (16) governs *THI* for broilers [47].

$$THI = 0.85T_{db} + 0.15T_{wb} \tag{16}$$

where *THI* represents temperature-humidity index (°C), and T_{wb} represents wet-bulb temperature of air (°C). The wet-bulb temperature for poultry birds is calculated by Equation (17) [48,49].

$$T_{wb} = T_{db} \tan^{-1} \left[\frac{0.151977 + (RH + 8.313659)^{\frac{1}{2}}}{-\tan^{-1}(RH - 1.676331) + 0.00391838 RH^{\frac{3}{2}} \tan^{-1}(0.023101 RH)} \right] - 4.686035 \tag{17}$$

where *RH* represents relative humidity of air (%).

THI has been developed based on body temperature responses instead of production responses [47]. Based on physiological parameters such as: body temperature, respiration rate, or pulse rate, heat production, or production performance, *THI* equations describe the importance of T_{db} and T_{wb} for a

range of animals including poultry birds and cattle [50]. However, THI fails to integrate the effect of air velocity (V) on animal thermal comfort [50]. Effects of air velocity on body temperature of poultry birds is accounted for by integrating V into THI [27]. Due to the nonlinear nature of V , the asymptotical function is considered [50]. Consequently, the temperature-humidity-velocity index (THVI) is used in this study for homeostasis (i.e., ability of an animal to maintain constant internal conditions in the face of fluctuating external conditions) of birds [27]. With increase in velocity up to a certain point (i.e., 1.2 m/s), optimum thermal comfort for poultry birds inside a poultry can be achieved [50]. THVI is calculated by Equation (18) given in the literature [27].

$$THVI = V^{-0.058} THI \tag{18}$$

4. Results and Discussion

The results from the developed EC systems are obtained for the climatic conditions of Multan (Pakistan), which are presented in Figure 6. Ambient air temperature ranges from 12.3 °C to 42.1 °C. The DEC system resulted in a temperature range of 10 °C to 32.3 °C, which created a temperature gradient of 10.9 °C. The IEC system resulted in a temperature range of 10.8 °C to 35.5 °C, which led to a temperature gradient (i.e., difference between ambient and supply air temperature) of 7.4 °C. The MEC system resulted in a temperature range of 13.2 °C to 31.6 °C, which created the maximum temperature gradient of 14.4 °C. From these results, the MEC system performs better when compared to the DEC and IEC systems in terms of the temperature gradient. The trend of relative humidity (%) of ambient air, DEC, IEC, and MEC systems is also presented in Figure 6. The DEC, IEC, and MEC systems resulted in relative humidity ranging from 72% to 98%, 51% to 78.5%, and 66.7% to 93.6%, respectively. A maximum increase in relative humidity is observed in case of the DEC system as compared to IEC and MEC systems. Additionally, Figure 6 shows that April to June are hot and dry months whereas July to October are hot and humid months, which indicated a need for AC in both. Figure 7 shows performance of the EC systems based on wet-bulb effectiveness for DEC, IEC, and MEC systems. The DEC and MEC systems resulted in relatively higher effectiveness when compared to the IEC system. MEC system achieved maximum effectiveness of 0.98 in November. Additionally, DEC and IEC systems achieved maximum wet-bulb effectiveness of 0.96 and 0.57 in September and May, respectively.

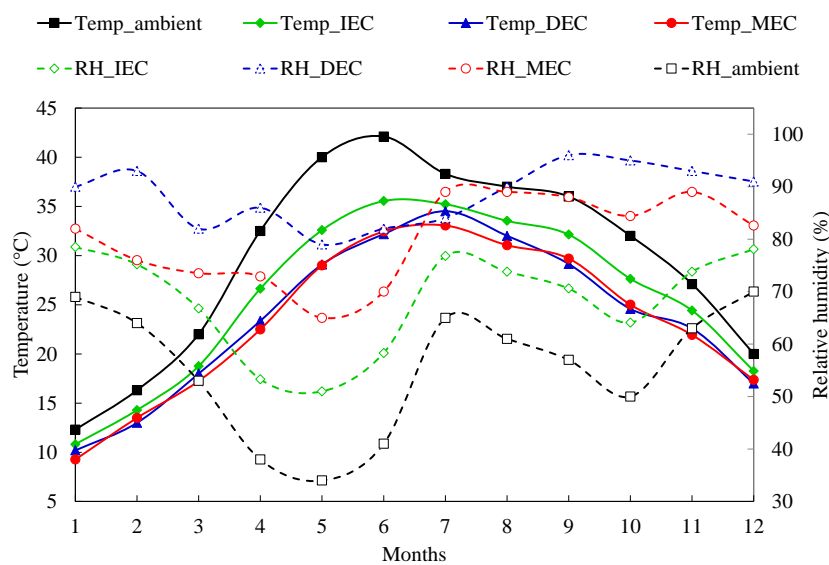


Figure 6. The annual profiles of temperature and relative humidity for ambient conditions of Multan and output conditions of the DEC, IEC, and MEC systems.



Figure 7. The achieved wet-bulb effectiveness of the EC systems against the results presented in Figure 6 for climatic conditions of Multan.

Figure 8 represents the relationship of heat production (HP) and temperature-humidity index (THI) with live weight of poultry birds. HP of poultry birds increases in linear function with respect to LW. In the early stage of poultry growth, higher THI is tolerated while justifying the earlier statement about use of heaters for one-week old chicks. Heat production is at peak when poultry birds achieve harvest mass. Poultry birds ready for harvest generate the highest heat (i.e., 171 W/m²) against THI of 18.2 °C at 2.75-kg live weight.

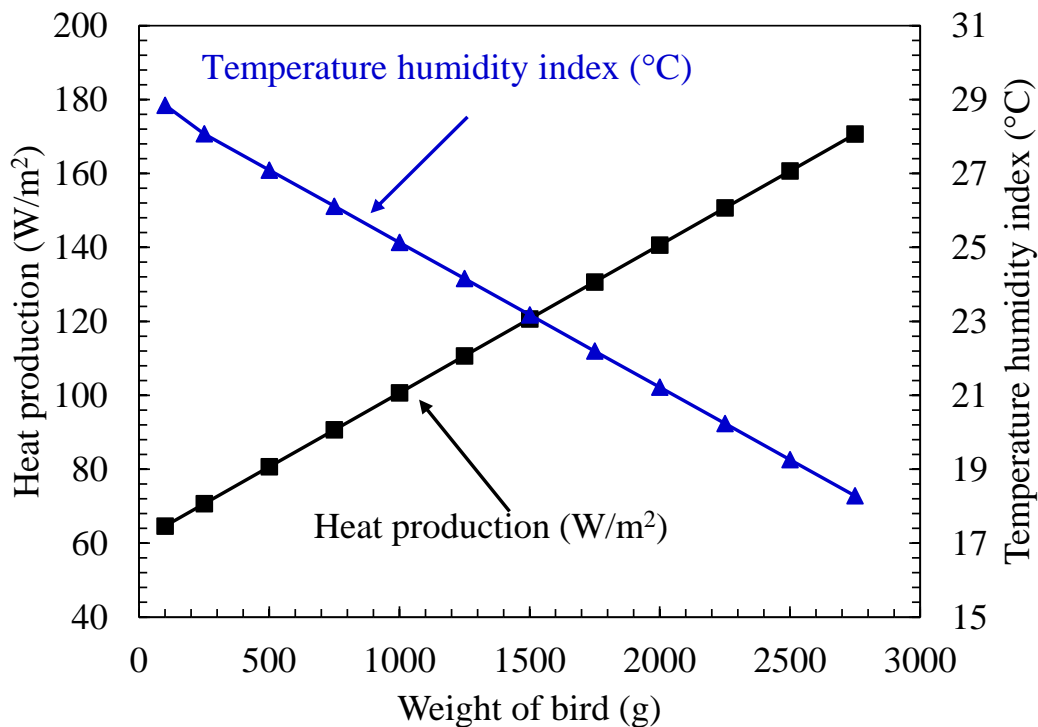


Figure 8. The variations of heat production and THI with respect to weight of poultry birds.

Figure 9 shows the relation of relative humidity and THI with reference to T_{db} . Increase in humidity up to the optimal value of dry-bulb temperature works accordingly to overcome heat stress. Figure 10 represents the effect of T_{db} on THVI with respect to varying air velocity. It is noticed that, at a fixed value of T_{db} , THVI decreases slightly with an increase in the velocity of air. Moreover, Figure 11 shows THI with a varying temperature and relative humidity. THI ranges from 28 °C to 30 °C, which indicates an alarming situation for the poultry birds. It turns into a dangerous situation when THI surpasses 30 °C. An emergency action is required if the THI value surpasses 31 °C. Poultry birds grow healthier at 18 °C to 29 °C and 50% RH [47].

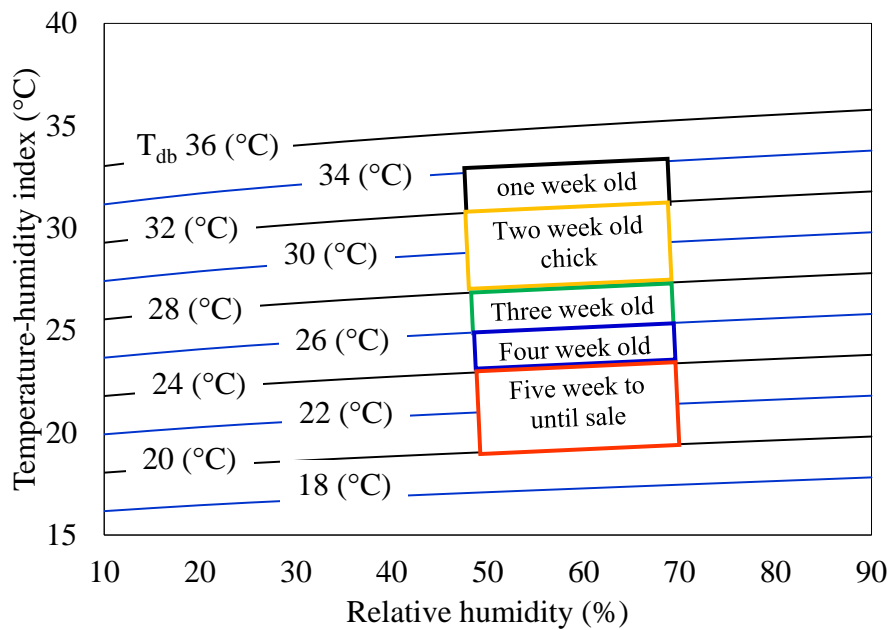


Figure 9. The optimum thermal comfort requirements of the poultry birds of different ages.

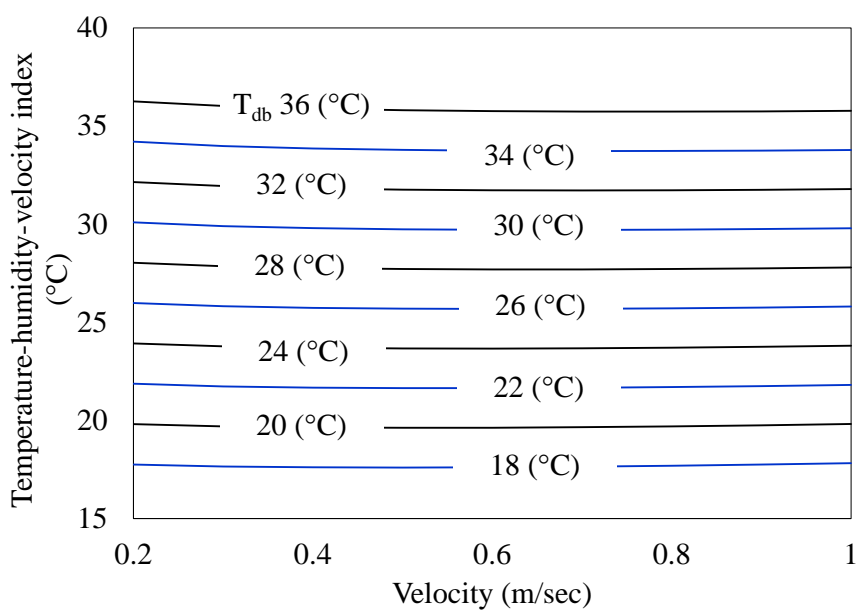


Figure 10. The variation of THVI as a function of air velocity at different T_{db} .

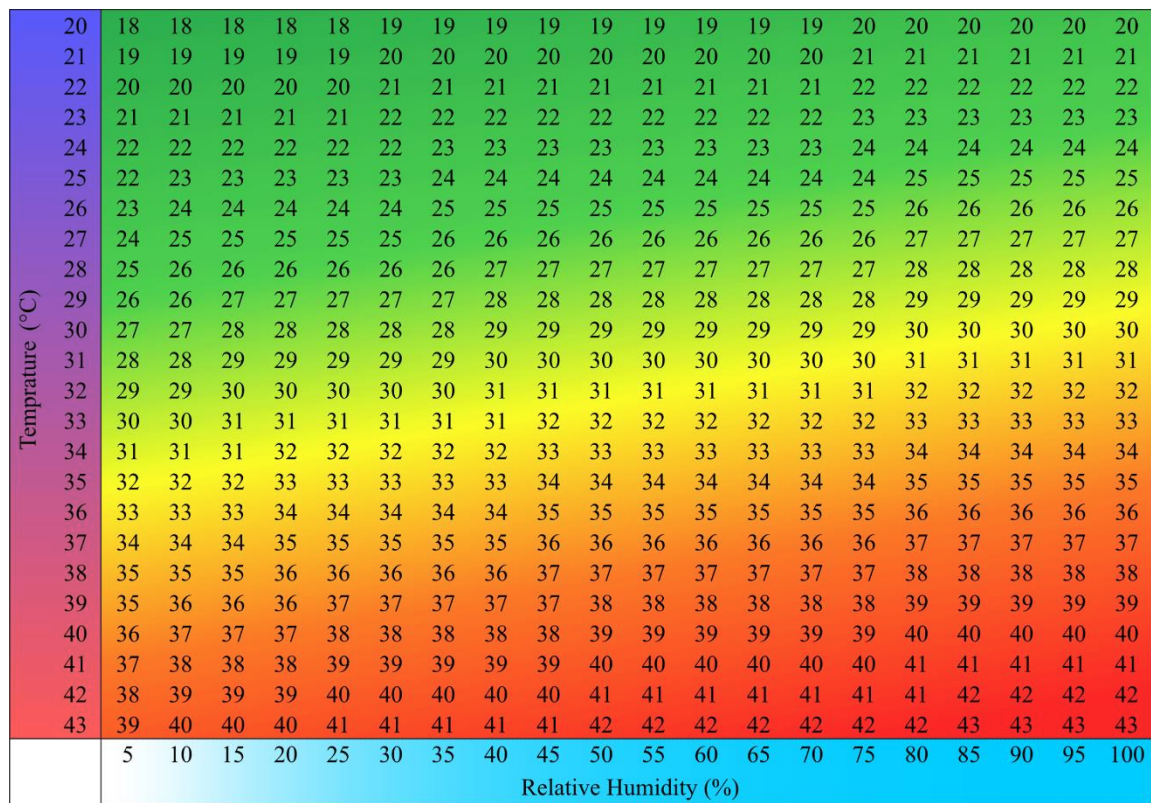


Figure 11. The numerical values of THI corresponding to various temperature and relative humidity levels. The green color presents relatively better THI whereas a red color reflects the worst scenario of THI.

Sensible and latent HP per bird directly effects their mortality rate. It also explains the complex situation of heat stress gained by poultry birds. As the ambient temperature starts increasing, HP per bird gets increased. Moreover, there remains a widening gap between the values of sensible and latent heat production per bird. Once this gap gets shrieked under any abnormal condition of ambient temperature, there comes an end to the welfare of poultry birds. Figure 12 represents the variations in heat production against the weight of poultry birds at different temperatures.

Figure 12a shows an increase in total HP by poultry birds since they gain weight at 18 °C. At an early stage, sensible HP increases comparatively higher than that of latent HP. This trend continues to grow. It is seen that, at 3 kg weight of poultry bird, sensible HP (i.e., 14.8 W/kg) is roughly double the value of latent HP (i.e., 7.5 W/kg). Similarly, Figure 12b–d shows the trend of total HP by poultry birds of different live weights at 30 °C, 40 °C, and 45 °C, respectively. Sensible (13.7 W/kg) and latent (7.7 W/kg) HP is observed at 30 °C. Sensible and latent HP of 6.9 W/kg and 8.1 W/kg as well as 3.4 W/kg and 4.5 W/kg at 40 °C and 45 °C, respectively. Additionally, Figure 12d indicates a higher latent HP compared to sensible HP indicating that the bird is suffocating due to an increase in the humidity ratio in the surrounding air. Moreover, at 40 °C, the difference between sensible and latent HP is at the lowest, which indicates that the bird is about to expire due to heat stress and suffocation. With increasing THI, poultry birds start losing their strength to fight against heat stress. Impact of T_{db} and T_{wb} on THI is further explored in Appendix A, as given by Figure A1.

Figure 13 shows yearly THI analysis of ambient air under DEC, IEC, and MEC systems. Permissible limit of THI denotes 30 °C T_{db} and 50% RH. THI of ambient air from November to March (winter) is within the permissible limit, which indicates no need of AC for poultry birds. Figure 14 shows a psychrometric representation of performance variation of EC systems from April to October for the climatic conditions of Multan against thermal comfort zones of poultry birds of different ages.

The detailed psychrometric representation of the EC systems performance for the months of April to October is provided in Appendix A, as given by Figure A2a–g, respectively. Results indicate that MEC, DEC, and IEC systems somewhat achieve required thermal comfort conditions of different ages of the poultry for some of the months (April to October). Moreover, applicability of the EC systems for poultry AC and ventilation from the viewpoint of THI is summarized in Table 1.

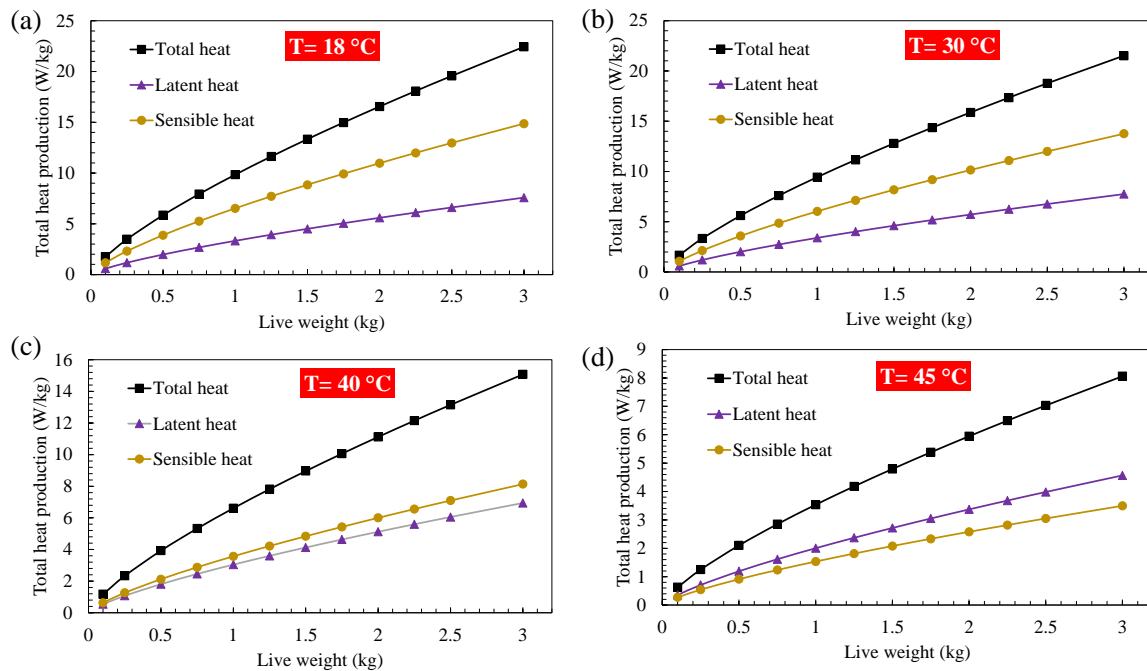


Figure 12. The sensible and latent heat production per poultry bird for (a) 18 °C, (b) 30 °C, (c) 40 °C, and (d) 45 °C.

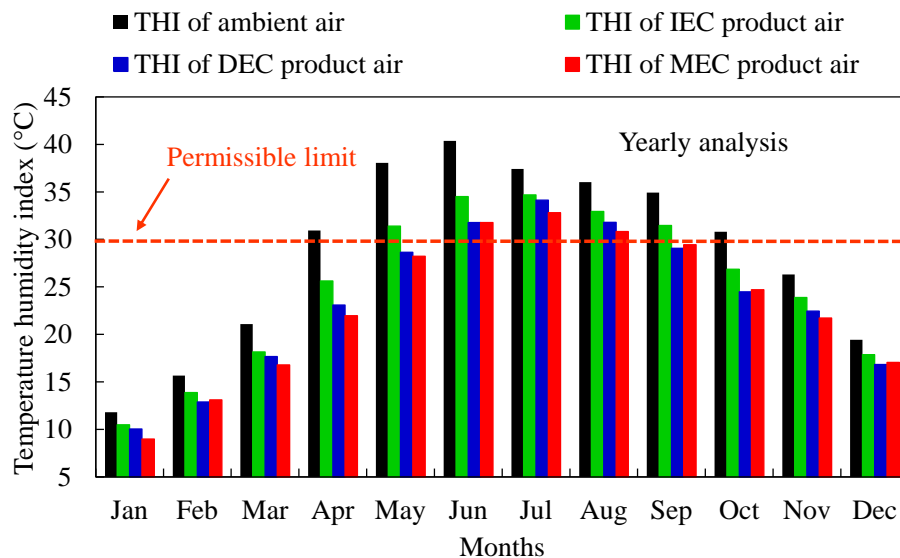


Figure 13. Annual profile of THI resulting from the EC systems for climatic conditions of Multan. The red dotted line shows the optimum level of THI i.e., 30.

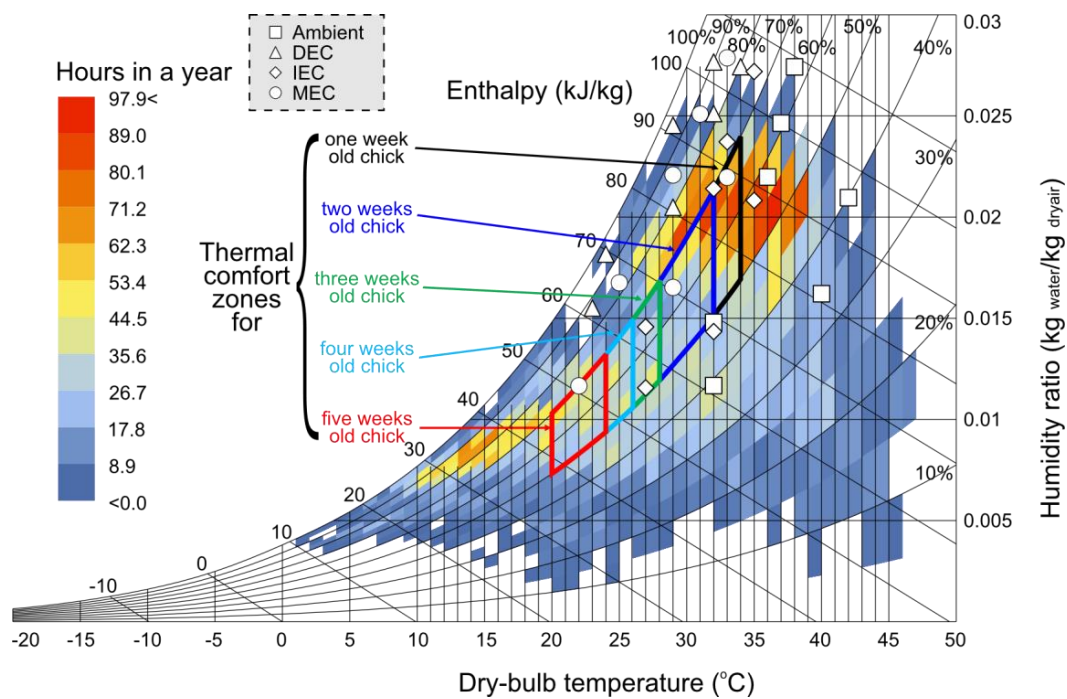


Figure 14. Psychrometric representation of the performances of EC systems for the months of April to October.

Table 1. Applicability/feasibility of the EC systems for the climatic conditions of Multan. The results are based on numerical values of THI.

Months	Ambient Conditions	DEC	IEC	MEC
January	✓	✓	✓	✓
February	✓	✓	✓	✓
March	✓	✓	✓	✓
April	×	✓	✓	✓
May	×	✓	×	✓
June	×	×	×	×
July	×	×	×	×
August	×	×	×	✓
September	×	✓	×	✓
October	×	✓	✓	✓
November	✓	✓	✓	✓
December	✓	✓	✓	✓

5. Conclusions

This study is aimed to analyze the performance of low-cost evaporative cooling (EC) options for climatic conditions of Multan (Pakistan). The hot and dry summer of Multan demands an efficient air-conditioning (AC) system for poultry birds. In this regard, the EC systems can provide cost-effective and an environmentally-friendly solution. Therefore, three kinds of EC systems, i.e., direct EC (DEC), indirect EC (IEC), and Maisotsenko-cycle EC (MEC) are investigated for thermal comfort of poultry birds. Thermal comfort of poultry birds in each case of the EC systems was assessed in terms of temperature-humidity (THI) and temperature-humidity-velocity (THVI) indices. Heat production against age and weight of poultry birds was also investigated. Weight of poultry birds with growing age increases. Consequently, heat production is also increased. This increased value of heat production (HP) gives birth to heat stress for growing birds. Young birds with less weight can survive a slightly higher range of THI compared to older birds, which show immense signs of heat stress with increasing weight. At ambient temperature higher than or equal to the normal poultry body temperature, latent

HP surpasses sensible HP, which causes suffocation due to an increased latent load in the ambient air. DEC, IEC, and MEC systems achieve the required thermal comfort sensation for poultry birds. However, the DEC system increases relative humidity up to such an extent that it causes suffocation for the birds. It is concluded that, in summer conditions (with $T_{db} > 40\text{ }^{\circ}\text{C}$) when poultry birds attain harvest mass, their heat production results in a higher latent load into the ambient air. Since the EC systems also contribute latent load into the supply air, poultry birds face suffocation due to excessive humidity in the air, which can be controlled by developing hybrid combinations of VCAC-EC systems. Additionally, MEC coupled with a desiccant air-conditioning unit (M-DAC) could potentially achieve thermal comfort of poultry birds for all months across Pakistan.

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Appendix A

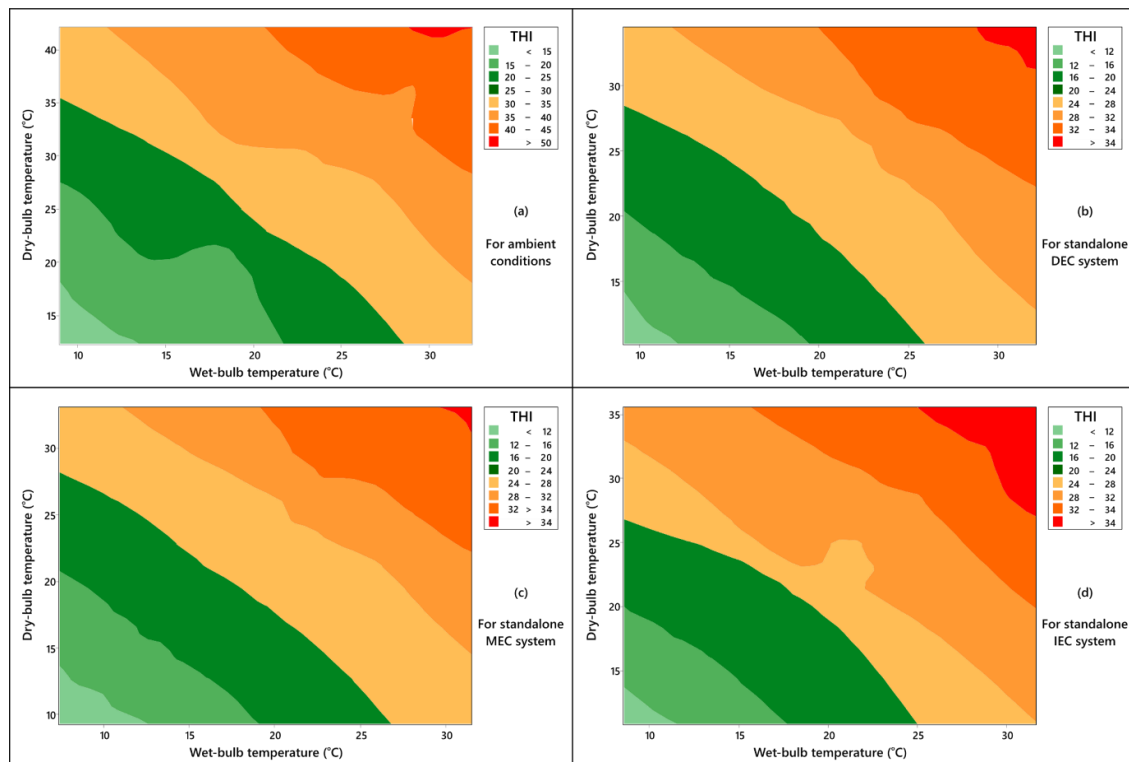


Figure A1. Impact of T_{db} and T_{wb} on THI for the EC systems represented on contour plots.

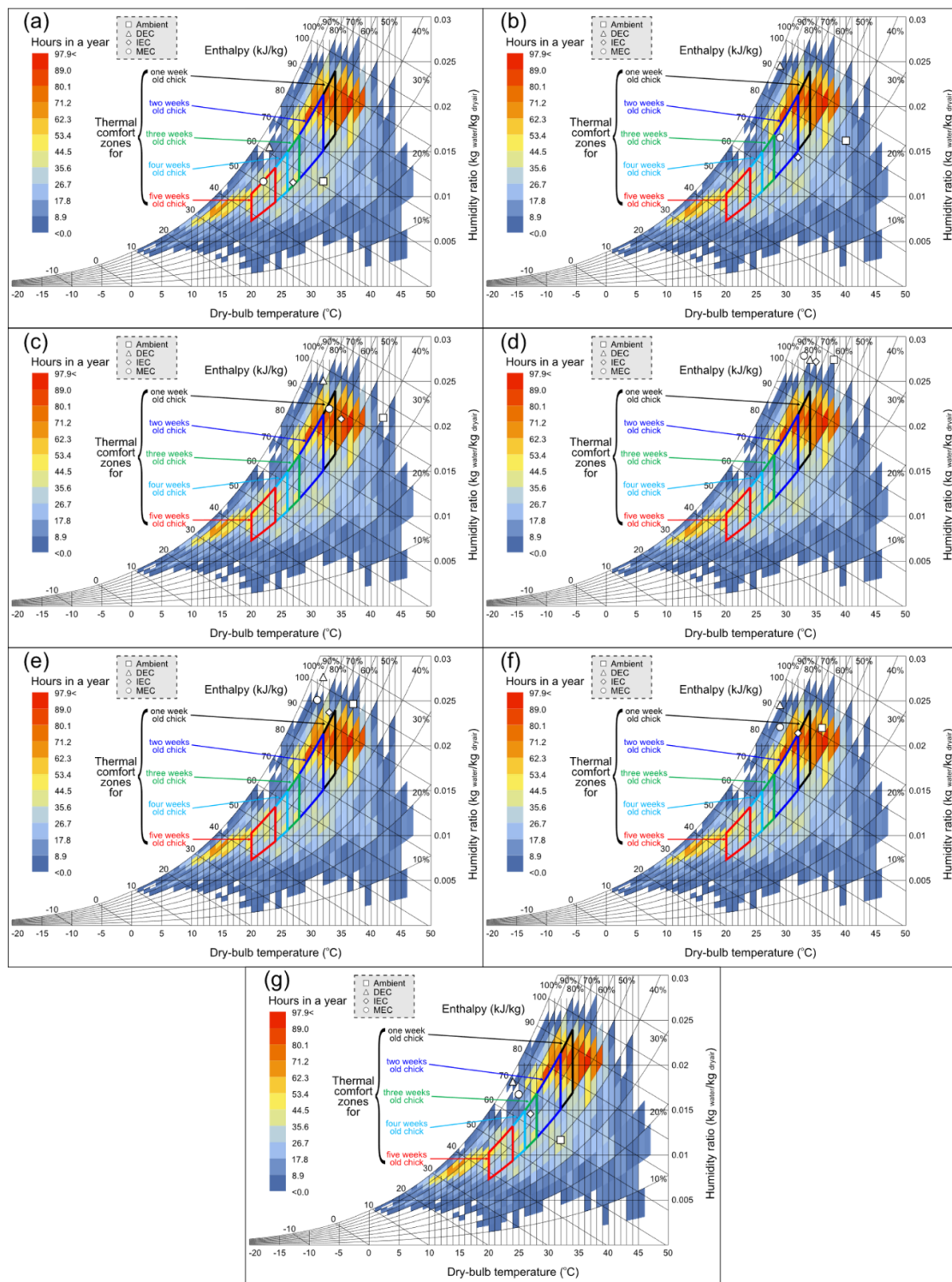


Figure A2. Psychrometric representation of the performances of EC systems for the months of (a) April, (b) May, (c) June, (d) July, (e) August, (f) September, and (g) October.

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