Uludag Bee Journal
Uludag Bee J.
e-ISSN: 2687-5594
ISSN 1303-0248
https://dergipark.org.tr/en/pub/uluaricilik
https://uadubj.uludag.edu.tr/

Thermal management for enhanced honeybee (*Apis mellifera* L.) survival and productivity under arid climate stress

Abdallah S. SHAFEY[1*], Yossef A. ELSHABARAWY[2], Mohamed A. SHEBL[1], Ahmed A. ELSHABARAWY[1], Zeinb E. ABD-ELLATIF[1], Samaa M. TAWFIK[1], Eman M. ABDALLAH[1], Aya A. SHOKRY[1], Soliman M. KAMEL[1]

[1]Plant Protection Department, Faculty of Agriculture, Suez Canal University, Egypt, Corresponding author E-mail: abdallahelshafey63@gmail.com

[2]School of Engineering and Technology, Badr University in Cairo, Egypt

Received: 27.11.2025 Accepted: 02.02.2026 Published: 02.03.2026

Abstract

Honeybee (*Apis mellifera* L.) colonies are increasingly exposed to climate-driven thermal extremes in arid regions such as Egypt. This two-year study (2024–2025) compared one programmable temperature-controlled (TC) hive equipped with ceramic heating for winter and dual fans for summer with one standard control (SC) hive, and the results were interpreted as proof-of-concept. The results showed that thermal regulation during winter improved colony performance. So, foraging activity in the TC hive averaged 301 bees compared to 93 bees in the SC hive. Feed consumption reached 90% in the TC Hive versus 24% in the SC Hive. Brood development increased more than five times in the TC hive (1250 cm² vs. 230 cm²), accompanied by a higher honey yield (1146 g vs. 410 g). Winter mortality was reduced in the TC hive (21 vs. 234 dead bees), and colony aggressiveness declined (3 vs. 24 stings). In summer, fan-based ventilation reduced internal temperatures by only 1–2 °C below ambient temperatures exceeding 40 °C. Consequently, differences between TC and SC hives were minimal across all measured parameters. These findings confirm that winter heating enhances colony resilience, whereas fan-only cooling is insufficient. Future systems should integrate evaporative cooling, thermoelectric modules, or solar-powered chillers.

Keywords: Colony loss, Climate change adaptation, Hive technology, Honeybee, Thermal mitigation

Kurak iklim koşullarında bal arılarının (*Apis mellifera* L.) yaşam süresi ve üretkenliğinin iyileştirilmesine yönelik termal yönetim

Öz

Bal arısı (Apis mellifera L.) kolonileri, Mısır gibi kurak bölgelerde iklim kaynaklı aşırı sıcaklıklara giderek daha fazla maruz kalmaktadır. Bu iki yıllık çalışma (2024–2025), kış için seramik ısıtma ve yaz için çift fan ile donatılmış bir programlanabilir sıcaklık kontrollü (TC) kovanı, bir standart kontrol (SC) kovanı ile karşılaştırmış ve sonuçlar kavram kanıtı olarak yorumlanmıştır. Sonuçlar, kış aylarında ısı düzenlemesinin koloni performansını iyileştirdiğini göstermiştir. Böylece, TC kovanındaki besin arama faaliyeti ortalama 301 arı iken, SC kovanında bu sayı 93 arıdır. Yem tüketimi TC kovanında %90'a ulaşırken, SC kovanında %24'tür. TC kovanında yavru gelişimi beş kattan fazla arttı (1250 cm²'ye karşı 230 cm²), buna daha yüksek bal verimi eşlik etmiştir (1146 g'ye karşı 410 g). TC kovanında kış ölümleri azalmış (21'e karşı 234 ölü arı) ve koloni saldırganlığı azalmıştır (3'e karşı 24 sokma). Yaz aylarında, fan tabanlı havalandırma ile 40 °C'yi aşan ortam sıcaklıklarını sadece 1-2 °C'nin altına düşürdük. Sonuç olarak, TC ve SC kovanları arasında ölçülen tüm parametrelerdeki farklar minimum düzeyde olmuştur. Bu bulgular, kışın ısıtmanın koloni direncini artırdığını, ancak sadece fanla soğutmanın yetersiz olduğunu doğrulamaktadır. Gelecekteki sistemler, evaporatif soğutma, termoelektrik modüller veya güneş enerjili soğutucuları entegre edilmelidir.

Anahtar kelimeler: Koloni kaybı, İklim değişikliğine uyum, Kovan teknolojisi, Bal arısı, Isı azaltma

INTRODUCTION

Honeybee (*A. mellifera* L.) colonies are essential for pollination and honey production worldwide and in Egypt, where apiculture has sustained rural livelihoods for millennia (Klein et al. 2007; Potts et al. 2016; Hung et al. 2018; Osman & Shebl 2020). In recent decades, beekeepers across the country have reported severe colony declines, reduced honey yields, and increased winter mortality trends closely linked to intensifying climatic extremes in this hyper-arid region (Abdel-Rahman & Moustafa 2012; Abou-Shaara, 2016; Ahmed 2019; Ali et al. 2023).

Egypt now experiences unusually cold winters, with ambient temperatures frequently dropping below 10 °C, the critical threshold for brood rearing, and scorching summers exceeding 40 °C, which disrupts foraging, elevates metabolic stress, and impairs hive homeostasis (Alattal & Alghamdi 2015; Mostafa et al. 2019). These seasonal thermal extremes challenge the colony's ability to maintain its optimal brood nest temperature (32–35 °C), a physiological requirement supported by sophisticated behavioral thermoregulation, such as clustering, fanning, and water evaporation (Tautz et al. 2003; Phillips 2003; Abou-Shaara et al. 2017).

Weak or small colonies are particularly vulnerable during winter, as they lack sufficient workforce to generate adequate heat through endothermic shivering, often leading to starvation, brood loss, or complete collapse even when food reserves are available (Winston 1987; Doke et al. 2015). Recent field evidence has confirmed that simple heating devices can significantly reduce winter losses in weak colonies (from 40% to 15%) and enhance brood development by maintaining internal hive temperatures within a survivable range (Çakmak et al. 2023). This aligns with earlier findings that artificial heating during cold months spares metabolic energy, allowing colonies to redirect resources toward reproduction and foraging rather than thermogenesis (Omran 2011; Southwick 1985).

In contrast, summer heat stress, although less lethal, still suppresses colony productivity through heat-induced fatigue, reduced foraging efficiency, and reallocation of workers to cooling behaviors (Alattal & Alghamdi 2015; Abou-Shaara 2016; Alqarni 2006). While bees naturally employ evaporative cooling via water collection, this mechanism becomes insufficient under extreme arid heat (>40 °C), especially when floral water sources are scarce (Stabentheiner et al. 2010). Given the limitations of natural cooling under extreme arid conditions and the combined challenges of cold winters and hot summers, engineered hive interventions offer a promising pathway to improve colony survival and productivity. However, most existing systems are tested under controlled or temperate conditions, with limited field validation in regions such as Egypt that experience simultaneous cold winters and extreme summers (Neumann & Straub 2023). Moreover, natural hive cavities provide superior thermal buffering (4–7× better than wooden Langstroth hives), highlighting the vulnerability of conventional hives to rapid temperature fluctuations (Mitchell 2016).

This study addresses this gap by evaluating a field-deployed, programmable TC hive equipped with ceramic heating for winter and dual-fan ventilation for summer under real-world Egyptian conditions over two consecutive years (2024–2025). We compared its performance against SC hive across key indicators: foraging activity, syrup consumption, brood and honey area, honey yield, mortality, and colony aggressiveness, which provides practical insights for climate-resilient beekeeping in arid environments.

MATERIALS AND METHODS

1. Study Location and Tested Colonies

The study was conducted at the Bee Research Center (BRC), Faculty of Agriculture, Suez Canal University, Ismailia, Egypt (30°37′11.9″N, 32°16′06.3″E). The experimental apiary housed Carniolan–Egyptian hybrid colonies, a strain widely maintained in Egyptian apiculture because of its adaptability to local climatic conditions.

The experiment spanned two consecutive years (2024–2025), covering the winter (January-February-March) and summer (June-July-August) seasons each year. Due to logistical constraints, only one colony per treatment was used each year (n = 1 replicate per treatment). To mitigate year-to-year variability, new colonies were introduced in 2025 (distinct from those in 2024), providing temporal replication. All colonies were initiated with comparable strength (10 frames fully covered with bees) and managed under identical apicultural protocols.

2. Colony Management and Equalization

At the beginning of each experimental season, colonies were standardized in strength, brood area, and food reserves. All colonies were headed by sister queens of similar ages and genetic backgrounds to minimize variability in colony behavior and productivity. Colonies **were fed 1000 g of 50% (w/v) sucrose solution once per week during the experimental months, with syrup** provided in an internal feeder.

3. Hives used

Two experimental hives were used in this study. The first hive was a temperature-controlled hive equipped with two DC brushless fans (Model YD12038HSL, 12V, 0.50A, 6 W) for ventilation and a ceramic heater (220–240V, 250W) for winter heating. The fans and heater were controlled by an Arduino-based system with programmed activation thresholds based on the hive's internal temperature. The second hive was a standard-controlled hive with no thermal intervention. In 2024, the TC hive contained a Carniolan–Egyptian hybrid colony with strength comparable to that of the SC hive, with each colony comprising 10 frames. Both hives were monitored during the three winter months (January, February, and March) and subsequently during the summer months (June, July, and August). In 2025, new honeybee colonies, distinct from those used the previous year, were introduced into both hives to ensure independent replication of the experiment**.** Each colony again consisted of a Carniolan–Egyptian hybrid of similar strength (10 frames), and the study was carried out during the same winter and summer months as in the previous year. This design ensured consistent comparisons between TC and SC hives under contrasting climatic conditions.

4. Design of the temperature-controlled hive (TC)

A prototype TC hive, consisting of three vertical boxes, was developed to buffer colonies against seasonal temperature extremes (Figure 1A).

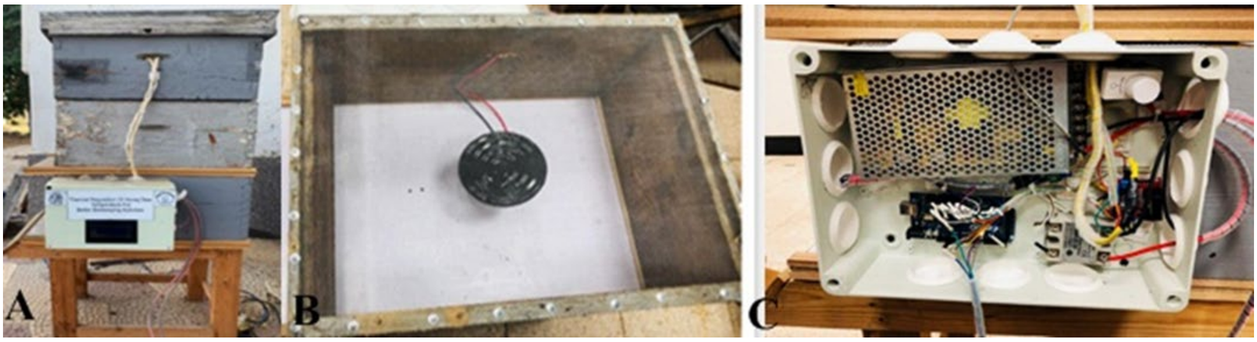

Figure 1. A-temperature-controlled hive. **B-** first box contains a heat source (a ceramic heater). **C-** external control attached box contains all the electronic components.

4.1 Heating box (lower box)

The first box contained a ceramic heater designed to generate and regulate the temperature inside the honeybee colony (Figure 1B). The heater was installed at the center of the box to ensure uniform heat distribution throughout the colony. Additionally, a mesh screen was mounted at the top of the heating box to prevent bees from entering the heating box from the second box (which housed the honeybee colony), while ensuring that heat was effectively transferred to the honeybee colony.

All electronic components, including the Arduino Mega 2560, a dimmer, a solid-state relay, a12V/5 a SMPS power supply, a 4×20 LCD display, and an L298N motor driver (Supplementary 1), were housed in a sealed external control box (30 × 30 cm) (Figure 1C), which was securely mounted to the exterior of the lower (heating) box to protect the circuitry from moisture and bee interference while maintaining easy access for maintenance and monitoring.

4.2 Colony box (middle Box)

The bee colony (queen, workers, and drones) was housed in a hive equipped with a Type K thermocouple sensor positioned at the center of the brood nest to monitor the internal temperature in real time (Figure 2). This sensor was connected to an Arduino Mega 2560 microcontroller, which was programmed using custom code uploaded via Arduino IDE (version 2.3.4). The program was designed to activate the heater whenever the internal temperature dropped below 30 °C (target: 35 °C) and to trigger cooling when the temperature exceeded 36 °C (target: 32 °C) (Supplementary 2).

Although continuous digital recording of the internal and external temperatures was not performed, the internal hive temperature was monitored using a digital display mounted on the external control box attached to the hive. This display showed the real-time internal hive temperature, which was observed daily during both daytime and nighttime in winter and summer to ensure that the system was operating normally. These manual observations consistently confirmed that the TC hive maintained temperatures between 30–35 °C in winter, while in summer the cooling system achieved only a modest reduction of 1–2 °C below ambient levels. To ensure safe and efficient operation, a fine mesh and a wooden flight board with small perforations were incorporated to allow gradual heat transfer while preventing bees from entering the heating box (Supplementary 2).

4.3 Cooling box (upper box)

The third box contained two fans; the first fan was installed at the center of the hive cover. It circulates air inside the hive, lowers the temperature, and reduces heat stress on the bees. The second fan was mounted on one side of the box, where an opening allowed hot air from the hive to be expelled. This fan served as an exhaust fan, removing hot air from the hive (Figure 2). A mesh barrier between this box and the colony box allowed ventilation while restricting bee movement.

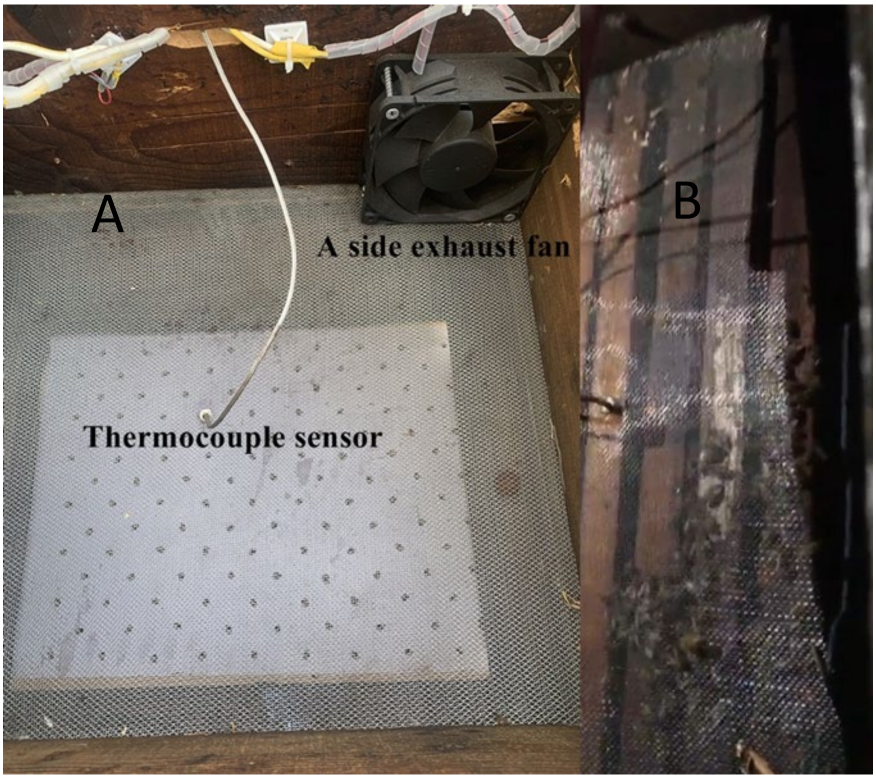

Figure 2. Temperature-controlled hive shown in two states: (A) empty, without bees, showing the cooling box with dual fans and the mesh screen positioned between the cooling box and the colony box; (B) in operation, with bees inside.

5. Studied parameters

Colony performance was compared between the TC hive and the SC hive under field conditions during the winters (January-February-March) and summers (June-July-August) of 2024 and 2025. The following parameters were studied:

4.1 Foraging activity: Bees entering and exiting the hive were counted for 15 minutes at the peak foraging time of 12:00 PM in this region (Kamel et al., 2013; Abdel-Galel et al., 2022), three times per week.

4.2 Sugar syrup consumption: Colonies were provided with 1000 g of a 50% (w/v) sucrose solution through internal feeders. The residual syrup was weighed after 24 hours using a digital scale to determine daily consumption. The feeding regimen was conducted four times per month during both winter and summer seasons, with one feeding provided each week to ensure consistent nutritional support and to evaluate colony activity under different thermal conditions

4.3 Colony mortality: Numbers of dead bees inside the hive and outside were counted three times per week throughout the winter and summer months. These observations were used to determine colony mortality rates and to evaluate the influence of internal thermal regulation on honeybee survival under different seasonal conditions.

4.4 Aggressiveness: Colonies were disturbed by six knocks on the hive wall, after which a gloved hand was inserted for 60 seconds, and the number of stings was recorded. This procedure was repeated three times per week during each winter and summer month to assess colony aggressiveness and monitor potential seasonal variations in defensive behavior under different thermal conditions.

4.5 Brood area: The sealed brood area on each frame was measured to estimate total brood coverage. For each brood side, four length measurements were taken from the four edges of the frame surface using a metric ruler. Opposite lengths were averaged by summing each pair and dividing by two to obtain a mean length, and the same procedure was applied to calculate the mean width. These average length and width values were then entered into an online area calculator (Omni Calculator 2024) to estimate the brood area in square centimeters (cm²). The total brood area per frame was determined by summing the brood areas of both sides of the frame. This procedure was performed for all brood frames in each colony type during every month of the winter and summer seasons.

4.6 Honey area: Honey storage area was assessed at the end of each three-month period of winter (January-February-March) and summer (June-July-August) during both 2024 and 2025. For each honey frame, four length measurements were taken from the outer edges of the sealed honey. Opposite lengths were summed and divided by two to obtain the average length, and the same procedure was applied to the two pairs of width measurements to determine the average width. These mean length and width values were then entered into an online area calculator (Omni Calculator 2024) to estimate the surface area of each frame side. The total honey area per frame was calculated by summing the areas of both sides. This measurement procedure was performed for all honey frames in each colony to evaluate the influence of thermal regulation on honey storage capacity across seasons.

4.7 Honey weight: Honey weight was determined after calculating the honey frame area. Each frame was weighed individually using a digital scale. To obtain the net honey weight, the average weight of an empty frame (600 g) was subtracted from the gross weight of each frame. The empty-frame weight was established by weighing ten empty frames and dividing the total by 10, ensuring accurate correction for frame weight. This method provided an accurate estimation of honey yield per frame and allowed comparison between the TC and SC hives across seasons.

Statistical analysis:

Data were analyzed, and graphs were generated using GraphPad Prism version 8.0 (GraphPad Software, San Diego, CA, USA).

Because the experimental design involved only one biological replicate per treatment per year (n = 1 TC hive and n = 1 SC hive), the study was considered exploratory and descriptive. No inferential statistical tests or p-values were conducted. Repeated measurements collected over time within each colony (e.g., foraging activity, syrup consumption, mortality, aggressiveness, and brood area) were summarized as monthly means and seasonal averages (winter: January-February-March, and summer: June-July-August) to illustrate trends only.

Honey area and honey weight were measured once per season (at the end of winter and summer) and were presented as single end-of-season values per colony.

Results are presented as means, percentages, and relative differences between TC and SC hives. Accordingly, all comparisons should be interpreted as proof-of-concept observations.

RESULTS

This study presents a descriptive, temporal comparison of a single temperature-controlled (TC) hive and a single standard control (SC) hive during the winter and summer seasons of 2024 and 2025. Observations focused on key biological and productive parameters, including foraging activity, sugar syrup consumption, colony mortality, aggressiveness, brood area, honey area, and honey yield based on repeated measurements within each colony. Due to the limited biological replication (n = 1 per treatment per year), this work should be interpreted as a pilot study and proof-of-concept study. These indicators were used to explore how thermal regulation may be associated with colony performance and survival under contrasting hot and cold conditions.

1. Foraging activity

1.1 Winter season

During the winter months (January-February-March), the TC hive consistently exhibited substantially higher foraging activity than the SC hive in both years. In 2024, the monthly mean foraging activity in the TC hive ranged from 290.5 to 307.5 bees per observation period, whereas the SC hive ranged from 70.8 to 111.5 bees (Figure 3a). A similar pattern was observed in 2025, with the TC hive ranging from 284.1 to 309.9 bees, compared to 79.9 to 118.2 bees in the SC hive (Figure 4a). Across the winter season, the TC hive showed approximately threefold higher activity than the SC hive, with mean values of 301.3 bees in 2024 and 299.3 bees in 2025, versus 93.3 bees in 2024 and 98.9 bees in 2025.

1.2 summer season

In contrast, during the summer months (June-July-August), foraging activity was high in both hives and differed only marginally. In 2024, the monthly means ranged from 362.4 to 414.5 bees in the TC hive and from 376.5 to 405.8 bees in the SC hive (Figure 3b), yielding similar seasonal averages (391.3 bees and 389.6 bees, respectively). In 2025, TC hive activity ranged from 379.5 to 434.7 bees, while SC hive activity ranged from 384.5 to 445 bees (Fig. 4b). Across the summer season, the TC and SC hives showed similar activity levels, with mean values of 391.3 and 389.6 bees in 2024 and 404.0 and 398.3 bees in 2025, respectively. Overall, these results indicate that thermal conditioning was associated with markedly enhanced foraging activity during cold periods, whereas under warm summer conditions both hives maintained similar high foraging levels.

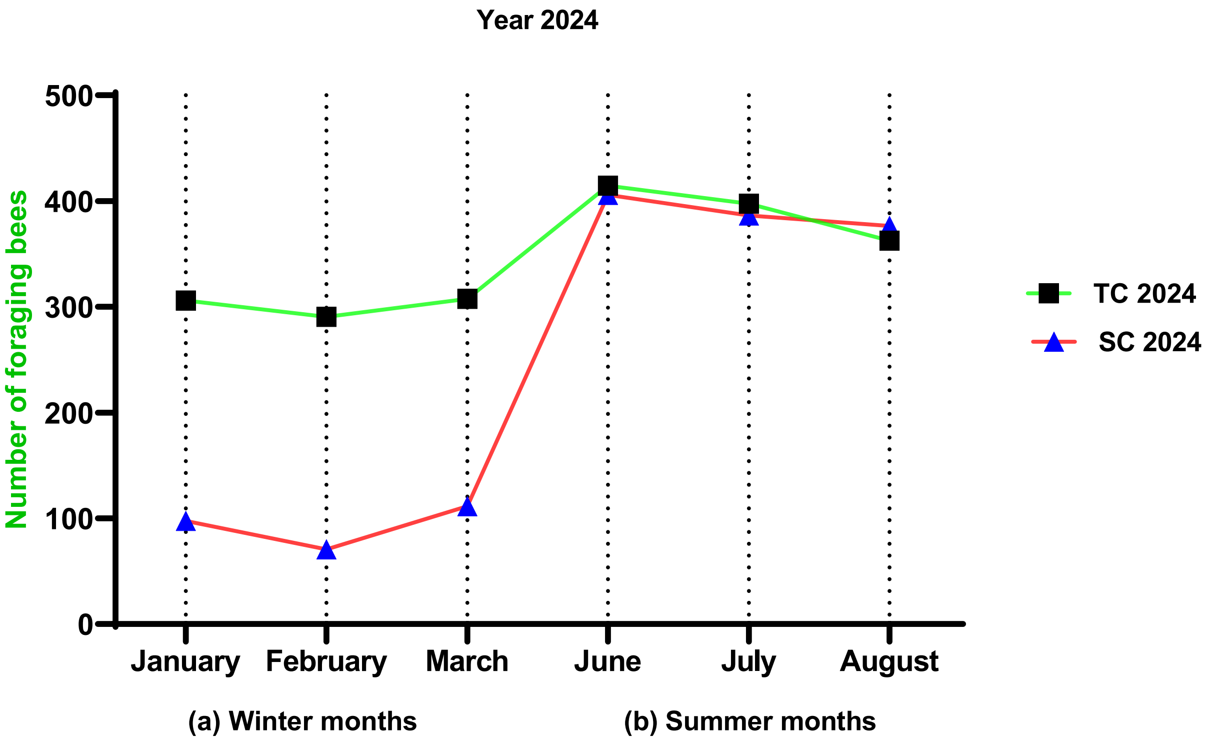

Figure 3. Monthly mean of foraging activity in temperature-controlled (TC) and standard control (SC) honeybee hives during 2024: (a) winter months (January-February-March) and (b) summer months (June-July-August).

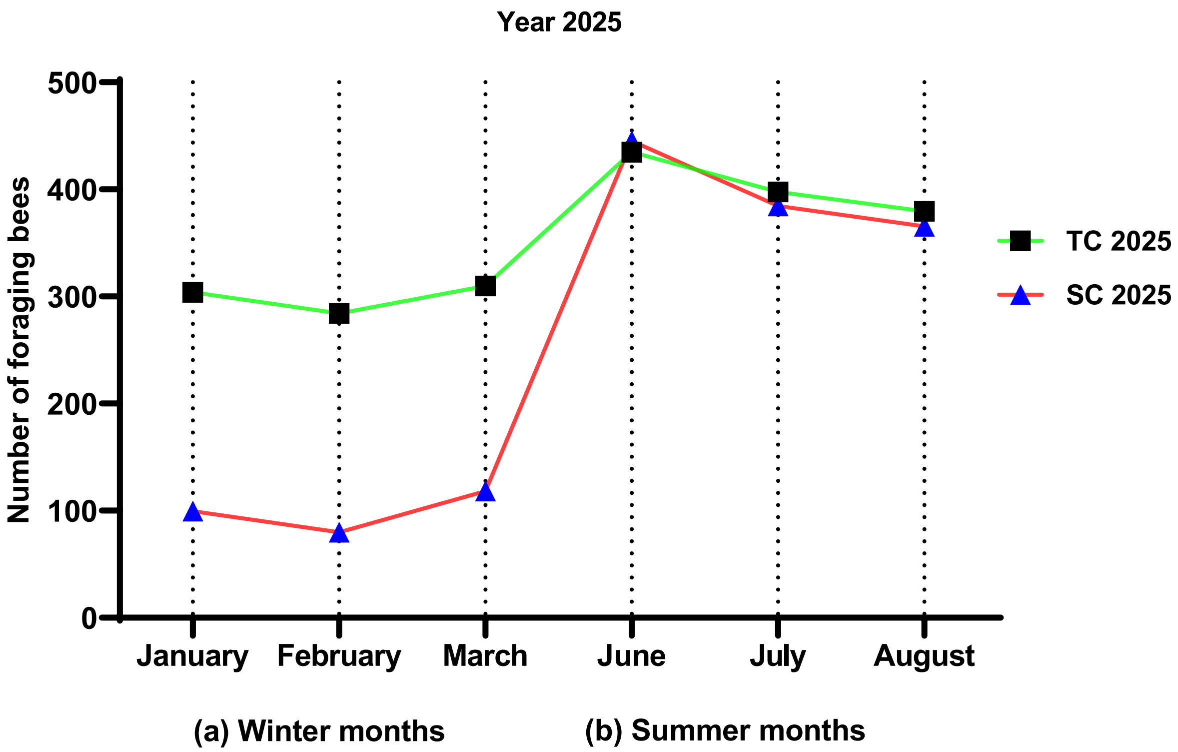

Figure 4. Monthly mean of foraging activity in temperature-controlled (TC) and standard control (SC) honeybee hives during 2025: (a) winter months (January-February-March) and (b) summer months (June-July-August).

2. Sugar Syrup Consumption

Seasonal differences in sugar syrup consumption were observed between the temperature-controlled (TC) and standard control (SC) honeybee hives during both years of the study (Table 1).

2.1 Winter season

During the winter months, sugar syrup consumption was higher in the TC hive than in the SC hive in both years. In 2024, the TC hive consumed an average of 916.5 g of sugar solution, corresponding to 91.6% of the provided amount, whereas the SC hive consumed only 244.6 g (24.4%). A similar pattern was observed in 2025, when the TC hive nearly consumed the entire amount of feed provided. With a mean of 995.2 g (99.5%), whereas the SC hive consumption remained low at 241.8 g (24.1%).

2.2 Summer season

In contrast, during the summer months, sugar syrup consumption was substantially lower and more comparable between the two hive types. In 2024, the TC and SC hives consumed mean amounts of 545.6 g (54.5%) and 511.0 g (51.1%), respectively. Likewise, in 2025, consumption levels remained similar, with mean values of 547.1 g (54.7%) for the TC hive and 513.7 g (51.3%) for the SC hive.

Overall, these results indicate that thermal conditioning was associated with a pronounced increase in sugar syrup consumption during cold winter conditions, whereas under warm summer conditions, both hives exhibited moderate, comparable syrup intake.

Table 1. Sugar syrup consumption (mean values and percentages) in temperature-controlled (TC) and standard control (SC) honeybee hives during winter and summer of 2024 and 2025.

Season	Year	Temperature-controlled (TC)		Standard control (SC)	
		Mean Consumption (g)	%Consumption	Mean (g)	%Consumption
Winter	2024	916.5	91.6	244.6	24.4
	2025	995.2	99.5	241.8	24.1
Summer	2024	545.6	54.5	511	51.1
	2025	547.1	54.7	513.7	51.3

Note: Percentages were calculated based on a fixed weekly provision of 1000 g of 50% (w/v) sucrose solution.

3. Colony mortality

3.1 Winter season

In winter 2024, the TC hive showed very low mortality (monthly means: 18.4, 36, and 16.9 dead bees in January, February, and March, respectively) (Figure 5a), corresponding to a seasonal mean of 23.8 dead bees. In contrast, the SC hive exhibited substantially higher mortality across the same period (199.8, 285.3, 215.6 in January, February, and March, respectively), yielding a seasonal mean of 233.6 dead bees. This represents an approximate 89.8% reduction in winter mortality in the TC hive compared to the SC hive.

A similar pattern was observed in winter 2025. The TC hive maintained low mortality (monthly means: 15.7, 35.7, 11.8 dead bees in January, February, and March, respectively) (Figure 6a), with a seasonal mean of 21.1 dead bees, whereas the SC hive remained high (224.9, 300.9, 209.8 dead bees in January, February, and March, respectively), with a seasonal mean of 245.2 dead bees. This corresponds to an approximate 91.4% reduction in winter mortality.

Across both winters, mortality peaked in February for both hive types, but absolute mortality remained consistently low in the TC hive and high in the SC hive.

3.2 Summer season

During summer, mortality increased in both hive types and the difference between TC and SC hives was comparatively small. In summer 2024, monthly mortality means in the TC hive were 158.4, 166.1, and 206.6 dead bees (June, July, and August, respectively) (Figure 5b), with a seasonal mean of 177.0 dead bees. The SC hive recorded monthly mortality means of 133.5, 191.1, and 256.7 dead bees, with a seasonal mean of 193.8 dead bees. This reflects a modest 8.6% reduction in summer mortality in the TC hive.

In summer 2025, mortality was higher overall, TC monthly means were 171.7, 225.8, and 254.7 dead bees (June, July, and August, respectively) (Figure 6b), seasonal mean 217.4 dead bees, while SC monthly means were 157.6, 245.9, and 291.4 dead bees (June-July-August, respectively), with seasonal mean of 231.6 dead bees. The TC hive showed a modest 6.1% reduction relative to the SC hive.

In both summers, mortality increased from June to August across both hive types, with the highest dead bee counts recorded in August.

Overall, these descriptive patterns indicate that winter heating was associated with a pronounced reduction in colony mortality under cold conditions, whereas fan-based summer ventilation appeared to have only a limited effect on mortality under hot conditions.

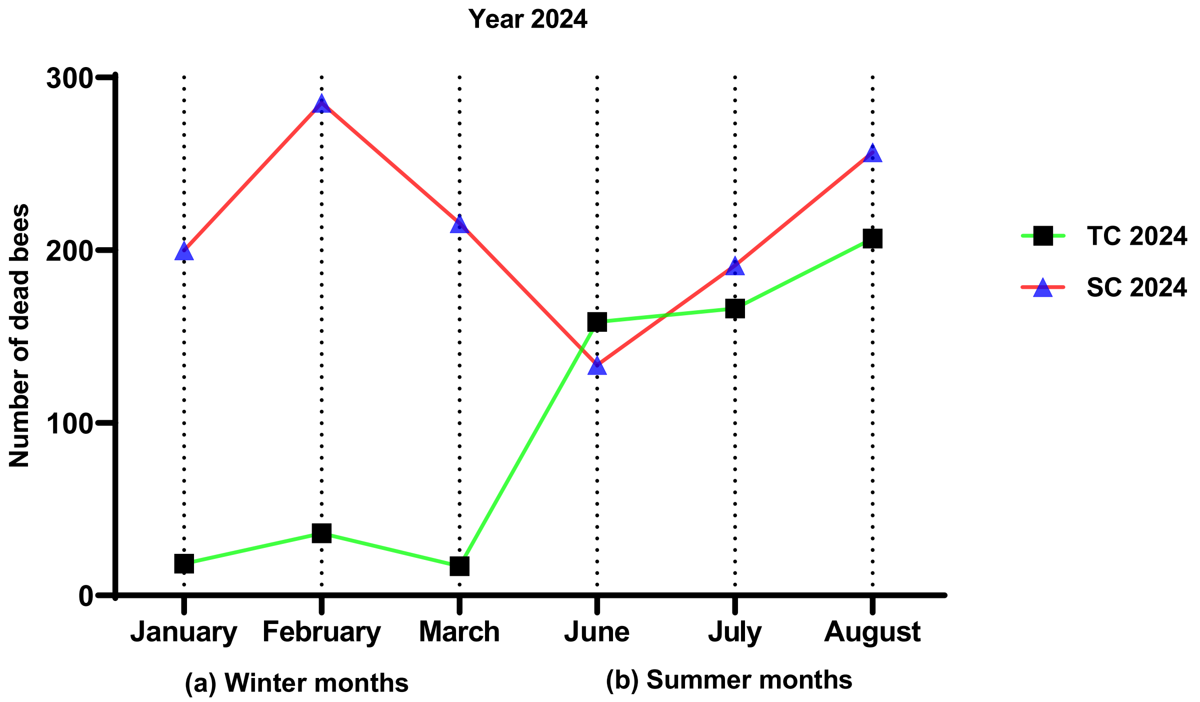

Figure 5. Monthly mean of mortality in temperature-controlled (TC) and standard control (SC) honeybee hives during 2024: (a) winter months (January-February-March) and (b) summer months (June-July-August).

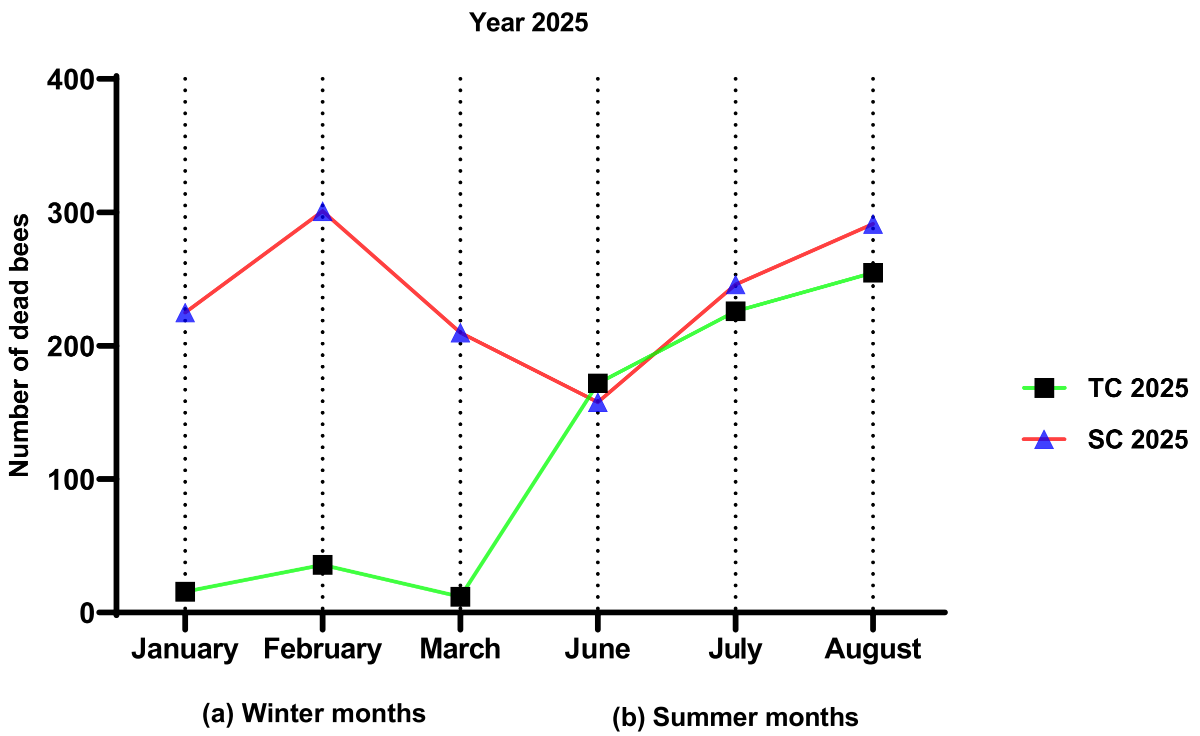

Figure 6. Monthly mean of mortality in temperature-controlled (TC) and standard control (SC) honeybee hives during 2025: (a) winter months (January-February-March) and (b) summer months (June-July-August).

4. Aggressiveness and gentleness

4.1 Winter season

In winter 2024, the temperature-controlled (TC hive exhibited consistently low aggressiveness (monthly means sting counts: 1.8, 5, and 3.2 stings in January, February, and March, respectively; winter mean = 3.3 stings). In contrast, the SC hive displayed markedly higher sting counts (22.9, 26.9, 23.2 stings in January, February, and March, respectively; winter mean = 24.3 stings) (Figure 7a). Overall, winter aggressiveness in the TC hive was approximately 86.3% lower than in the SC hive (mean difference = 21 stings on average).

A comparable pattern was observed in winter 2025. Monthly sting counts in the TC hive remained low (2.5, 4.2, 2.5 stings in January, February, and March, respectively; winter mean = 3.1 stings), whereas the SC hive exhibited substantially higher aggressiveness (26.3, 31.5, 18.1 stings in January, February, and March, respectively; winter mean = 25.3 stings) (Figure 8a). This corresponds to an approximate 87.88% reduction in winter sting counts (mean difference = 22.2 stings). In both winters, aggressiveness peaked in February for both hive types, but the absolute levels remained consistently low in the TC hive and high in the SC hive.

4.2 Summer season

During summer, sting counts increased in both hive types and the difference between TC and SC hives was comparatively modest. In summer 2024, the TC hive recorded monthly means of 29.9, 34.6, and 34.8 stings in June, July, and August, respectively (summer mean = 33.1 stings), while the SC hive recorded 29.9, 36.7, and 38.1 stings in June, July, and August, respectively (summer mean = 34.90 stings) (Figure 7b). This represents an approximate 5.1% lower summer aggressiveness in the TC hive (mean difference = 1.8 stings).

In summer 2025, a similar pattern was observed. The TC hive recorded 28.1, 34, and 37.5 stings in June, July, and August, respectively (summer mean = 33.2), compared to 31.3, 36.6, and 37.2 stings in June, July, and August, respectively in the SC hive (summer mean = 35.03 stings) (Figure 8b), corresponding to an approximate 5.2% reduction in sting counts (mean difference =1.8 stings). In both summers, aggressiveness increased from June to August, with the highest sting counts occurring in August.

Overall, these descriptive results indicate that winter heating was associated with a pronounced reduction in colony aggressiveness under cold conditions, whereas fan-based summer ventilation was associated with only a minor reduction in sting counts during hot conditions.

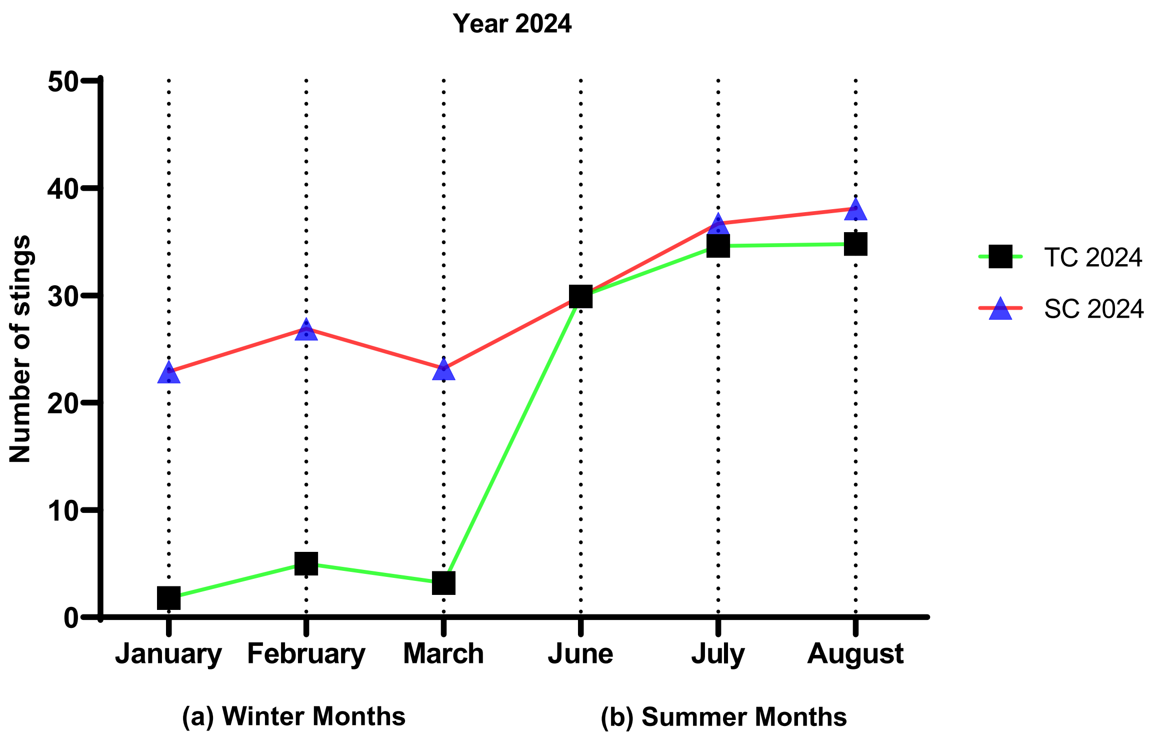

Figure 7. Monthly mean of aggressiveness and gentleness in temperature-controlled (TC) and standard control (SC) honeybee hives during 2024: (a) winter months (January-February-March) and (b) summer months (June-July-August).

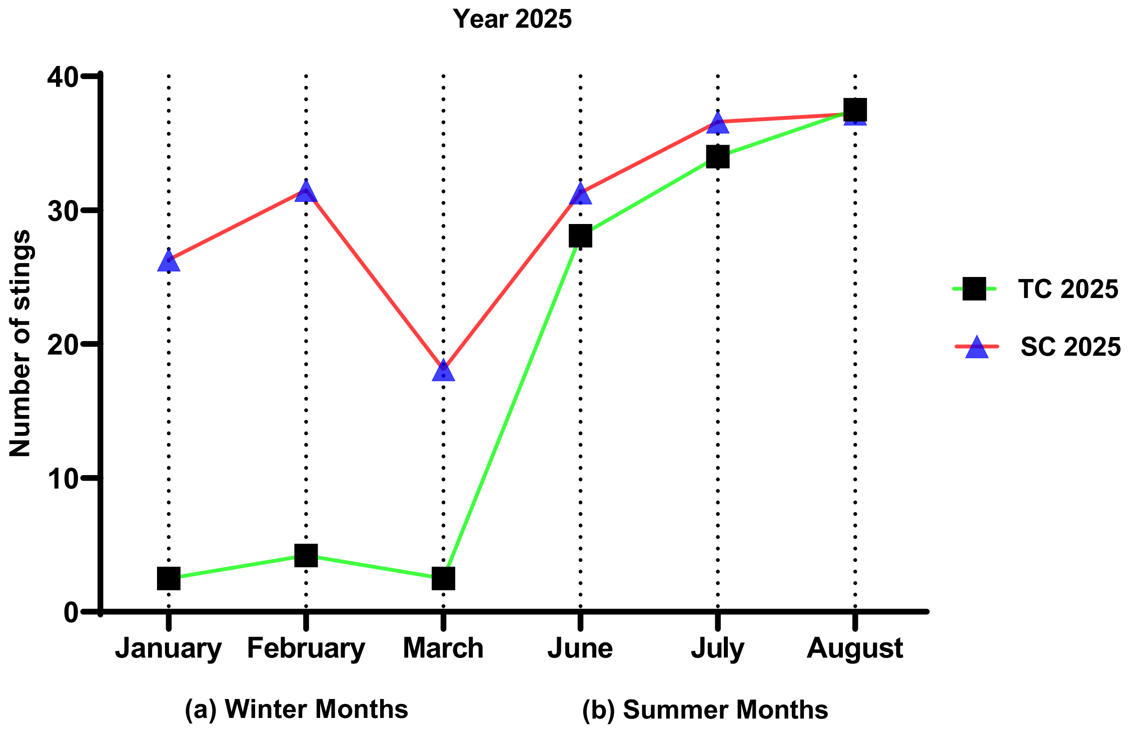

Figure 8. Monthly mean of aggressiveness and gentleness in temperature-controlled (TC) and standard control (SC) honeybee hives during 2024: (a) winter months (January-February-March) and (b) summer months (June-July-August).

5. Brood area

5.1 Winter season

In winter 2024, the temperature-controlled (TC) hive maintained a high brood area throughout the season (monthly means: 1272.1, 1100, and 1343.3 cm² in January, February, and March, respectively; winter mean = 1245.03 cm²). In contrast, the standard control (SC) hive exhibited very limited brood rearing under cold conditions (233, 193, and 254.5 cm² in January, February, and March, respectively; winter mean = 228.5 cm²) (Figure 9a). Overall, the TC hive had an approximately 4.45-fold larger brood area than the SC hive during winter (mean difference = 1016.4 cm²).

A similar pattern was observed in winter 2025. The TC hive sustained a high brood area (1275.0, 1103.8, and 1383.8 cm² in January, February, and March, respectively; winter mean = 1262.31 cm²), whereas the SC hive remained low (261.6, 158.8, and 286.6 cm² in January, February, and March, respectively; winter mean = 238.88 cm²) (Figure 10a). This corresponds to an approximately 4.28-fold larger brood area in the TC hive than in the SC hive (mean difference = 1023.4 cm²). Across both winters, brood area in the TC hive remained consistently high, while brood area in the SC hive was suppressed.

5.2 Summer season

During summer, the brood area was high in both hive types, and the differences between TC and SC hives were small. In summer 2024, the TC hive recorded monthly brood areas of 1568.2, 1329.7, and 1219.7 cm² in June, July, and August, respectively (summer mean = 1387.6 cm²), while the SC hive recorded 1525.8, 1340.0, and 1119 cm² in June, July, and August, respectively (summer mean = 1343.4 cm²) (Figure 9b). The TC hive exhibited a modest 3.2% higher brood area than SC (mean difference = 44.1 cm²).

In summer 2025, the TC hive recorded 1578.2, 1327.7, and 1142.2 cm² in June, July, and August, respectively (summer mean = 1367 cm²), compared to 1495.8, 1334.7, and 1146.0 cm² in June, July, and August, respectively (summer mean = 1338.6 cm²) in the SC hive (Figure 10b). This reflects a small 2.1% increase in brood area in TC compared with SC (mean difference = 28.38 cm²). In both summers, the brood area tended to decline from June to August in both hive types.

Overall, these descriptive patterns indicated that winter heating was associated with a pronounced enhancement of brood rearing under cold conditions, whereas fan-based summer ventilation was associated with only minor differences in brood area during hot conditions.

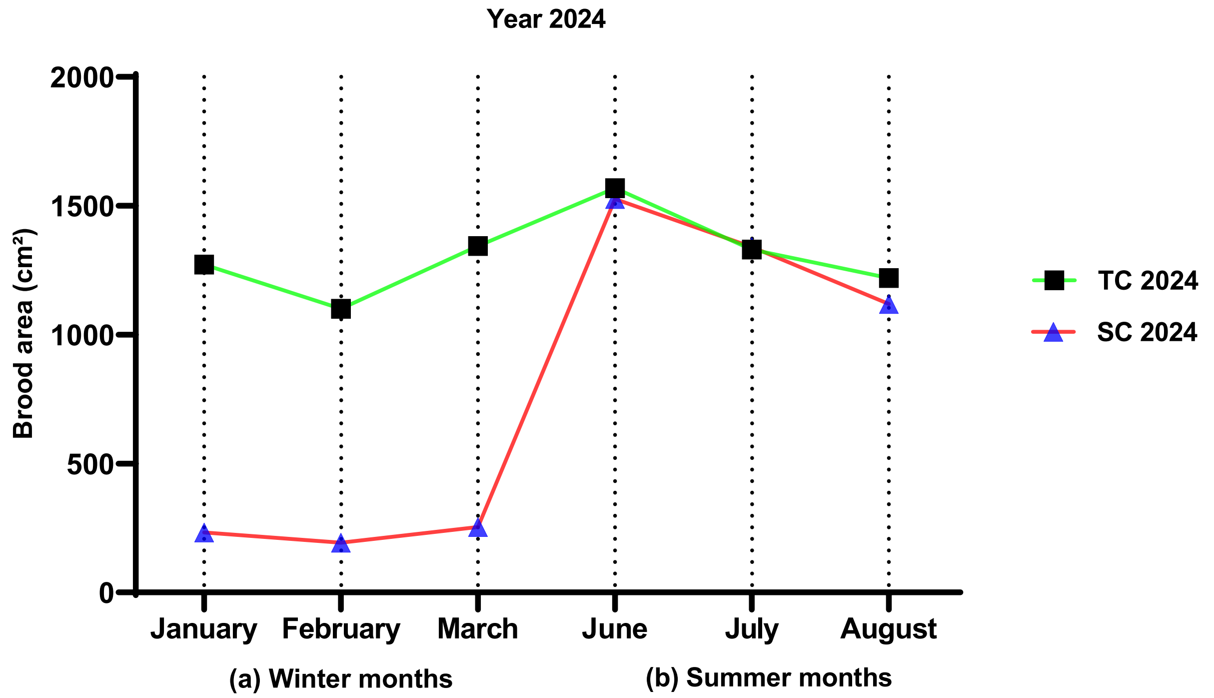

Figure 9. Monthly mean of brood area in temperature-controlled (TC) and standard control (SC) honeybee hives during 2024: (a) winter months (January-February-March) and (b) summer months (June-July-August).

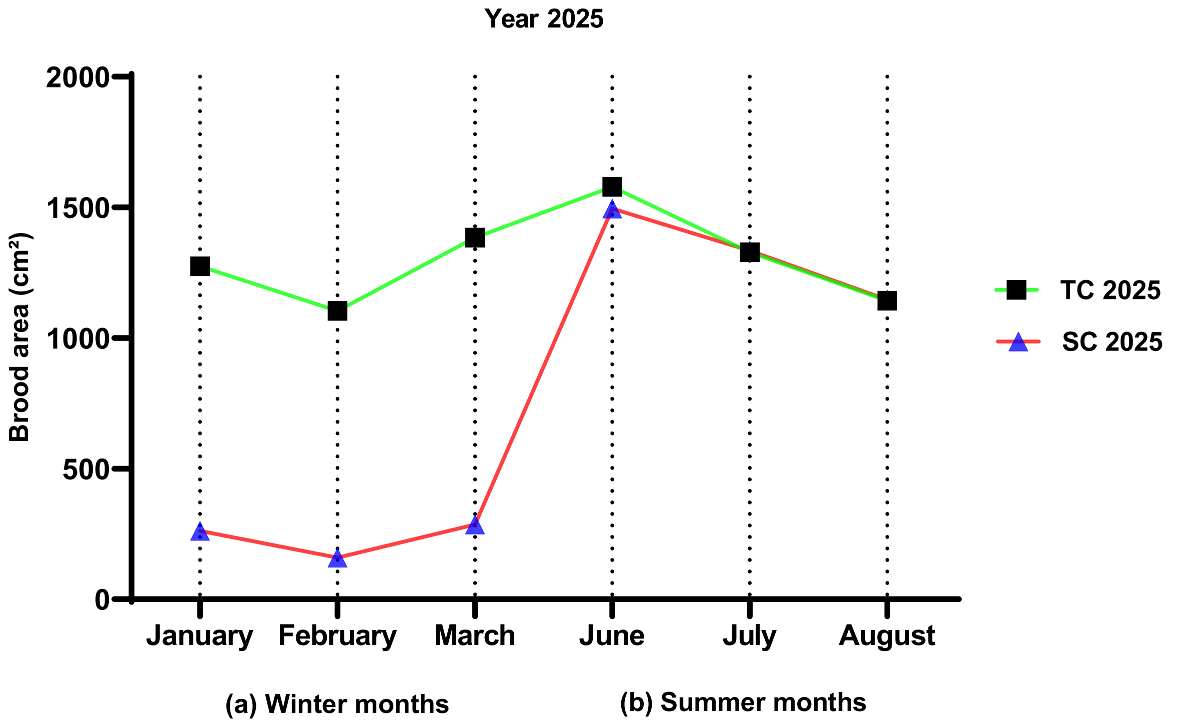

Figure 10. Monthly mean of brood area in temperature-controlled (TC) and standard control (SC) honeybee hives during 2025: (a) winter months (January-February-March) and (b) summer months (June-July-August).

6. Honey area

6.1 Winter season

At the end of winter 2024, the TC hive showed a substantially larger sealed honey area 378.2 cm² compared to the SC hive 513.0 cm², corresponding to an absolute difference of 865.2 cm². This represented an approximately 2.69-fold larger honey storage area in the TC than in the SC (168.7% higher). A similar pattern was observed at the end of winter 2025. The TC hive exhibited a higher honey area of 1322.4 cm² compared to the SC 436.6 cm², with an absolute mean difference of 885.8 cm² (Figure 11a). This corresponds to an approximately 3.03-fold larger honey area, 202.9% higher in the TC hive than in the SC.

6.2 Summer season

In contrast to winter, the end-of-season measurements in summer indicated very small differences between hive types. At the end of summer 2024, the sealed honey area was 1328.5 cm² in TC and 1316.1 cm² in SC (mean difference 12.4 cm², 0.94% higher in the TC hive). Similarly, at the end of summer 2025, the TC recorded 1299.1 cm² and the SC hive 1281.5 cm² (mean difference 17.6 cm², 1.37% higher in the TC hive) (Figure 11b).

Overall, end-of-season honey area measurements indicated that winter heating was associated with markedly greater honey storage under cold conditions, whereas fan-based summer ventilation was associated with only minimal differences in honey storage area under hot conditions.

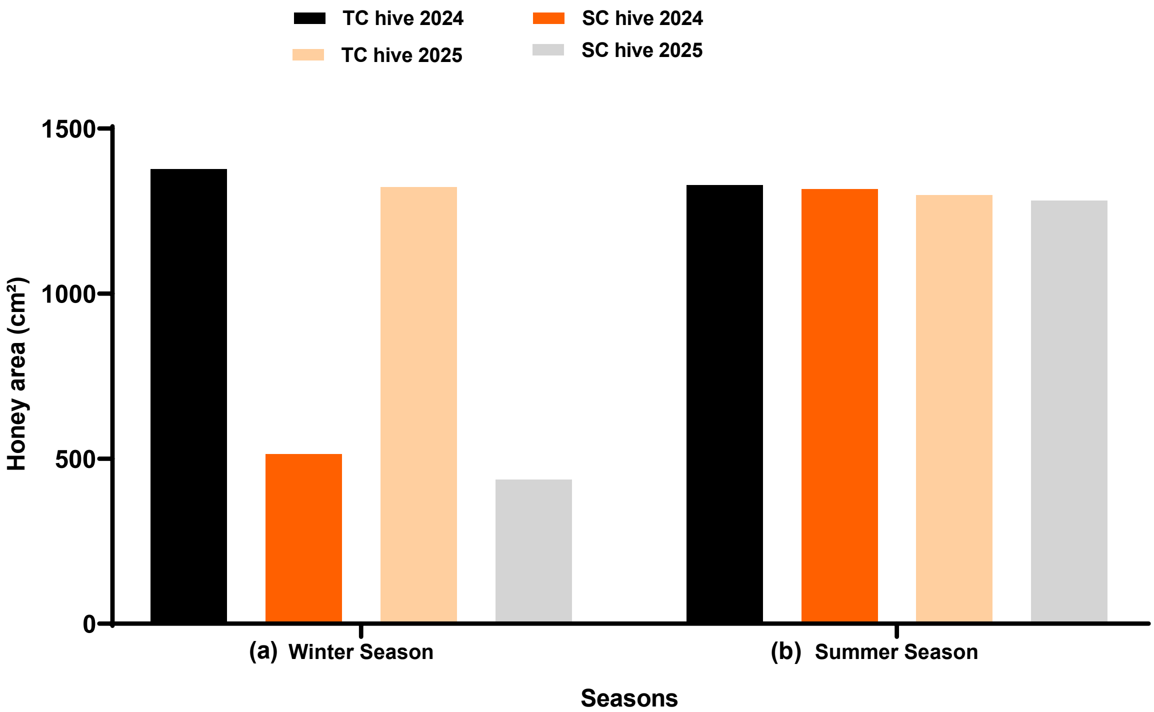

Figure 11 a & b. Seasonal mean of honey area in temperature-controlled (TC) and standard control (SC) honeybee hives during winter and summer of 2024 and 2025.

7. Honey weight

7.1 Winter season

At the end of winter 2024, the TC hive produced a higher honey yield 1021 g compared to 410.8 g in the SC hive, corresponding to an absolute difference of 610.2 g. This represented an approximately 2.4-fold higher honey yield in the TC hive (148.5% higher) compared to the SC hive. A similar trend was observed at the end of winter 2025, where honey yield in the TC hive reached 1146.4 g compared to 365.8 g in the SC hive (mean difference 780.6 g) (Figure 12a). This resulted in approximately a 3.13-fold higher winter honey yield in the TC hive (213.4%) compared to the SC hive.

7.2 Summer season

In contrast to winter, end-of-season summer honey yields were similar between hive types. At the end of summer 2024, TC yielded 1186.0 g and SC yielded 1165.666 g, a small difference of 20.334 g (~1.74% higher in TC). Likewise, at the end of summer 2025, TC produced 1189.5 g, compared to 1142.166 g in SC (a difference of 47.334 g, 4.14% higher in TC) (Figure 12b).

Overall, end-of-season honey weight measurements indicated that winter heating was associated with substantially greater honey yield under cold conditions, whereas fan-based summer ventilation was associated with only minor differences in honey yield under hot conditions.

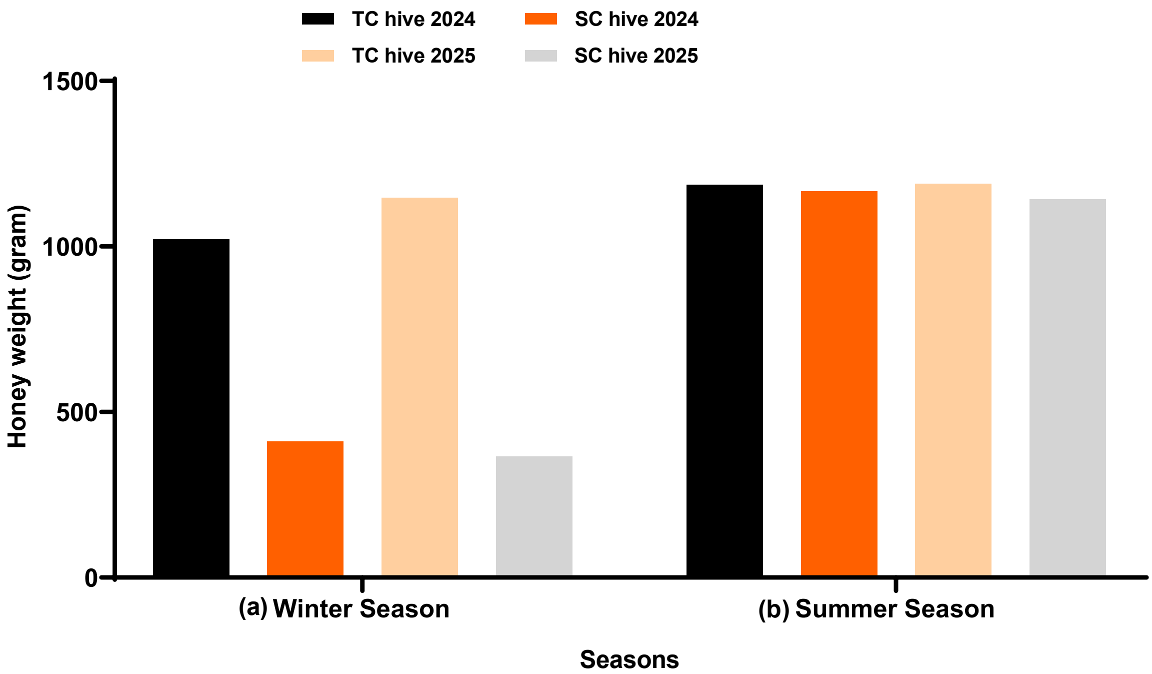

Fig 12 a & b. Seasonal mean of honey weight in temperature-controlled (TC) and standard control (SC) honeybee hives during winter and summer of 2024 and 2025.

DISCUSSION

This two-year field study (2024–2025), conducted under Egypt's increasingly arid climate (Hamed et al., 2023; Abdelaal, 2024), reveals a clear seasonal asymmetry in the effectiveness of thermal interventions in honeybee (*A. mellifera*) hives under arid conditions in Egypt. Specifically, programmable winter heating in the TC hive improved colony performance and survival-related indicators, whereas fan-based summer ventilation produced only minor internal cooling (1–2 °C during operational checks) and did not translate into meaningful biological or productive benefits when ambient temperatures exceeded 40 °C.

This asymmetry reflects fundamental biological and physical constraints on honeybee colonies, which function as tightly thermoregulated superorganisms (Seeley 1997). As a result, colonies actively maintain brood-nest temperatures within a narrow physiological range (32–36 °C), which is essential for brood development, worker performance, and colony stability (Kleinhenz et al. 2003; Stabentheiner et al. 2021). However, sustaining this range is challenging, deviations below this range during winter impose substantial energetic costs for thermogenesis, while deviations above this range during summer push the limits of behavioral cooling mechanisms such as fanning and evaporative water use (Debnam et al. 2024). Consequently, external heating effectively alleviated cold stress and its downstream consequences, whereas ventilation alone was unable to reduce hive temperatures below ambient levels and therefore offered little relief from extreme heat stress.

During winter, ambient night temperatures in Egypt often fall below 10 °C, forcing colonies to invest substantial metabolic resources into endogenous heat production through shivering of flight muscles and specialized heater bee behaviors (Bujok et al. 2002; Stabentheiner et al. 2010). In the present study, the TC hive was programmed to activate below 30 °C with a target near 35 °C, thereby reducing exposure to suboptimal brood temperatures. This intervention resulted in larger brood and honey areas, higher honey yield and syrup consumption, reduced mortality, and calmer defensive behavior. These patterns are consistent with an energy reallocation mechanism, in which external heating offloads thermogenic demand, allowing workers to redirect their effort toward brood care, foraging, and nectar processing (Cook et al. 2021; Oskin & Kudryavtseva 2021; Oh et al. 2024).

The observed winter benefits align with previous field studies showing improved overwintering success and brood development in heated colonies (Omran 2011; Vollet-Neto et al. 2011), and with evidence that brood temperature stability strongly predicts colony survival (Colin et al. 2023; Minaud et al. 2024). The consistently larger brood areas in heated hives are biologically coherent with the strong temperature dependence of queen oviposition, larval development, and nursing behavior, which all decline under cold stress (Stabentheiner et al. 2010; Zeaiter & Myerscough 2020). Although continuous temperature logging was not implemented, repeated operational verification of heater function supports the inference that the TC hive experienced fewer and shorter cold exposures. Varroa and disease pressure were low during the study, minimizing confounding effects. However, because heating can expand brood availability for mite reproduction, routine parasite monitoring remains essential in heated systems (Çakmak et al. 2023).

In contrast, summer ventilation using axial fans failed to reduce thermal stress. The reason is that ventilation enhances air exchange but cannot reduce air temperature below ambient without heat removal or latent heat exchange (Jarimi et al. 2020; DeGrandi-Hoffman et al. 2025). Under hyper-arid conditions with temperatures exceeding 40 °C, airflow replaces hot internal air with hot external air. Thus, colonies therefore rely on endogenous cooling strategies such as fanning and evaporative water use (Johnson et al. 2023; Staron et al. 2026), but these behaviors approach energetic and physiological limits under extreme heat and may divert workers from foraging and nursing (Bordier et al. 2017; Kamboj et al. 2024; Lu et al. 2025). This explains the similarity between TC and SC hives in summer brood production, honey yield, mortality, and defensiveness, and indicates that fan-only cooling is fundamentally insufficient under these conditions. The energetic costs and thermoregulatory constraints of water collection and evaporative cooling under variable ambient conditions are consistent with detailed measurements of water-foraging honeybees (Kovac et al. 2010; Kovac et al. 2018) and broader syntheses of the sensitivity of colony activities to temperature and humidity (Abou-Shaara et al. 2017).

Given that Egypt is a climate change hotspot, with projected summer temperature increases of up to 8 °C by 2100 (Hamed et al. 2023; Abdelaal 2024), future hive designs must go beyond passive ventilation and incorporate cooling strategies that are both biologically effective and physically feasible. Drawing on the principles of evaporative and thermoelectric cooling, two solar-compatible and field-testable approaches appear particularly promising for arid environments.

First, a solar-powered evaporative pre-cooling chamber can be integrated upstream of hive intake fans using wetted pads (e.g., jute or cellulose). This design exploits Egypt's low ambient humidity to enhance latent heat exchange and has been shown to achieve internal air temperature reductions of approximately 5–15 °C in greenhouse and beehive-related applications under arid conditions (Fuchs et al. 2006; Hegazy et al. 2022). Multilayer pad configurations further increase the cooling efficiency, with reported efficiencies of 68–84% in dry climates (Getinet et al. 2008; Nada et al. 2019). Such reductions are within the biologically meaningful range needed to return brood-nest temperatures to optimal levels during extreme heat events.

Second, thermoelectric (Peltier) cooling modules represent an alternative to active cooling. Solid-state Peltier devices, powered by DC solar panels, can provide precise temperature control with no moving parts and minimal maintenance requirements (Korprasertsak & Leephakpreeda 2024; Nabil & Mansour 2024; Satif et al. 2025). Although their efficiency decreases with large temperature differentials, modeling and experimental studies suggest that, in a well-insulated hive, targeting a modest 5–8 °C reduction during midday thermal peaks could be sufficient to maintain brood temperatures within the optimal physiological range (Stalidzans et al. 2017; Zheng et al. 2024).

Overall, this study demonstrated that programmable winter heating effectively enhanced colony performance and survival in arid environments by alleviating thermoregulatory burden. In contrast, fan-only summer ventilation was inadequate under extreme heat. This seasonal dichotomy provides a clear roadmap for climate-resilient beekeeping: buffering cold stress through heating and addressing heat stress through integrated, thermodynamically viable cooling strategies. Future studies should incorporate continuous microclimate monitoring and replicated field trials to optimize these interventions for the escalating thermal extremes facing apiculture in arid regions.

Conclusion

The present study provides clear evidence that TC hives equipped with ceramic heating elements markedly improved the performance and survival of honeybee colonies during the winter months in Egypt. Maintaining the internal hive temperature within the optimal physiological range of 32–35 °C allows colonies to remain active, sustain brood rearing, and store more honey despite cold external conditions. These results demonstrate that thermal stabilization during winter reduces metabolic stress and energy expenditure on thermoregulation, enabling colonies to redirect energy toward essential biological and productive functions.

Conversely, the fan-based cooling system implemented for summer management proved ineffective in mitigating the extreme heat stress typical of Egyptian summers, where ambient temperatures frequently exceed 40 °C. The modest 1–2 °C reduction achieved by the cooling mechanism was insufficient to maintain the internal hive temperature within a comfortable range for bees, resulting in no measurable improvement in colony behavior, mortality, or productivity compared to the SC hive.

Overall, winter heating improved colony performance, whereas fan cooling did not provide meaningful benefits under extreme summer conditions. These findings highlight the importance of aligning thermal management strategies with seasonal climatic stressors, and additional biological replicates are recommended for future studies.

Therefore, future research should prioritize active cooling technologies capable of achieving at least a 5 °C reduction in temperature under peak summer loads. Promising approaches include phase-change materials integrated into hive walls and solar-driven absorption chillers that circulate cooled liquids through hive panels. Implementing advanced cooling strategies could strengthen colony resilience and enhance beekeeping sustainability in regions increasingly affected by climate change.

Acknowledgments: We thank the Suez Canal University Bee Research Center for technical support.

Authors' contributions: ASS, MAS, and SMK were responsible for planning, experimental design, and writing the manuscript. YAE was responsible for the electronic and programming components inside the hive. ASS, AAE, ZEA, SMT, EMA, and AAS participated in hive assembly and data collection. All authors read and approved the final manuscript.

Conflict of interest: The authors declare that there are no conflicts of interest related to this work.

Data availability: Data will be available upon request.

Ethical Issue: An ethical certificate is not required for a honey bee study.

Financial source: None.

REFERENCES

Abdelaal MM. Rainfall characteristics in Egypt from 1960 to 2017: patterns, variability, driving mechanisms, and impacts. Hydroclimatic Extremes in the Middle East and North Africa. 2024; 149-175. https://doi.org/10.1016/B978-0-12-824130-1.00001-1

Abdel-Galel R, Elbanna S, Semida F. Foraging rhythm of honeybees *Apis mellifera* in Ismailia, Egypt. Catrina: The International Journal of Environmental Sciences. 2021; 23(1):2733. https://doi.org/10.21608/cat.2021.196712

Abdel-Rahman MO, Moustafa AD. An estimate of honeybee colony losses and their perceived reasons during two years in Qena and Luxor Governorates, Upper Egypt. Assiut Journal of Agricultural Sciences. 2012; 43(2): 91-104. https://doi.org/10.21608/ajas.2012.266714

Abou-Shaara HF, Owayss AA, Ibrahim YY, Basuny NK. A review of impacts of temperature and relative humidity on various activities of honeybees. Insectes sociaux. 2017; 64(4): 455-463.https://doi.org/doi:10.1007/s00040-017-0573-8.

Abou-Shaara HF. Expectations about the potential impacts of climate change on honeybee colonies in Egypt. Journal of Apiculture. 2016; 31(2), 31(2):157-64.

Ahmed Z. H. Investigations of some multiple factors affecting honeybee colony losses at Assiut Governorate (Upper Egypt), with special reference to the role of nutritional aspects. Assiut University, Ph.D. thesis. Assiut, Egypt, 2019, (Access date: 29.12.2025). https://lib.mans.edu.eg/eulc_v5/Libraries/Thesis/BrowseThesisPages.aspx?fn=PublicDrawThesis&BibID=12605606

Alattal Y, AlGhamdi A. Impact of temperature extremes on survival of indigenous and exotic honeybee subspecies, *Apis mellifera*, under desert and semiarid climates. Bulletin of Insectology. 2015; 68(2): 219-222.

Ali MA, Abdellah IM, Eletmany MR. Climate change impacts on honeybee spread and activity: A scientific review. Chelonian Conservation and Biology. 2023; 18(2): 531-554.

Alqarni AS. Tolerance of summer temperature in imported and indigenous honeybee *Apis mellifera* L. races in central Saudi Arabia. Saudi J. Biol. Sci. 2006; 13(2): 123-127.

Becher MA, Scharpenberg H, Moritz RF. Pupal developmental temperature and behavioral specialization of honeybee workers (*Apis mellifera* L.). Journal of Comparative Physiology A. 2009; 195(7): 673-679. https://doi.org/10.1007/s00359-009-0442-7

Bordier C, Suchail S, Pioz M, Devaud JM, Collet C, Charreton M, Le Conte Y, Alaux C. Stress response in honeybees is associated with changes in task-related physiology and energetic metabolism. Journal of Insect Physiology. 2017; 98: 47-54. https://doi.org/10.1016/j.jinsphys.2016.11.013

Bujok B, Kleinhenz M, Fuchs S, Tautz J. Hot spots in the beehive. Naturwissenschaften. 2002; 89(7):299-301. https://doi.org/10.1007/s00114-002-0338-7

Çakmak I, Kul B, Ben Abdelkader F, Seven Çakmak S. Effects of temperature adjustment with a heating device in weak honeybee colonies in cold seasons. International Journal of Biometeorology. 2023; 67(11): 1765-1774. https://doi.org/10.1007/s00484-023-02537-w

Colin T, Dakos V, Barron AB, Meikle WG, Altmann EG, Latty T. Temperature as an early warning signal of honeybee colony failure. Ecological Informatics. 2025;103445. https://doi.org/10.1016/j.ecoinf.2025; 92: 103445

Cook D, Blackler A, McGree J, Hauxwell C. Thermal impacts of apicultural practice and products on the honeybee colony. Journal of Economic Entomology. 2021; 114(2): 538-46. https://doi.org/10.1093/jee/toab023

Debnam SE, McCormick MB, Callaway RM, Woods HA. Energetic costs of raising brood in honeybee colonies are high, but heater bees are cheap. Journal of Insect Physiology. 2024; 153:104613. https://doi.org/10.1016/j.jinsphys.2024.104613

DeGrandi-Hoffman G, Graham H, Corby-Harris V, Chambers M, Watkins-deJong E, Ihle K, Bilodeau L. Adapting Overwintering Honeybee (*Apis mellifera* L.) Colony Management in Response to Warmer Fall Temperatures Associated with Climate Change. Insects. 2025; 16(3): 266. https://doi.org/10.3390/insects16030266

Doke MA, Frazier M, Grozinger CM. Overwintering honeybees: biology and management. Current opinion in insect science. 2015; 10: 185-193. https://doi.org/10.1016/j.cois.2015.05.014

Fuchs M, Dayan E, Presnov E. Evaporative cooling of a ventilated greenhouse rose crop. Agricultural and Forest Meteorology. 2006; 138(1-4):203-215. https://doi.org/10.1016/j.agrformet.2006.05.002

Getinet H, Seyoum T, Woldetsadik K. The effect of cultivar, maturity stage and storage environment on quality of tomatoes. Journal of Food Engineering. 2008; 87(4): 467-478. https://doi.org/10.1016/j.jfoodeng.2007.12.031

Hamed MM, Kyaw AK, Nashwan MS, Shahid S. Spatiotemporal changes in universal thermal climate index in the Middle East and North Africa. Atmospheric Research. 2023; 295: 107008. https://doi.org/10.1016/j.atmosres.2023.107008

Hegazy A, Farid M, Subiantoro A, Norris S. Sustainable cooling strategies to minimize water consumption in a greenhouse in a hot arid region. Agricultural Water Management. 2022;274:107960. https://doi.org/10.1016/j.agwat.2022.107960

Hung KL, Kingston JM, Albrecht M, Holway DA, Kohn JR. The worldwide importance of honeybees as pollinators in natural habitats. Proceedings of the Royal Society B: Biological Sciences. 2018; 285 (1870): 20172140. https://doi.org/10.1098/rspb.2017.2140

Jarimi H, Tapia-Brito E, Riffat S. A Review on Thermoregulation Techniques in Honeybees'(*Apis Mellifera*) Beehive Microclimate and Its Similarities to the Heating and Cooling Management in Buildings. Future Cities & Environment. 2020; 6(1): 1-8. https://doi.org/10.5334/FCE.81

Johnson MG, Glass JR, Dillon ME, Harrison JF. How will climatic warming affect insect pollinators?. Advances in insect physiology 2023; 64: 1-115. https://doi.org/10.1016/bs.aiip.2023.01.001Get rights and content

Kamboj P, Kaur G, Gupta G. Understanding the Impact of Heat Stress on Honeybee Populations: Insights into Thermoregulation, Colony Dynamics, and Environmental Interactions. Uttar pradesh journal of zoology. 2024;45(12):1-3. https://doi.org/10.56557/upjoz/2024/v45i124098

Kamel SM, Mahfouz HM, Blal AE, El-Wahed MS, Mahmoud FM. Foraging activity of four bee species on sesame flowers during two successive seasons in Ismailia Governorate, Egypt. Pesticidi i fitomedicina. 2013; 28(1): 39-45. https://doi.org/10.2298/PIF1301039K

Klein AM, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tscharntke T. Importance of pollinators in changing landscapes for world crops. Proceedings of the royal society B: biological sciences. 2007; 274(1608):303-313. https://doi.org/10.1098/rspb.2006.3721

Kleinhenz M, Bujok B, Fuchs S, Tautz J. Hot bees in empty broodnest cells: heating from within. Journal of Experimental Biology. 2003; 206(23):4217-4231. https://doi.org/10.1242/jeb.00680

Korprasertsak N, Leephakpreeda T. Maximizing cooling/heating performance of thermoelectric modules across variable thermal loads via optimal control based on COP curves. Heliyon.2024;10(1):e24063. https://doi.org/10.1016/j.heliyon.2024.e24063 Get rights and content

Kovac H, Käfer H, Stabentheiner A. The energetics and thermoregulation of water collecting honeybees. Journal of Comparative Physiology A. 2018; 204(9): 783-90. https://doi.org/10.1007/s00359-018-1278-9

Kovac H, Stabentheiner A, Schmaranzer S. Thermoregulation of water foraging honeybees—balancing of endothermic activity with radiative heat gain and functional requirements. Journal of Insect Physiology. 2010; 56(12): 1834-1845.

Lu Y, Hong W, Wu W, Zhang J, Li S, Xu B, Wei K, Liu S. The impact of temperature regulation measures on the thermodynamic characteristics of bee colonies based on finite element simulation. Biosystems Engineering. 2025;250:306-316. https://doi.org/10.1016/j.biosystemseng.2025.01.012

Minaud E, Rebaudo F, Mainardi G, Vardakas P, Hatjina F, Steffan-Dewenter I, Requier F. Temperature in overwintering honeybee colonies reveals brood status and predicts colony mortality. Ecological Indicators. 2024; 169:112961. https://doi.org/10.1016/j.ecolind.2024.112961

Mitchell D. Ratios of colony mass to thermal conductance of tree and man-made nest enclosures of *Apis mellifera*: implications for survival, clustering, humidity regulation and *Varroa destructor*. International journal of biometeorology. 2016; 60(5): 629-638. https://doi.org/10.1007/s00484-015-1057-z

Mostafa AN, Wheida A, El Nazer M, Adel M, El Leithy L, Siour G, Coman A, Borbon A, Magdy AW, Omar M, Saad-Hussein A. Past (1950–2017) and future (− 2100) temperature and precipitation trends in Egypt. Weather and Climate Extremes. 2019; 26: 100225.

Nabil T, Mansour TM. Enhancing photovoltaic panel efficiency with innovative cooling Technologies: An experimental approach. Applied Thermal Engineering. 2024; 253: 123846. https://doi.org/10.1016/j.applthermaleng.2024.123846

Nada SA, Fouda A, Mahmoud MA, Elattar HF. Experimental investigation of energy and exergy performance of a direct evaporative cooler using a new pad type. Energy and Buildings. 2019; 203: 109449.

Neumann P, Straub L. Beekeeping under climate change. Journal of Apicultural Research. 2023;62(5):963-968. https://doi.org/10.1080/00218839.2023.2247115

Oh DG, Son MW, Akongte PN, Lee CH, Choi YS, Kim DW. The Effects of Using Heating Panels in Smart Beekeeping Systems on Honeybee (*Apis mellifera*) Colonies during Winter: Worker Bee Activity. Journal of Apiculture. 2024;39(1):1-0. https://doi.org/10.17519/apiculture.2024.04.39.1.1

Omni Calculator. Area of a rectangle calculator (2D geometry calculator). https://www.omnicalculator.com/math/rectangle 2024, (retrieved by: 29.12.2025)

Omran, N. S. M. Wintering of honeybee colonies (Apis mellifera L.) by using a new technique during winter season in Sohag region, Egypt. Journal of Applied Sciences Research. 2011;174-182.

Oskin SV, Kudryavtseva AA. Models of the Thermal Condition of Winter Aggregation of Bees with Electric Heaters Installed in the Hive. IOP Conference Series: Earth and Environmental Science.2021;666:032091. https://doi.org/10.1088/1755-1315/666/3/032091

Osman M. A., Shebl M. A. Vulnerability of crop pollination ecosystem services to climate change. In “Climate Change Impacts on Agriculture and Food Security in Egypt: Land and Water Resources—Smart Farming—Livestock, Fishery, and Aquaculture”, Springer International Publishing, Cham, Switzerland, 2020, p.223–247.

Phillips, K. Climate control, bee style. The Journal of Experimental Biology. 2003; 206 (23):4181. https://doi.org/10.1242/JEB.00728

Potts SG, Imperatriz-Fonseca V, Ngo HT, Aizen MA, Biesmeijer JC, Breeze TD, Dicks LV, Garibaldi LA, Hill R, Settele J, Vanbergen AJ. Safeguarding pollinators and their values to human well-being. Nature. 2016; 540(7632): 220-229. https://doi.org/10.1038/nature20588

Satif A, Mekhfioui M, Elgouri R. Advanced techniques for maximizing photovoltaic power: A systematic literature review. Scientific African. 2025; 30: e02989. https://doi.org/10.1016/j.sciaf.2025.e02989

Seeley T. The wisdom of the hive: the social physiology of honeybee colonies. Harvard University Press, Cambridge, Massachusetts, USA, 1997, p.1–20.

Southwick EE. Allometric relations, metabolism and heart conductance in clusters of honeybees at cool temperatures. Journal of Comparative Physiology B. 1985; 156(1): 143-149. https://doi.org/10.1007/BF00692937

Stabentheiner A, Kovac H, Brodschneider R. Honeybee colony thermoregulation–regulatory mechanisms and contribution of individuals in dependence on age, location and thermal stress. PLoS one. 2010; 5(1): e8967. https://doi.org/10.1371/journal.pone.0008967

Stabentheiner A, Kovac H, Mandl M, Käfer H. Coping with the cold and fighting the heat: thermal homeostasis of a superorganism, the honeybee colony. Journal of Comparative Physiology A. 2021; 207(3): 337-351. https://doi.org/10.1007/s00359-021-01464-8

Stalidzans E, Zacepins A, Kviesis A, Brusbardis V, Meitalovs J, Paura L, Bulipopa N, Liepniece M. Dynamics of weight change and temperature of *Apis mellifera* (Hymenoptera: Apidae) colonies in a wintering building with controlled temperature. Journal of economic entomology. 2017; 110(1): 13-23. https://doi.org/10.1093/jee/tow282

Staron M, Rajčáková Ľ, Planý M, Abou-Shaara H. Interactive effects of diet, tebuconazole, and elevated temperature on survival and body water loss in honeybee workers. Environmental Toxicology and

Pharmacology. 2025; 121: 104913. https://doi.org/10.1016/j.etap.2025.104913

Tautz J, Maier S, Groh C, Rössler W, Brockmann A. Behavioral performance in adult honeybees is influenced by the temperature experienced during their pupal development. Proceedings of the National Academy of Sciences. 2003; 100(12):7343-7347. https://doi.org/10.1073/pnas.1232346100

Vollet-Neto A, Menezes C, Imperatriz-Fonseca VL. Brood production increases when artificial heating is provided to colonies of stingless bees. Journal of Apicultural Research. 2011; 50(3):242-247. https://doi.org/10.3896/IBRA.1.50.3.09

Winston M. L. The biology of the honeybee. Harvard University Press, Cambridge, Massachusetts, USA, 1991, p.1–15.

Zeaiter Z, Myerscough MR. Poor hive thermoregulation produces an Allee effect and leads to colony collapse. Journal of Theoretical Biology. 2020; 503: 110361. https://doi.org/10.1101/2020.01.21.914697

Zheng Y, Cao X, Xu S, Guo S, Huang R, Li Y, Chen Y, Yang L, Cao X, Idrus Z, Sun H. Intelligent beehive monitoring system based on internet of things and colony state analysis. Smart Agricultural Technology. 2024; 9: 100584. https://doi.org/10.1016/j.atech.2024.100584