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Exploring Bee Colony Dynamics: Temperature and Humidity Monitoring as Indicators of Colony Activity

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Abstract

Honeybee (Apis mellifera) colonies play a crucial role in supporting both ecological balance and agricultural productivity through their pollination activities. Understanding the internal conditions of a honeybee colony is essential for assessing its health, productivity, and seasonal behavior. In recent years, the concept of precision beekeeping has gained momentum, introducing digital tools and sensor-based methods to continuously monitor hive parameters without disturbing the bees. Temperature and humidity are two key physical variables that have been widely recognized as indicators of colony status. Monitoring these factors provides valuable insights into the hive's internal microclimate, which can directly affect brood development, metabolism, and the colony's overall health.

Building upon this understanding, the present study focuses on the continuous monitoring of temperature and humidity both inside and outside the hive, as well as within the brood nest. The goal was to evaluate how the internal thermal dynamics of the hive reflect colony activity and environmental interactions. By tracking these parameters, author aims to explore their potential as non-invasive indicators of colony well-being. These data can help beekeepers better understand how environmental factors influence colony productivity and health, ultimately contributing to more effective management strategies.

Keywords: Bee colony dynamics; Honeybee colony monitoring; Precision apiculture; Precision beekeeping; Smart beekeeping;

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1. Introduction

Honeybee colonies (Apis mellifera) are vital not only for sustaining ecological balance but also for supporting diverse forms of agricultural production. In addition to being the primary pollinators for numerous crops, bees serve as sensitive indicators of environmental health. Over the past decades, alarming trends such as Colony Collapse Disorder (CCD) and widespread bee population declines have been linked to environmental stressors, including climate change, pollution, and disease outbreaks. Among the innovative tools for assessing hive status, bioacoustics analysis - focused on detecting and interpreting bee-generated sounds and vibrations - has shown potential as a non-invasive diagnostic method (Uthoff et al., 2023). Acoustic signals produced by bees, through wing movements or internal hive communication, can offer insights into colony vitality, queen presence, swarming tendencies, and stress responses related to illness or resource shortages (Capela et al., 2022). While bioacoustics monitoring can provide valuable data on hive health, the present study prioritizes temperature and humidity as key parameters for continuous monitoring of hive conditions.

Recent advancements in sensor-based technologies (Marchal et al., 2020; Meikle and Holst, 2015; Zaman and Dorin, 2023) have laid the foundation for Precision Beekeeping - a data-driven approach to apiary management that optimizes productivity while minimizing resource usage (Zacepins et al., 2015). Smart hive systems, which integrate sensors for temperature, humidity, and bioacoustics data, have enabled real-time tracking of hive conditions, allowing for timely interventions to prevent colony decline (Marchal et al., 2020; Zecepins et al., 2015). While bioacoustics has become a valuable tool in hive diagnostics, temperature and humidity sensors are increasingly used to monitor the internal microclimate of the hive. These environmental parameters are strongly linked to colony behavior, brood development, and overall health. By tracking these factors alongside acoustic data, beekeepers can gain a comprehensive view of hive conditions and respond proactively to early signs of distress. Despite these advancements, traditional beekeeping remained largely dependent on natural swarming behaviors, offering limited control over colony health and productivity (Crane, 1999).

In summary, while bioacoustics monitoring remains a promising tool for assessing colony health, this study emphasizes the potential of environmental monitoring through temperature and humidity as essential indicators of colony well-being. Together, these approaches offer valuable support for apicultural practices, especially in light of global challenges such as climate change, pollution, and the rising incidence of bee diseases.

2. Material and methods

The study was carried out at a hobbyist apiary located in Brzeski Poviat, Lesser Poland (approximate coordinates: 49°53'00.0"N, 20°34'00.0"E). The exact location is withheld to preserve privacy of the beekeeper. The apiary, operated by a Master Beekeeper with over four decades of experience, houses around 40 colonies of Apis mellifera. Two colonies were selected for monitoring based on the beekeeper's expertise. Each colony was maintained in Apipol hives (see Figure 1), a variation of the 1/2 Langstroth design constructed from expanded polystyrene (EPS). These hives are known for their modular structure and thermal insulation properties. Each hive included a ventilated bottom board, brood chambers, honey supers with a queen excluder, an inner cover, an empty super, and a ventilated roof. Colony 1 was headed by a three-year-old queen, while Colony 2 had a two-year-old queen and exhibited higher activity levels. Both colonies of Carniolan honey bees (*Apis mellifera carnica*) used two brood chambers containing ten frames each.

Figure 1: Apipol hive - variation of the 1/2 Langstroth design

Sensor Configuration and Placement

Digital sensors were deployed to measure temperature, humidity, and weight at key locations within and around the hive (see Figure 2)

Figure 2: Apipol hive - placement of sensors

These sensors provide complementary data that cannot be captured through basic environmental monitoring alone. Temperature and humidity sensors help monitor the hive's microclimate, which plays a crucial role in brood development, colony metabolism, and disease susceptibility. The weight sensor offers insights into nectar intake, food reserves, and foraging activity, enabling the detection of changes in colony productivity (see Figure 3).

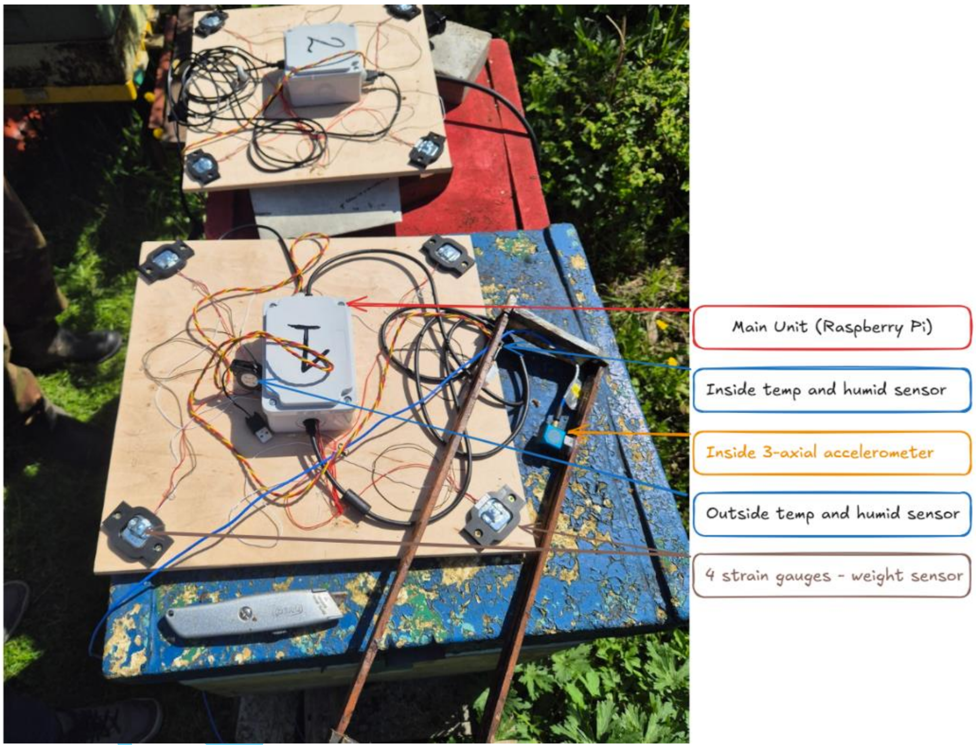

Figure 3: Apipol hive - additional digital sensors

By integrating these environmental parameters, a more complete and context-aware picture of colony health and behavior can be achieved. The following sensors were used:

- **DHT11**: Installed outside the hive to measure ambient temperature and relative humidity in the immediate environment. This provided baseline climatic conditions for comparison with internal hive measurements.
- **DHT22**: Placed inside the hive to monitor internal air temperature and humidity. The DHT22 offers higher accuracy and a wider measurement range than the DHT11, making it suitable for detecting subtle changes in hive microclimate. This sensor was embedded into the frame structure.
- **DS18B20**: Installed within the brood area to capture precise temperature readings directly from the nest. This sensor was located below the partition grid of the hive, where temperature regulation is most critical for larval development.
- **Weight sensor**: Each hive was placed on a dedicated wooden platform equipped with a custom-built weight measurement system. The system consisted of four strain gauges connected to a HX711 signal amplifier. This configuration allowed for continuous monitoring of hive weight, which reflects nectar inflow, food stores, and foraging activity.

Table 1: Technical specification of digital sensors

Sensor Type	Sensor Model	Accuracy	Range	Placement
Temperature, Humidity	DHT11	±2 °C, ±5% RH	0-50 °C, 20-90% RH	Outside hive
Temperature, Humidity	DHT22	±0.5 °C, ±2-5% RH	-40 to 80 °C, 0-100% RH	Inside hive
Temperature	DS18B20	±0.5 °C	-55 to 125 °C	Brood chamber
Weight	HX711 + 4 strain gauges	±0.01 kg (calibrated)	0-200 kg	Under the hive

Table 1 summarizes the technical specifications and placement of the sensors.

Power Supply

Each measurement unit (Raspberry Pi with connected sensors) was powered by a 5 V DC supply from a mains adapter, protected by a voltage stabilizer and surge protection circuit. This ensured uninterrupted operation and measurement stability during the entire monitoring period.

Data Acquisition and Transfer

Data from all sensors (temperature, humidity, and weight) were collected and processed by a Raspberry Pi microcomputer. A single sample was recorded every 10 seconds, and the values were averaged and stored locally every 60 seconds. The data were periodically transferred via Wi-Fi to a secure local server for backup and analysis.

Data Analysis and Visualization

The recorded datasets were processed and analysed using MATLAB (MathWorks Inc.). MATLAB scripts were used to filter data, perform time-series analyses, and generate plots for visual representation of temperature, humidity, and weight changes over time.

Measurement Duration and Environmental Conditions

Measurements were conducted continuously between 1st and 31st of July. The ambient temperature and humidity values recorded by the external sensor represent local environmental conditions in the vicinity of the hives. The apiary is situated in a small depression surrounded by trees, which provides natural wind protection and helps to stabilize the microclimate.

Flowering Conditions During the Measurement Period

During the first half of July, local vegetation still provided abundant nectar and pollen resources, though the main spring bloom had already ended. The small-leaved lime (Tilia cordata) was among the last trees in full flower, ensuring one of the final strong nectar flows from woody plants. Meadows and farmlands offered continuous forage from cornflower (Centaurea cyanus), common poppy (Papaver rhoeas), St John's wort

(Hypericum perforatum), yarrow (Achillea millefolium), and successive cuts of clover (Trifolium spp.) and alfalfa (Medicago sativa). In the second half of July, the floral composition shifted as tree flowering subsided. Meadows remained productive, featuring tansy (Tanacetum vulgare), great mullein (Verbascum densiflorum), and white sweet clover (Melilotus alba). Forest edges and gardens contributed additional forage, with species such as wild raspberry (Rubus idaeus), oleaster (Elaeagnus angustifolia), coneflower (Echinacea purpurea), catnip (Nepeta cataria), and teasel (Dipsacus fullonum) dominating the late-summer landscape.

3. Results and Discussion

The collected dataset provides a detailed view of short-term colony dynamics during midsummer conditions. The analysis focuses on variations in hive weight and temperature-humidity relationships both inside and outside the colonies. Particular attention is given to identifying characteristic daily patterns and assessing how environmental and behavioural factors influence the monitored parameters. The results are presented alongside relevant discussion to interpret these patterns in the context of colony activity and environmental stability.

The following figures present individual sensor-derived measurements for July 2025. Detailed analyses of each parameter - weight, temperature, humidity, and outside versus brood temperature - are provided in the corresponding subsections, allowing focused interpretation of temporal dynamics and their relation to key management events in Hive 1 and Hive 2.

3.1 Long-Term Monitoring: Monthly Variations in Colony Conditions

3.1.1 Weight Profile

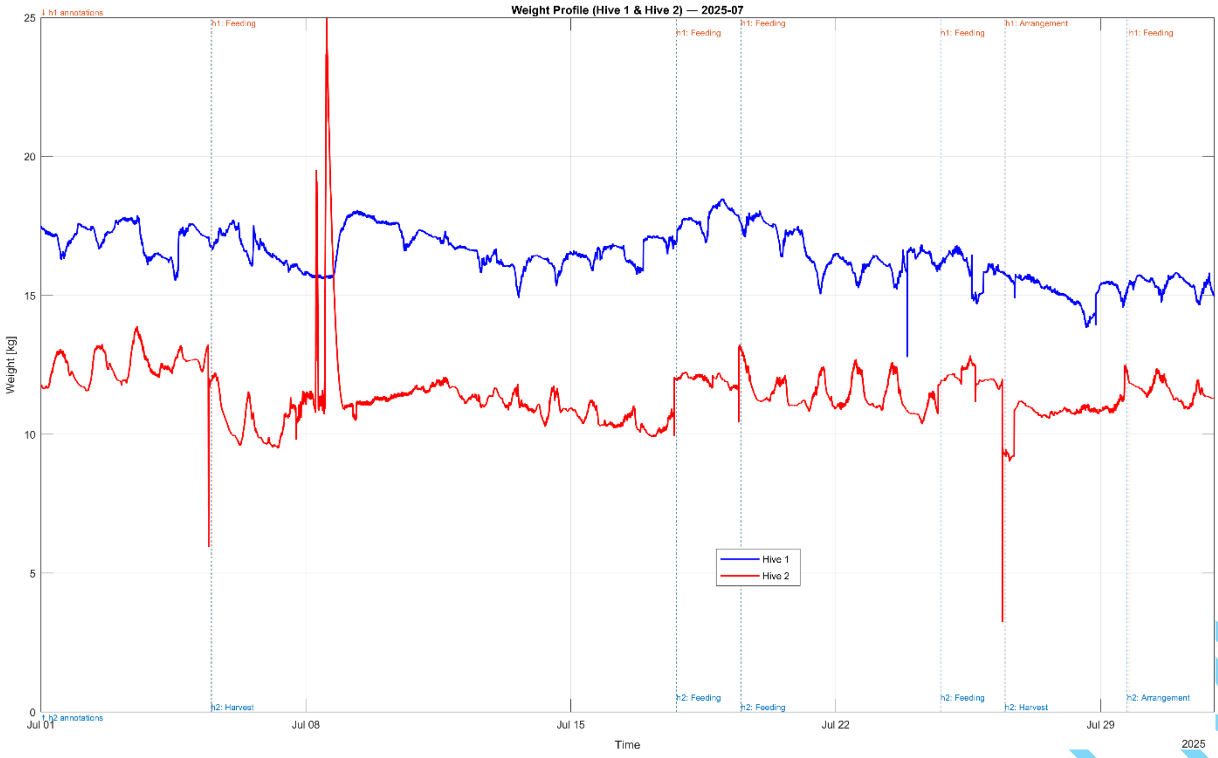

Figure 4: Hives weight profiles in July 2025

The Figure 4 presents the weight profiles of Hive 1 (blue line) and Hive 2 (red line) during July 2025. The weight fluctuations reflect foraging activity, nectar intake, and colony management interventions such as feedings, harvests, and rearrangements (indicated by vertical dashed lines and labelled annotations). Hive 1 consistently maintains a higher overall weight than Hive 2, suggesting a stronger colony or greater honey reserves. Both hives display daily weight oscillations corresponding to foraging cycles and nectar moisture loss, while pronounced stepwise decreases align with honey harvests and increases with feeding events. Occasional sharp spikes, particularly around early July, are likely artifacts caused by transient sensor instabilities - such as electrical noise, vibration, or environmental disturbances - and do not represent real changes in hive mass. The overall gradual decline in late July suggests a reduced nectar flow or increased internal consumption by the colonies.

3.1.2 Temperature Profile

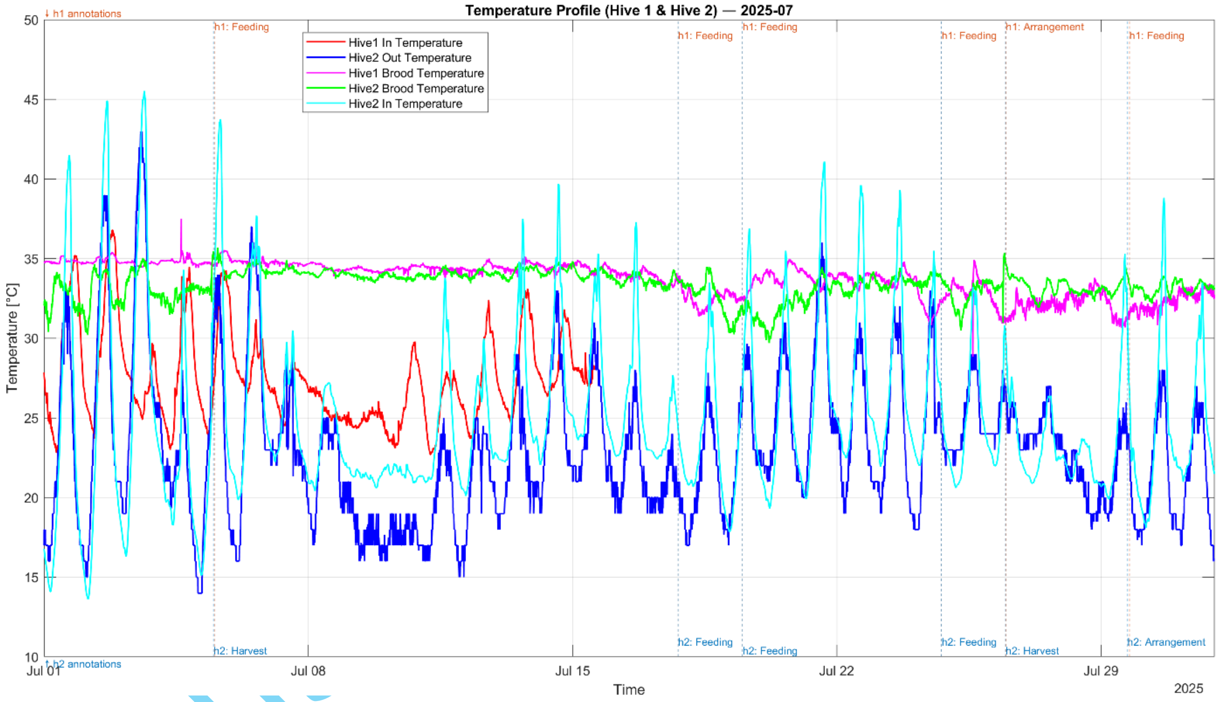

Figure 5: Hives temperature profiles in July 2025

The Figure 5 illustrates temperature dynamics for both hives, with internal hive temperature (Hive 1 In Temperature - red, Hive 2 In Temperature – light blue) and brood nest temperatures. The plot also includes the external temperature recorded near Hive 2 (note that hives were places within 2m distance from each other). Brood temperatures in both hives remain relatively stable around 34-36°C, consistent with optimal brood-rearing conditions, despite larger fluctuations in external temperatures (ranging roughly 18-40°C). Internal hive temperatures show more variation than brood temperatures, particularly in Hive 2, which demonstrates increased sensitivity to external temperature oscillations. Temperature stability within the brood zone reflects active thermoregulation by worker bees, an essential behaviour for maintaining brood viability. The correspondence between intervention markers and slight temperature shifts suggests that colony manipulations briefly affected internal thermal balance.

3.1.3 Humidity Profile

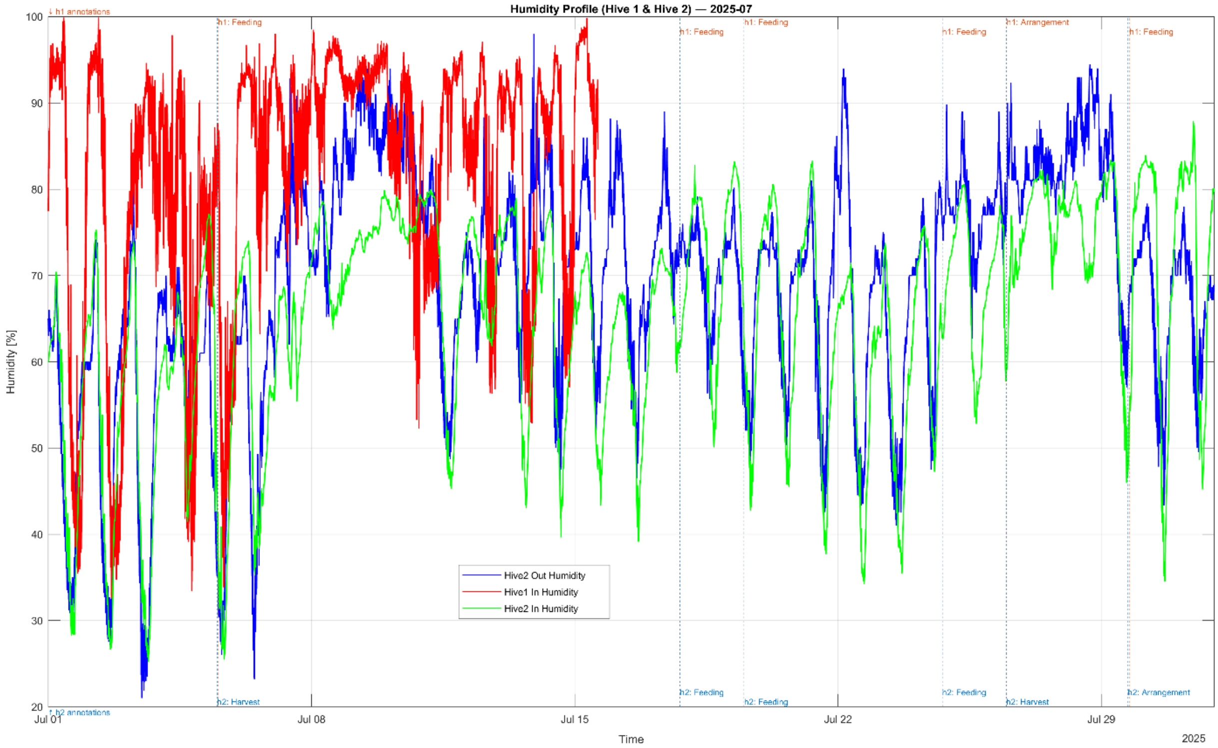

Figure 6: Hives humidity profiles in July 2025

The Figure 6 shows the humidity profiles within and outside the hives. Hive 1 internal humidity (red line) and Hive 2 internal humidity (green line) are compared with external humidity measured at Hive 2's location (blue line). External humidity exhibits large diurnal fluctuations between approximately 40% and 100%, consistent with normal outdoor variability. In contrast, internal humidity remains more regulated, averaging between 50% and 75%, depending on the hive. Hive 1 shows slightly higher internal humidity stability than Hive 2, suggesting better colony control of hive microclimate. Peaks in humidity correspond to nocturnal condensation and rainy periods, while dips align with midday drying. Changes following feeding or rearrangement events may indicate temporary ventilation adjustments by bees responding to disturbance or sugar solution introduction.

3.1.4 Outside vs. Brood Temperature

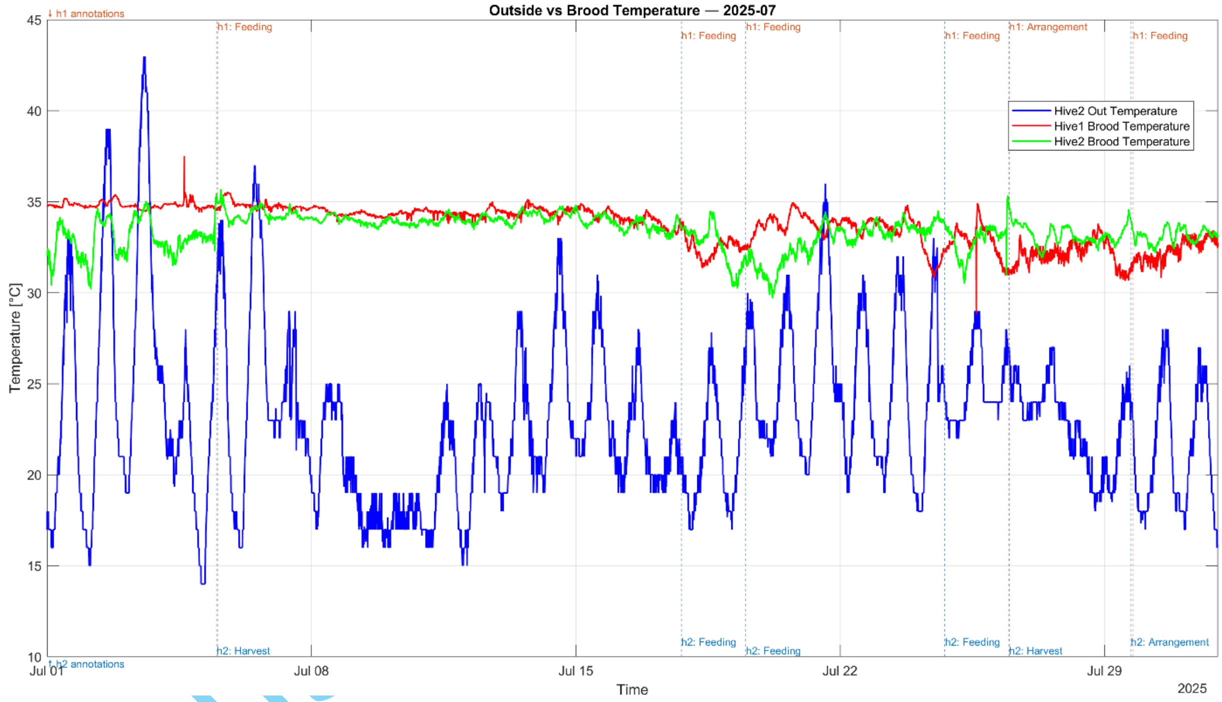

Figure 7: Outside versus brood temperature profiles in July 2025

The Figure 7 compares external temperature (Hive 2) to brood nest temperatures for both hives. The external temperature (blue line) follows a pronounced diurnal cycle with strong peaks around midday and drops at night. In contrast, both brood temperatures (green and red lines) remain remarkably stable, with minimal fluctuation across the same period. This visual contrast underscores the thermal homeostasis maintained within the brood region despite ambient environmental variability. Hive 2 shows slightly greater brood temperature oscillation than Hive 1, possibly reflecting differences in colony population strength or brood coverage.

3.1.5 Observations

Temperature measurements inside the brood area of both hives remained remarkably stable throughout July 2025, despite substantial fluctuations in external temperature. This stability highlights the colonies’ capacity to maintain a controlled internal environment essential for brood development. In contrast, external temperature exhibited pronounced swings, particularly during the daytime, reflecting normal environmental variability. The data suggest that the bees effectively buffer the brood area against these fluctuations, likely aided by the thermoregulatory properties of the hive structure itself. Humidity trends within the hives were more responsive to external conditions than temperature, indicating a dynamic interaction between moisture regulation and environmental variability. These fluctuations may reflect changes in hive ventilation, nectar processing, or other colony activities that influence internal humidity. Hive weight data further complemented these observations, showing daily variations linked to foraging activity, food storage, and colony growth. Taken together, the four datasets - internal temperature, internal humidity, external conditions, and hive weight - illustrate how colonies actively regulate their microclimate while responding to environmental cues. Across all figures, vertical dashed lines mark apiary management interventions, such as feedings, hive rearrangements, and harvests. These annotations provide temporal context, linking observed environmental dynamics to specific beekeeping actions. Overall, the combined dataset underscores the value of continuous, sensor-derived monitoring as a non-invasive approach for assessing colony health, productivity, and resilience.

3.2 Short-Term Dynamics: A 24-Hour Hive Microclimate Profile

To further explore short-term dynamics within the colonies, a 24-hour monitoring session was analysed to capture detailed fluctuations in temperature, humidity, and hive weight. The following figure presents representative daily profiles illustrating diurnal variations in hive activity, thermoregulation, and humidity control.

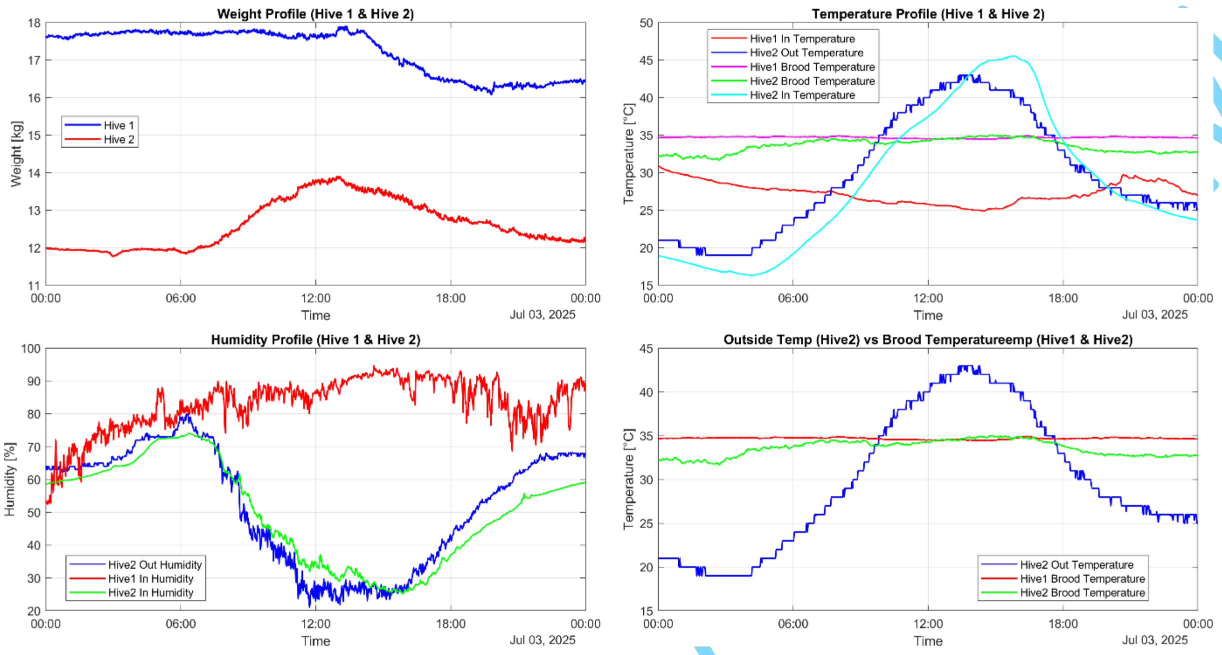

Figure 8: Daily weight, temperature, and humidity profiles of Hive 1 and Hive 2 (July 3, 2025).

The Figure 8 presents a comprehensive 24-hour dataset illustrating the environmental and behavioural dynamics of the same colonies as above. The plots summarize weight, temperature, and humidity fluctuations recorded on July 3, 2025, as indicators of colony activity and internal regulation processes.

In the Weight Profile (top left), both hives exhibit characteristic diurnal patterns. Hive 2 shows a gradual increase in weight during the morning and early afternoon, likely reflecting foraging activity and nectar collection, followed by a steady decline toward evening as moisture evaporates from stored nectar and bees return to the hive. Hive 1 displays relatively stable weight throughout the early day, with a noticeable drop in the late afternoon, possibly linked to reduced foraging or changes in colony behaviour. These fluctuations reflect the colonies' metabolic and foraging rhythms, highlighting their responsiveness to external conditions. The Temperature Profile (top right) contrasts the internal and brood temperatures of both hives with the external temperature. Brood temperatures remain remarkably stable for both hives (around 33–36 °C), demonstrating effective thermoregulation by worker bees despite significant external variation. The outside temperature, represented by Hive 2's outdoor sensor, shows a distinct diurnal rise peaking above 40 °C around midday. This contrast underscores the bees' ability to maintain a controlled internal microclimate critical for brood development, even under thermal stress. The Humidity Profile (bottom left) reveals complementary trends. External humidity decreases sharply during the day as ambient temperatures rise, while internal hive humidity remains relatively elevated and stable, particularly in Hive 1. This indicates active moisture regulation by the bees to sustain brood and food storage conditions. Hive 2's internal humidity shows stronger variability, possibly reflecting differences in colony size, ventilation behaviour, or hive insulation. Finally, the Outside vs. Brood Temperature plot (bottom right) further illustrates the decoupling of internal hive temperature from environmental fluctuations. Despite a diurnal amplitude of more than 20 °C in outside air temperature, brood temperatures remain within a narrow, biologically optimal range. Such stability reflects the efficiency of collective thermoregulation mechanisms, such as fanning and clustering, which are essential for colony survival and productivity.

Overall, these data demonstrate how continuous monitoring of temperature, humidity, and weight can serve as reliable, non-invasive indicators of colony activity and well-being. The observed patterns highlight the capacity of honeybee colonies to buffer environmental variability through coordinated behavioural and physiological regulation - an essential aspect of resilience under changing climatic conditions.

4. Conclusions

This study underscores the critical role of monitoring temperature and humidity within and around honeybee hives as essential indicators of colony health and productivity. Through continuous sensor-based measurements, author observed how these parameters, both inside and outside the hive, are closely linked to the internal microclimate of the colony. The results consistently demonstrated that the hive's internal conditions, particularly in the brood nest, remain stable despite significant fluctuations in external temperature and humidity. This highlights the bees' remarkable ability to regulate their internal environment, ensuring optimal conditions for brood development, colony metabolism, and overall health. The results revealed that the internal microclimate of the hives - particularly within the brood area - remained remarkably stable despite substantial fluctuations in external temperature and humidity. This stability reflects the bees' ability to actively regulate their nest environment to maintain optimal conditions for brood development and metabolic processes.

Weight data further illustrated characteristic patterns linked to daily foraging cycles, nectar collection, and colony management interventions such as feeding, harvesting, and rearrangements. Short-term mass drops and recoveries corresponded to foraging rhythms and moisture loss in stored nectar, while pronounced stepwise changes coincided with beekeeper interventions. Occasional sharp spikes in the weight curves were identified as artifacts caused by temporary sensor instabilities, vibrations, or electrical noise, rather than genuine changes in colony mass. Monitoring these parameters continuously provides a non-invasive and data-driven approach to evaluating colony condition. Such measurements allow beekeepers to detect deviations from normal environmental regulation that may signal stress, disease, or resource scarcity. When integrated with records of local flowering conditions, this approach offers valuable insight into how external nectar availability influences colony behaviour and productivity.

By integrating temperature and humidity monitoring into precision beekeeping practices, this study contributes to a deeper understanding of how honeybee colonies interact with their environment. The potential for these environmental parameters to serve as non-invasive indicators of colony status paves the way for more effective management strategies aimed at improving colony health and enhancing agricultural productivity. The continuous monitoring of these factors promises to be an invaluable tool in advancing precision beekeeping and fostering more sustainable beekeeping practices in the face of ongoing environmental challenges.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT-5 in order to improve the readability and language of the manuscript. After using this service, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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