Advances in Beehive Monitoring Systems: Low-Cost Integrating Sensor Technology for Improved Apiculture Management

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Abstract. The integration of monitoring systems in beekeeping has significant implications for the health and sustainability of honeybee colonies. These advanced systems, which include sensors for temperature, humidity, hive weight, and sound analysis, allow for real-time tracking of hive conditions, enabling beekeepers to respond promptly to potential threats such as disease, pests, or environmental stressors. Research shows that such technology can lead to improved colony management, reducing the incidence of colony collapse disorder (CCD) by facilitating early intervention. Additionally, continuous data collection helps in identifying patterns and anomalies in hive behavior, contributing to a better understanding of bee biology and environmental interactions. However, the effectiveness of these systems depends on the accuracy of the data collected and the beekeeper's ability to interpret and act upon this information. Moreover, while monitoring systems have the potential to enhance colony health, there are concerns about the cost, accessibility, and the need for technical expertise, which could limit widespread adoption among small-scale beekeepers. Overall, the use of monitoring systems in beehives represents a promising tool for enhancing bee colony health, though its success will rely on overcoming the challenges of implementation and ensuring that beekeepers can utilize the data effectively to support their colonies.

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1 Introduction

Beekeeping is essential for global food production, biodiversity, and environmental health. However, beekeepers face numerous challenges, including colony collapse disorder, environmental stressors, and diseases that threaten the sustainability of their operations. Addressing these challenges requires a coordinated approach involving research, policy changes, and support for sustainable practices to ensure the survival of bee populations and the vital services they provide. Beekeeping is vital for pollination, which is crucial for approximately 75% of the world's leading food crops. Honeybees are particularly effective pollinators, enhancing agricultural yields and ensuring food security. The absence of these pollinators would significantly reduce the production of many fruits, vegetables, and nuts, leading to food scarcity and higher costs [1].

Bees are essential in maintaining biodiversity by pollinating wild plants, which supports diverse ecosystems and wildlife. The decline in bee populations threatens the survival of many plant species and, by extension, the animals that depend on them for food and habitat [2] and contributes to the economy through the production of honey, beeswax, and other bee products. Moreover, the pollination services provided by bees have an estimated global economic value of hundreds of billions of dollars annually, underscoring their importance to agriculture [3]. From point of view of ecosystem bees are sensitive to environmental changes, making them good indicators of ecosystem health. Monitoring bee populations can provide valuable insights into the impacts of environmental stressors, such as pollution and climate change, on local ecosystems [4].

The Colony Collapse Disorder (CCD) is characterized by the sudden disappearance of worker bees from a hive, leaving behind the queen, food, and a few nurse bees. The exact causes of CCD are not fully understood, but it is believed to result from a combination of factors, including pesticides, pathogens, and environmental stressors [5]. CCD has caused significant losses in bee populations, particularly in the United States and Europe. This loss not only affects honey production but also the availability of pollination services, which are crucial for many crops [6]. The most important causes with an important impact on bee health and colony survival are: i. the climate change - who affects the availability and quality of forage plants, disrupts the timing of flowering, and can lead to mismatches between bee activity and plant availability [7]; ii. Pesticides - these chemicals weaken bees, making them more susceptible to diseases and reducing their survival rates [8]; iii. Habitat Loss - the expansion of urban areas and intensive agriculture reduces the availability of natural habitats and floral diversity, which are essential for bees' nutrition and overall health. This habitat loss contributes to the decline in bee populations worldwide [9] [10]; iv. Diseases and Pests - varroosis, nesomosis, american foulbrood, european foulbrood, chalkbrood, sac brood virus, deformed wing virus, and stonebrood, can severely impact colony [11] [12]; v. Economic Pressures - fluctuating honey prices, the costs of managing diseases, and the need to replace lost colonies. These economic pressures are compounded by the high rates of colony loss due to CCD and other factors, making beekeeping a financially precarious occupation [13]; vi. Regulatory and Policy inconsistent regulations on pesticide use, coupled with inadequate support for sustainable agricultural practices, hinder beekeepers' efforts to protect their bees [14].

To meet the challenges of maintaining healthy honey bee populations, monitoring through high-performance sensor systems can provide important non-invasive and preventive data on the health status of the colonies. The use of monitoring sensors in bee colonies is crucial for advancing our understanding of colony health, behaviour, and environmental interactions, which are vital for both ecological balance and agricultural productivity. These sensors enable continuous, non-invasive monitoring of critical parameters such as temperature, humidity, hive weight, and bee activity, providing real-time data that can detect early signs of stress, disease, or environmental changes. For instance, fluctuations in hive temperature can indicate brood rearing activities or the presence of a queen, while changes in hive weight can reflect nectar flow or foraging efficiency [15]. Additionally, sensors help in studying the impact of external stressors like pesticides, climate change, and habitat loss on bee populations by providing precise data that can be correlated with these factors [16]. Furthermore, advanced acoustic and vibrational sensors can detect the bees sound and movement patterns, offering insights into colony health and communication, which are often precursors to swarming or colony collapse [17]. The integration of these technologies into beekeeping practices not only aids researchers in understanding the complex dynamics of bee colonies but also empowers beekeepers to make informed decisions, potentially mitigating colony losses and improving honey production. Thus, the deployment of monitoring sensors in bee colonies is a pivotal tool for ensuring the sustainability of bee populations and, by extension, global food security.

The main objective of the work is to develop a high-performance system for monitoring bee colonies by using CO2, CO, NO2, VOC, and Noise sensors in order to obtain information on the state of health of the colonies, their stress level and the capacity for resilience to meteo-climate, anthropogenic and pollution challenges [18] [19]. The use of CO2, CO, and NO2 sensors in bee colony monitoring plays a significant role in understanding the environmental factors affecting bee health and behaviour [20] [21]. These sensors can detect the presence of gases that may indicate internal hive issues or external pollution sources, which can have direct and indirect impacts on colony vitality. For instance, elevated CO2 levels within a hive can suggest poor ventilation or high respiratory activity, possibly indicating overcrowding or health stress among the bees. Similarly, monitoring CO levels is crucial as it can be an indicator of combustion or other harmful activities [22] near the hive that could introduce toxic elements into the colony environment [23]. NO2 sensors, on the other hand, are essential for detecting pollution, particularly from agricultural activities or nearby vehicular traffic, which can contribute to the decline in bee populations due to the toxic effects of nitrogen oxides on bees and their food sources [24].

Noise monitoring in bee colonies, specifically through the use of acoustic and vibrational sensors, is an emerging field that offers valuable insights into the health and behaviour of honeybee colonies [25]. These monitoring techniques allow researchers and beekeepers to detect key colony activities, such as the presence or absence of a queen, swarming preparations, and stress responses to environmental factors. For example, acoustic monitoring has been used to detect the distinct sounds associated with queen loss and swarming, which are critical for colony management and preventing potential collapse [26] [27]. Additionally, advanced machine learning techniques are being applied to analyse these acoustic data, improving the accuracy of detecting various colony states through sound, despite the presence of background noise from the environment [25]. These methods represent a non-invasive approach to monitoring bee colonies, reducing the stress caused by traditional inspection methods and providing continuous, real-time data that can help in early intervention and better colony management.

By integrating these sensors into hive monitoring systems, researchers and beekeepers can gain valuable insights into the environmental stressors affecting bee colonies, enabling more proactive management and conservation efforts.

2 Data and methods

The development of a test beehive monitoring system model from Institute of Wildlife and Mountain Resources from Miercurea Ciuc (ICDCRM) involves a combination of hardware and software components designed to collect, transmit, and analyse data from beehives, providing insights into the health and behaviour of bee colonies. The system often includes sensors for measuring temperature, humidity, sound, and weight, and also environmental which are critical indicators of hive conditions.

Hardware Components contain a Power Supply: Solar panel + 12V battery + charge controller. The charge controller optimizes the battery charging. The stable 12V DC from the charge controller is reduced to 5V, necessary for powering the SoC, sensors and other modules (SIM/SD), using a voltage regulator. Single-board System (SoC – System on Chip): The ESP32 SoC is responsible for managing the sensors (initialization/calibration/reading), communicating with other systems (ESP-NOW/Bluetooth), sending SMS messages via the GSM module, accurate sleep/wake functionality using the RTC, and saving data to an SD card via the SD module. SIM Module (SIM800L): Receiving and sending 2G/2G+ messages. Real-Time Clock (RTC): Setting real-time and measuring the passage of time, even when the device is not powered. The ESP32 SoC wakes up precisely with the help of the RTC. SD Card Module: Saving data/audio recordings to a MicroSD card.

Temperature and humidity sensors are used to monitor the internal environment of the hive, ensuring it remains within the optimal range for bee survival and productivity. Weight sensors track the hive's weight changes, offering insights into honey production and overall hive activity. Acoustic sensors are employed to capture the sound within the hive, which can be analysed to detect swarming or other unusual behaviours. The collected data is typically transmitted wirelessly to a central database or cloud service using communication modules like Zigbee, LoRa, or GSM, depending on the distance and power requirements. The data is then processed using algorithms to provide real-time alerts and long-term analytics. The software component often includes a user interface, for web or mobile application, where beekeepers can visualize the data and receive notifications. The system's power supply used solar-powered with battery backup to ensure continuous operation in remote locations. This combination of hardware and software allows for continuous, non-invasive monitoring of beehives, enabling early detection of potential issues and facilitating better management practices.

2.1 Firmware Development

The firmware development is as below:-

- Sensor Data Reading: Write firmware to initialize and read data from each sensor periodically.
- Data Processing: Implement algorithms to filter and process raw sensor data, converting it into meaningful information (e.g., concentration levels).
- Data Transmission: Program the microcontroller to send processed data to a cloud server or local storage via the communication module.
- Alerts and Notifications: Implement thresholds in the firmware to trigger alerts if certain gas concentrations exceed safe levels.

2.2 Prototyping and Testing

The prototyping and testing were done as follows:-

- Breadboard Prototyping: Assemble a prototype on a breadboard to test the circuit design and firmware before finalizing the PCB design.
- PCB Fabrication: Once the prototype is validated, design the PCB using software like Eagle or KiCad, and then fabricate it using a PCB manufacturer.\
- Assembly and Testing: After receiving the PCB, assemble the components, and perform thorough testing to ensure functionality and reliability in the field.

2.3 Final Deployment

The steps is as below:-

- Enclosure Design: Create an enclosure to protect the motherboard and sensors from environmental factors such as moisture and dust.
- Field Testing: Deploy the system in a real beehive environment, monitor performance, and adjust the design as necessary based on field data.

2.4. System Design

Detailed description of the beehive monitoring system used in the study, including types of sensors (e.g., temperature, humidity, weight), data logging, and communication technologies.

2.5 Experimental Setup

Information on the location of hives, the number of hives monitored, and the duration of monitoring.

2.6 Data Collection

Methods for data acquisition, including how data is logged, transmitted, and stored.

2.7 Data Analysis

Description of the statistical or analytical methods used to process and interpret the data.

2.8 Limitations

Regular sensors calibration are made for accurate readings. The steps were as follows:-

- Protective Housing: Sensors are place in weatherproof housings to protect them from rain, wind, and direct sunlight, which can affect their accuracy.
- Data Analysis: Data are used from sensors to track trends over time, helping to predict. In this context, for this study, the effect sizes coefficients were selected according to the available data, thus resulting in: small effect (d=0.2), medium effect (d=0.5) and large effect (d=0.8).

3 Results and discussions

This motherboard design integrates a solar-powered energy system with an ESP32-based control unit, supporting a wide range of functionalities required for remote sensing and communication applications. The efficient power management, reliable communication via GSM, and robust data storage capabilities make this system ideal for deployment in off-grid, low-power environments.

The developed system is designed to integrate a solar-powered system with an ESP32 SoC, supported by a 12V battery, a charge controller, and various peripheral modules including a SIM800L GSM module, an RTC, and an SD card module. The design ensures efficient power management, reliable communication, and data storage.

Power Supply System, provides renewable energy input to the system and it is connected to the charge controller to manage and optimize the charging of the 12V battery. The battery as the primary power storage, ensuring consistent power supply during periods of low sunlight. The stores the energy generated by the solar panel. Charge Controller manages the charging of the 12V battery, ensuring it operates within safe limits and prolonging its life and stabilizes the output to deliver a consistent 12V DC power supply.

A voltage regulator was included to converts the stable 12V DC from the charge controller down to 5V DC. Powers the ESP32 SoC, sensors, SIM module, RTC, and SD card module.

Central Processing and Control (Fig, 1) consists of:-

ESP32 SoC	Sensor Management:	• Initializes, calibrates, and reads data from connected sensors
	Communication:	• Supports ESP-NOW and Bluetooth for local wireless communication. • Interfaces with the SIM800L module to send and receive. • Supports ESP-NOW and Bluetooth for local wireless communication. • Interfaces with the SIM800L module to send and receive SMS messages.
	Power Management:	• Utilizes the RTC for accurate sleep/wake cycles to conserve power.
	Data Handling:	• Saves sensor data and other relevant information to the SD card.

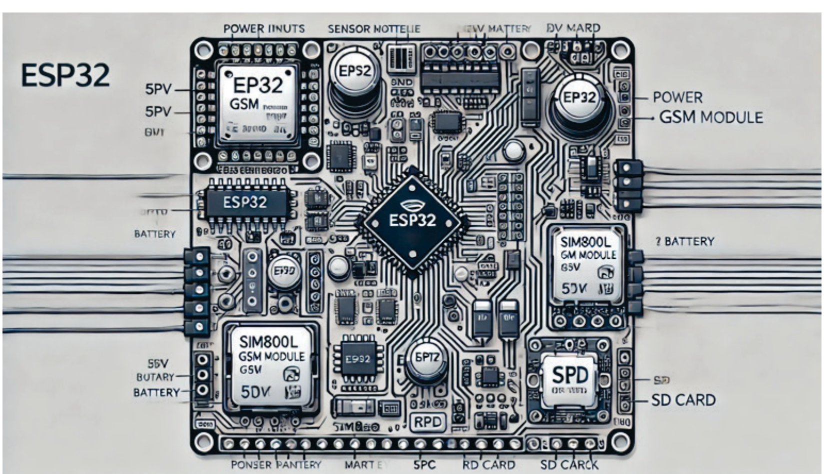

Fig. 1. Central processing and control.

For Peripheral Modules consist of:-

Peripheral Modules	SIM800L GSM Module:	• Handles 2G/2G+ network communication. • Capable of sending and receiving SMS messages based on commands from the ESP32.
	Real-Time Clock (RTC):**	• Maintains accurate timekeeping even when the system is powered off. • Synchronizes with the ESP32 to manage precise sleep/wake cycles, optimizing power consumption.
	SD Card Module:	• Provides data storage capabilities. • Saves sensor readings, logs, and potentially audio recordings from the system.

For connections and layout be made of:

Connection	Power Distribution:	• The 12V output from the charge controller feeds directly into the voltage regulator. • The 5V output from the voltage regulator is distributed via traces to the ESP32, SIM800L, RTC, and SD card module. • ESP32 Connections: GPIO pins of the ESP32 are assigned for sensor inputs, SIM800L communication (using UART), SD card interface (SPI), and RTC communication (I2C).
	SIM800L Module:	• Connected to the ESP32 via UART for serial communication. • Powered by the 5V supply.
	RTC Module:	• Communicates with the ESP32 via I2C protocol. • Provides accurate time data and manages wake-up interrupts.
	SD Card Module:	• Interfaced with the ESP32 using SPI for data storage and retrieval. • Powered by the 5V supply from the voltage regulator.
PCB Layout Considerations:	Power Traces:	• Ensure thick traces for the 12V and 5V power lines to minimize voltage drop. • Place the voltage regulator close to the charge controller output for efficient power conversion.
	Signal Integrity:	• Separate the digital and analog ground planes to reduce noise interference. • Route high-frequency communication lines (SPI, UART) carefully to minimize crosstalk.
	Component Placement:	• Position the ESP32 centrally to reduce trace lengths to peripheral modules. • Keep the SIM800L module away from sensitive analog circuits to avoid RF interference.

Monitoring the temperature and humidity of a beehive is crucial for ensuring the health and productivity of the colony (Fig. 2). External environmental conditions directly influence the internal climate of the hive, which can affect bee behavior, honey production, and overall colony health. Bees are highly sensitive to temperature fluctuations. The ideal temperature range inside the hive is between 32°C and 35°C (89.6°F and 95°F). If the external temperature is too low, bees will cluster to generate warmth, which can limit their ability to forage. Conversely, if the temperature is too high, bees may expend energy on cooling the hive, which can lead to reduced honey production and stress on the colony. The humidity level inside a beehive typically ranges from 50% to 70%.

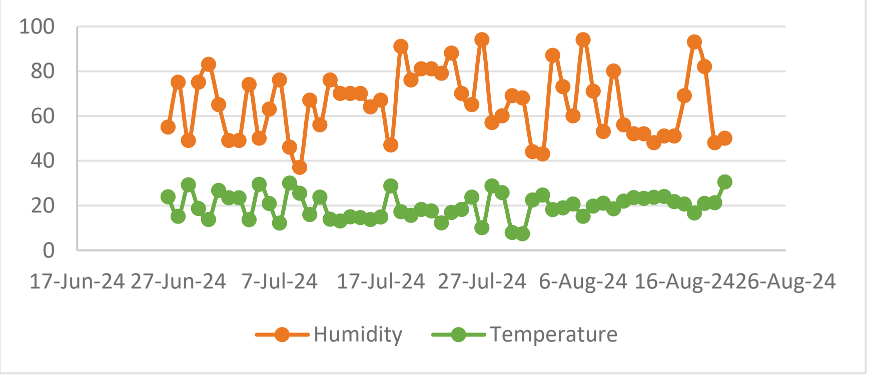

Fig. 2. Variation of humidity and temperature during the studied period.

Humidity levels outside this range can impact the hive's moisture content, affecting honey ripening and storage. High humidity can lead to condensation, which may cause mold growth, while low humidity can result in overly dry conditions, affecting bee brood development. Digital temperature sensors it is placed outside the hive to monitor the ambient temperature. These sensors often use thermocouples or thermistors and can be linked to data loggers transmitters for real-time monitoring.

Humidity sensors, such as capacitive or resistive sensors, are used to measure the relative humidity outside the hive. These sensors are combined with temperature sensors in a single device to provide comprehensive data on environmental conditions.

Data Logging and Remote Monitoring: Modern beekeeping practices often involve the use of IoT (Internet of Things) or GPS devices that transmit data to a central system. Beekeepers can use mobile apps or web interfaces to monitor hive conditions in real-time, allowing for timely interventions if conditions fall outside the optimal range. The system created by us comes to complete the data from the outside of the hive with the situation inside it, in order to obtain data on the evolution of the bee colony, to determine the internal external correlation factors, in order to optimize the actions taken by the apiary (as non-invasive as possible) for the creation of an economically efficient apiary. While sensors provide precise data, beekeepers also rely on visual inspections and manual instruments like hygrometers to assess hive conditions.

The monitoring of impacts of external temperature and humidity on hive health in cold weather when external temperatures drop significantly, bees cluster to conserve heat, which can reduce their activity and affect the hive's ventilation. This situation led to increased moisture inside the hive, causing issues like mold growth or dysentery in bees. In hot weather conditions, high external temperatures force bees to expend energy on cooling the hive through fanning and water collection. Prolonged heat stress can weaken the colony and reduce honey production (Fig. 3).

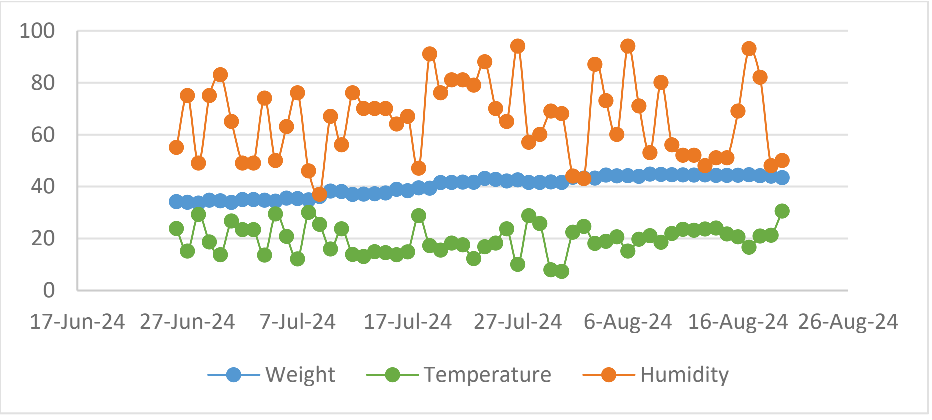

Fig. 3. Variation of weight, temperature and humidity during the studied period

In case of external high humidity can lead to moisture accumulation inside the hive, creating an environment conducive to fungal diseases and pests like the small hive beetle. In the summer perriod In dry conditions, bees may have difficulty maintaining the moisture balance needed for brood development, which can lead to brood mortality and reduced colony growth.

The meteorological and environmental parameters monitoring from the exterior of the beehive must to be strictly correleted with the same parameters from inside. Monitoring meteorological and environmental parameters within beehives is crucial for maintaining the health and productivity of honeybee colonies, as these factors directly influence hive conditions, which in turn affect bee behavior, physiology, and overall hive success. Key parameters such as temperature, humidity, and CO_2 levels within the hive are vital for the survival and productivity of the colony. For instance, bees maintain a narrow temperature range (33-36°C) for brood development, and any deviation can negatively impact larval development and survival rates [28]. Moreover, maintaining optimal humidity levels is essential to prevent fungal growth and preserve the integrity of stored honey [29]. Additionally, monitoring CO_2 concentrations provides insights into hive ventilation and the bees' metabolic activity, which are crucial for understanding colony health during different seasons [30]. Furthermore, external meteorological conditions, including ambient temperature and humidity, directly impact foraging activity and nectar collection, thus influencing hive productivity [31]. Continuous monitoring enables beekeepers to make informed decisions, such as adjusting hive insulation during extreme weather or providing supplemental feeding during nectar dearths, ultimately ensuring the sustainability and resilience of bee colonies against environmental stresses.

Temperature monitoring in beehives is critical for maintaining the health, productivity, and survival of bee colonies. Bees meticulously regulate the internal hive temperature to ensure the proper development of their brood, which is highly sensitive to temperature variations. The ideal temperature range for brood development is around 34.5°C. Deviations from this range can lead to developmental issues or even brood mortality. For instance, if the temperature drops below 32°C, the development of the larvae slows down, while temperatures exceeding 36°C can cause overheating, potentially resulting in brood death [28]. Additionally, temperature monitoring is essential for detecting swarming events, as bees often raise the internal hive temperature before swarming. It also plays a crucial role in identifying queenlessness; when a hive loses its queen, the temperature often becomes less stable due to the lack of brood, which the queen typically helps to regulate [32]. Furthermore, during winter, consistent temperature monitoring can indicate the hive's ability to maintain cluster warmth, with sudden drops in temperature signaling potential threats to colony survival. Therefore, continuous temperature monitoring provides beekeepers with vital data to take timely actions, ensuring the colony's health and optimizing honey production [33].

In the following, we have developed a mathematical model by which we have determined a Theoretical Evolution of Temperature in Beehive in Miercurea Ciuc, Romania in order to have the theoretical basis regarding the actual measurements by sensors. To determine the external temerat we used the data from the Santinell 2 databases. This model provide insights into how different colony conditions can impact the ability of bees to maintain a stable hive temperature, particularly in the extreme climate of Miercurea Ciuc.

The calculation model used to create the graphical representation of temperature evolution within a beehive in Miercurea Ciuc, Romania, is based on the following assumptions and steps:

- Winter: External temperatures in Miercurea Ciuc during winter are assumed to range between -20°C and -10°C (Fig. 4)
- Spring: External temperatures are assumed to rise from 0°C to 15°C
- Summer: External temperatures are assumed to range from 15°C to 30°C
- Fall: External temperatures are assumed to decrease from 5°C to -5°C

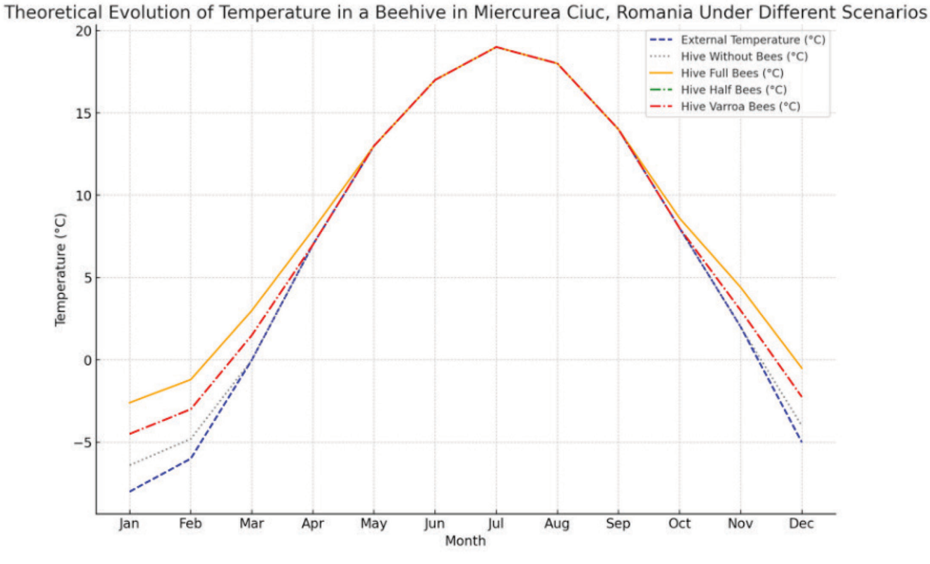

Fig. 4. Beehive temperature evolution under different conditions.

Internal Hive Temperature Regulation: in winter, bees cluster tightly and generate heat through increased metabolic activity, maintaining an internal temperature of approximately 25°C. This value is lower than the brood area temperature but sufficient for survival. Spring, as external temperatures rise, bees begin preparing for brood rearing, maintaining a stable internal temperature around 34°C and in summer, bees actively ventilate the hive to prevent overheating. The internal temperature is assumed to be slightly elevated, ranging from 34°C to 36°C, to account for varying levels of ventilation.

Fall: Bees reduce brood rearing, and the internal temperature begins to drop, stabilizing around 30°C as the colony prepares for winter.

For the model implementation we assumed, a linear progression of external temperatures for each season (Fig. 5 (a)). Internal Temperatures for winter, spring, and fall, are held constant within each season. In summer, a linear increase in internal temperature is modeled due to the bees' ventilation activity.

The x-axis of the graph represents the progression of time across the four seasons. Each season is represented by a set of temperature points, with external and internal temperatures plotted against these points. The graph plots external temperatures with a dashed blue line and internal hive temperatures with a solid orange line. This visual comparison highlights the effectiveness of bees' thermoregulation strategies across different seasons in a cold climate like Miercurea Ciuc.

This model simplifies the actual thermodynamic processes occurring within a beehive but provides a clear theoretical framework for understanding how hive temperatures might evolve in response to extreme seasonal variations in Miercurea Ciuc, Romania under four different scenarios:

- Beehive Without Bees: The gray dotted line represents a hive without bees, where the internal temperature closely follows the external temperature due to the absence of heat generation from bees. The hive temperature is slightly higher than the external temperature due to the insulation but cannot rise significantly on its own.
- Beehive with Full Colony: The orange solid line shows the temperature of a hive with a full, healthy colony of bees. This scenario demonstrates the bees' ability to generate sufficient heat, maintaining the hive temperature above the external temperature, particularly during cold months. Even in the coldest periods, the hive temperature stays around 20°C.
- Beehive with Half of the Bees: The green dash-dot line represents a hive with only half of its bees. With reduced heat generation, the internal temperature is lower than that of a full colony but still significantly higher than the external environment, especially in winter.
- Beehive with Bees Affected by Varroa: The red dash-dot line depicts the hive with bees affected by Varroa mites, which weakens their ability to generate heat. As a result, the hive temperature drops even further compared to a hive with a full or half colony, potentially making it difficult for the bees to survive through harsh winter conditions.

Also the humidity monitoring in beehives is essential for maintaining optimal conditions for the health and productivity of bee colonies. The internal humidity of a hive plays a significant role in the brood development process and the preservation of honey. Bees maintain a specific range of humidity, typically between 50% and 70%, which is critical for the proper development of larvae. If the humidity level is too low, it can lead to the desiccation of the brood, adversely affecting their growth and survival. Conversely, excessive humidity can promote the growth of mold and fungi, which are harmful to both the bees and the stored honey [34]. Furthermore, the right humidity levels are crucial for the process of honey ripening. Bees reduce the moisture content of nectar to around 18% to turn it into honey; excessive humidity can hinder this process, leading to fermentation and spoilage of honey [35]. Humidity monitoring also helps in detecting the health of the colony; for example, a sudden drop in humidity may indicate a decrease in hive activity or a potential issue with the colony's ventilation [33]. Therefore, continuous monitoring of humidity levels within the hive enables beekeepers to maintain a stable environment, ensuring the well-being of the bees and the quality of the honey produced (Fig. 5 (b)).

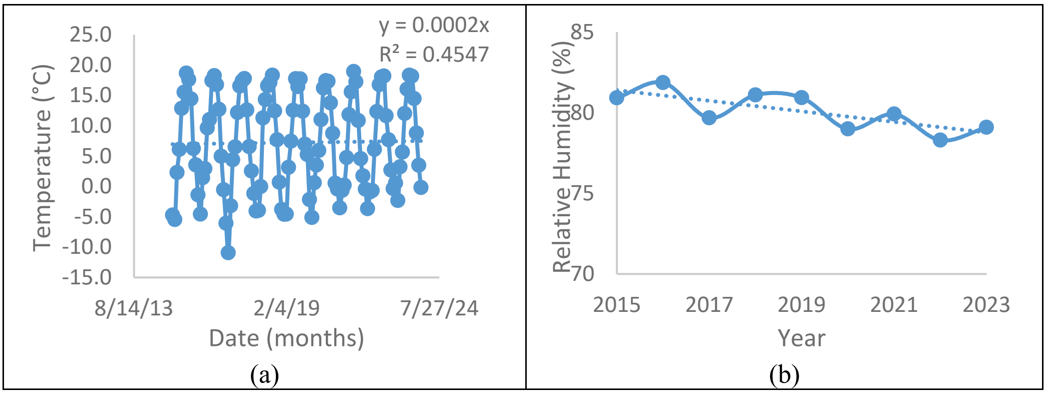

Fig. 5. Regression analysis in 2015 – 2023 period for; (a) temperature and (b) relative humidity.

Noise monitoring in beehives is an emerging tool that provides valuable insights into the health and behavior of bee colonies. Bees produce a variety of sounds through their wing movements, vibrations, and other activities, which can be indicative of different states within the hive. For example, changes in the acoustic patterns can signal swarming, queenlessness, or distress within the colony. Monitoring these sounds allows beekeepers to detect such events early, enabling timely interventions [36].

Specifically, the frequency and intensity of the buzz can provide information about the bees' behavior; a higher frequency buzz is often associated with swarming or agitation, while lower frequencies may indicate a calm or resting colony [37]. Acoustic monitoring also helps in detecting diseases such as American foulbrood, where infected colonies exhibit distinct sound patterns due to the reduced activity and altered behavior of the bees [33]. Furthermore, the analysis of hive acoustics can be used to assess the overall vitality of the colony, as healthy hives tend to have a consistent and harmonious sound, whereas stressed hives often display irregular acoustic patterns. Thus, acoustic monitoring provides a non-invasive method to continuously track the internal dynamics of a hive, offering a crucial tool for maintaining the health and productivity of bee colonies.

In this study we present a relevant one minute noise simulation beehive colony with - Varroa Destructor Infested Colony (Fig. 6). The graph illustrates erratic and reduced frequencies, which is consistent with the findings of Ramsey et al [17], who documented the behavioral and physiological stress caused by Varroa destructor in bee colonies. Such infestations disrupt normal vibrational patterns due to the mites' parasitic effects. Also we coud put in evidence the absence of queen and the results is a chaotic and lowered frequencies, as observed by Schneider and Lewis [38]. Their research highlights how the loss of a queen leads to significant changes in colony behavior, which is reflected in altered acoustic and vibrational signals. Colony with Two Queens (have an acute frequency) the frequency patterns become more dynamic and pronounced, reflecting the heightened interactions within the hive. This phenomenon has been studied by Gilley (2001) [39], who found that the competition between queens leads to increased vibrational activity.

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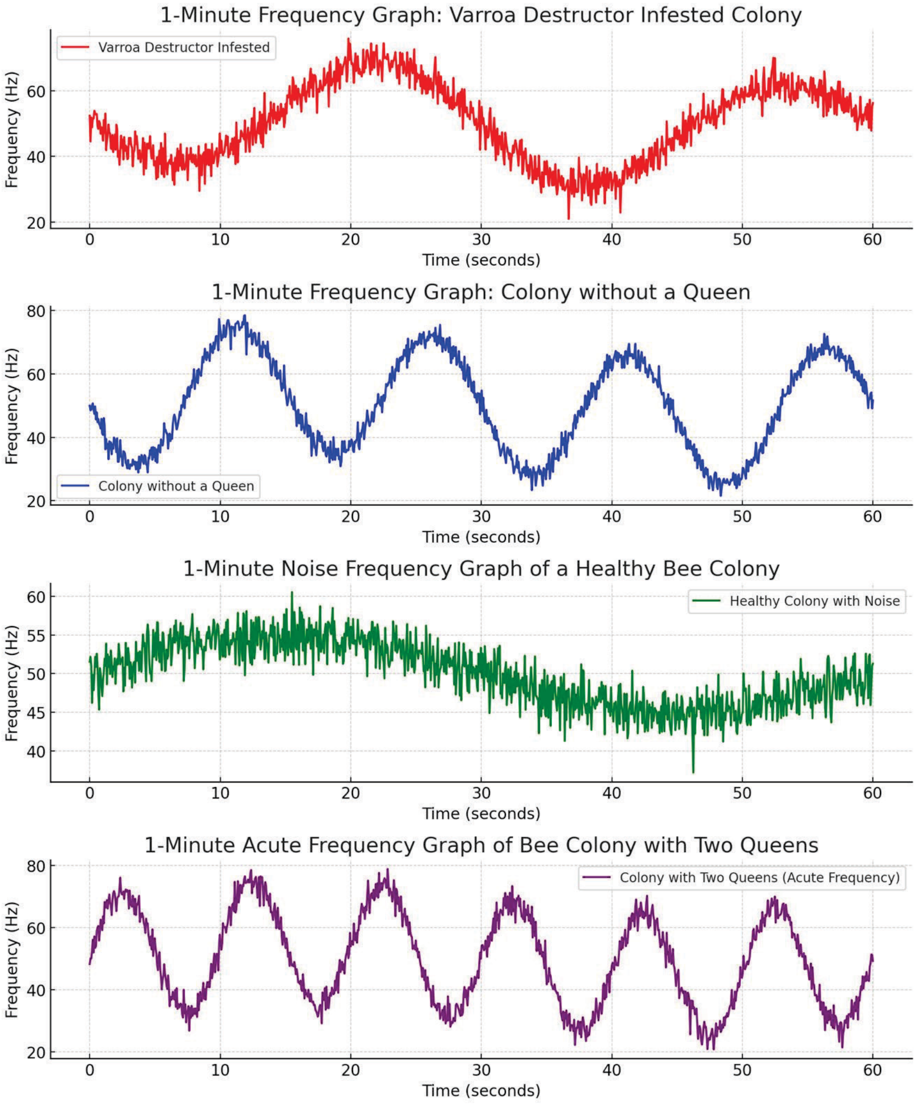

Fig. 6. Colony frequencies under different circumstances.

If we compare the enunced three situation with a Healthy Colony, the frequency graph for this shows minor fluctuations around a stable frequency, which aligns with observations from Seeley et al. (2012) [40]. They describe how normal background noise within a healthy colony can slightly perturb the overall stable vibrational patterns, reflecting the colony's routine activities.

Monitoring carbon dioxide (CO_2) levels inside a beehive is an important aspect of understanding and maintaining the health of the colony. Elevated CO_2 levels can indicate poor ventilation, overcrowding, or other issues within the hive that may stress the bees and impact their productivity. Research shows that CO_2 levels in a well-functioning hive should ideally remain below 0.5% (5000 ppm). If levels rise significantly above this, it could suggest that the bees are struggling to ventilate the hive adequately, which might lead to negative consequences for their health and the hive's overall performance.

Several studies have utilized advanced sensor technologies to monitor CO_2 levels in hives [41]. In our study we have been used the sensors described below to measure CO_2 concentrations with high accuracy and reliability. These sensors, can detect CO_2 levels and provide real-time data that can be critical for timely interventions. We found that CO_2 levels within hives varied significantly throughout the day and across different seasons, with levels sometimes exceeding 5000 ppm during periods of high bee activity. These fluctuations are believed to be managed by the bees through fanning behavior, which helps to regulate the internal environment of the hive. The ability to monitor these CO_2 levels can help beekeepers identify when the hive is under stress and may require additional ventilation or other management strategies [42]. Moreover, integrating these sensors with GSM has allowed for more sophisticated monitoring systems, providing beekeepers with real-time insights into the hive's internal conditions. This approach not only helps in maintaining the bees' health but also optimizes honey production by ensuring that the internal environment remains conducive to bee activity and productivity [43]. These mesearurments can be particularly useful in preventing hive collapse by alerting beekeepers to potentially dangerous conditions before they become critical [42].

The graph above illustrates the CO_2 levels inside the beehive over a period of four weeks in july 2024. As observed the average CO_2 levels of week 1 din stupul monitorizat, were at 3150 ppm, which is within the acceptable range.populatia de albine a fost dezvoltata la 7 rame. Deschiderea zonei de zbor a fost de 1 cm pentru a putea determina capacitatea de ventilare in contitiile aracrilor vispilor dezvoltati foarte mult in anul in curs datorita unei ierni foarte blande

Analiza stupului monitorizat din Week 2 shows a slight increase to 4380 ppm, still within safe limits in conditiile dezvoltarii familiei de albine la 8 rame. Week 3 recorded a spike to 6270 ppm, surpassing the 5000 ppm threshold, which could indicate inadequate ventilation or overcrowding in the hive. Aceasta saptsamana se caracterizeaza prin eclozare masiva, stupul atingand de 9,5 rame limita de dezvoltare. This is a real risk factor that stress the bees and requires attention.

In Week 4, ropnyilas a fost largit la 10 cm latime si 3.5 cm inaltime the CO_2 levels dropped back to 3720ppm, which is an improvement from Week 3 but still higher than the initial levels. The spike in CO_2 levels during week 3 suggests that the hive may have been experiencing a natural and colony ventilation issues and increase in bee activity that required more oxygen. This could be due to seasonal changes, an increase in hive population, or other environmental factors. The subsequent decrease in Week 4 indicates that conditions may have improved, possibly due to continue the corrective actions taken, such as enhancing ventilation or reducing hive congestion. In conclusion in case of CO_2 the continuous monitoring of CO_2 levels is crucial. If levels approach or exceed 5000 ppm, immediate action should be taken to prevent stress and potential health risks to the colony.

The concentration of nitrogen dioxide (NO_2) inside beehives is a topic of growing interest due to its potential implications for bee health and colony survival. NO_2 is a pollutant that primarily originates from the combustion of fossil fuels. Potential sources of NO_2 near beehives include - traffic emissions, industrial processes and agricultural practices.

The potential implications of $_{NO2}$ for Beehives with effects on bee health, including

- respiratory stress bees have an open respiratory system, making them vulnerable to airborne pollutants like NO_2, which can impair their respiration and reduce their ability to function.
- behavioral changes: Exposure to NO_2 can affect the bees ability to navigate, forage, and communicate, which are critical for colony survival.
- increased susceptibility to diseases: high levels of NO_2 can weaken bees' immune systems, can exacerbate certain bee diseases making them more susceptible to infections like Nosema and Varroa destructor infestations. In case of Nosema

disease NO_2 exposure can weaken bees' gut microbiota, making them more vulnerable to Nosema apis and Nosema ceranae, which are gut parasites. While NO_2 doesn't directly cause Varroa mite infestations, it can stress bees, making them less able to suviver. In general NO_2 exposure can compromise the immune system of bees, leading to increased prevalence of viral infections such as deformed wing virus (DWV).

Monitoring and managing NO_2 levels around beehives is crucial for ensuring the health and survival of bee colonies. Elevated NO_2 levels can contribute to respiratory stress, behavioral changes, and increased vulnerability to diseases, making it a significant concern for beekeepers and environmental scientists alike. Determining the exact critical level of nitrogen dioxide inside a beehive is challenging due to the lack of specific studies directly quantifying the threshold at which NO_2 becomes harmful to bees. General Threshold for NO_2 in environmental studies, NO_2 levels above 40-50 ppb over prolonged periods are considered harmful to sensitive ecosystems. While not specific to bees, this provides a baseline for potential concern.

Monitoring volatile organic compounds (VOCs) inside beehives is crucial for understanding the health and sustainability of bee colonies, which are essential pollinators in many ecosystems. VOCs in beehives originate from various sources, including plants, hive materials, and environmental pollutants like pesticides and industrial emissions. Elevated levels of harmful VOCs, such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), can indicate environmental contamination and stress within the hive [43]. These stressors are linked to phenomena such as Colony Collapse Disorder (CCD), where bees abruptly disappear from the hive, leading to significant declines in bee populations. By monitoring VOCs, we can identify and quantify these pollutants, allowing for the early detection of harmful environmental conditions that could threaten bee health. This proactive approach not only helps in protecting bee colonies but also serves as a broader indicator of environmental health, given the bee's role as a bioindicator species. Moreover, understanding the VOC profile within beehives can lead to better management practices to mitigate the effects of these contaminants, ultimately supporting the preservation of biodiversity and ecosystem services. The study "Biomonitoring: Developing a Beehive Air Volatiles Profile as an Indicator of Environmental Contamination Using a Sustainable In-Field Technique" [44] highlights the role of volatile organic compounds (VOCs) in beehives as both indicators of environmental health and potential stressors on bee colonies. VOCs within beehives, including contaminants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and monocyclic aromatic hydrocarbons (BTEX), were analyzed using membrane inlet mass spectrometry (MIMS) in both urbanized and rural settings. The findings indicate that VOC concentrations vary significantly between different environments, reflecting the level of environmental pollution [44]. High levels of VOCs, particularly those associated with human activities, are implicated in the phenomenon of Colony Collapse Disorder (CCD), where increased exposure to pollutants is linked to heightened infection rates and bee mortality [44]. This study emphasizes the critical need for monitoring VOCs in beehives as they can serve as bioindicators of environmental health and predictors of colony viability. Additionally, the implications for human health are profound, as the collapse of bee colonies could lead to broader ecological disruptions that impact food security and biodiversity.

4 Conclusions

The application of environmental and meteorological monitoring sensors in beehives is an emerging area of research that focuses on understanding the influence of environmental factors on bee health and behavior. Sensors measuring CO2, NO2, VOCs, humidity, temperature, noise, and weight are particularly valuable for assessing the internal conditions of beehives and their impact on colony dynamics. Studies conclude that elevated CO2 levels within hives can indicate poor ventilation or overcrowding, potentially stressing the bees, while NO2 levels, often linked to nearby pollution sources, can affect bee foraging behavior and health. VOC sensors are instrumental in detecting the emission of pheromones or other organic compounds that signal hive status, which is critical for maintaining colony harmony. Monitoring humidity and temperature is essential as bees are highly sensitive to these parameters, with deviations leading to issues such as brood development problems or increased susceptibility to diseases. Noise sensors help detect abnormal acoustic signals, such as those related to swarming or distress, providing early warnings of hive disturbances. Finally, weight sensors track the hive's weight fluctuations, which can correlate with honey production, food stores, or bee population changes. Integrating these sensors allows for a comprehensive, non-invasive monitoring system that supports beekeepers in maintaining healthy hives and responding proactively to environmental stressors. These findings suggest that such sensor technologies could play a crucial role in improving bee management practices, ensuring the sustainability of bee populations, and by extension, global agricultural productivity.

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