

<https://doi.org/10.48047/AFJBS.7.5.2025.897-912>



African Journal of Biological Sciences

Journal homepage: <http://www.afjbs.com>



Research Paper

Open Access

IoT integrated Multi-Sensor Beehive Monitoring for Real-time Bee Colony Health Analysis and Tracking Using Machine Learning

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Volume 7, Issue 5, May 2025

Received: 15 Mar 2025

Accepted: 05 Apr 2025

Published: 09 May 2025

[doi:10.48047/AFJBS.7.5.2025.897-912](https://doi.org/10.48047/AFJBS.7.5.2025.897-912)

Introduction: The Sundarbans community relies on mangrove forests for wild honey but is faced with remoteness, lack of filtering options and risky collection. The region is also home to Royal Bengal tigers and estuarine crocodiles. To battle these risks, sustainable beekeeping and beehive monitoring needs to be embraced. **Methods:** This study introduces a multi-sensor system that uses Raspberry Pi for collecting and processing of beehive data to monitor beehive conditions in real-time. A variety of sensors, such as those for humidity, air quality, sound, air flow and pressure, are integrated into this system and connected to a Raspberry Pi, in contrast to conventional monitoring techniques that frequently rely on single-sensor systems with few environmental inputs. **Result:** This setup makes it possible to continuously check on the hive using IoT. With this setup, hive health can be continuously monitored and possible dangers, such low air quality or odd sound patterns, can be identified early. Bee hive sound data was analyzed using CNN on Edge Impulse and 96% accuracy was achieved. **Conclusion:** By moving the processed data to the Blynk Cloud, the ESP32 microcontroller expands the capability. The system provides a strong answer for contemporary beekeeping by supporting sophisticated data analysis using machine learning, improving forecast accuracy, and lowering false alarms through its local processing capacity.

Keywords: Bee Hive monitoring, Bee colony health, machine learning, IoT, Raspberry-pi, sensors.

Introduction

About 13% of all visits to flowers are made by honey bees, particularly the western honey bee (*Apis mellifera*), which are the most prevalent pollinators in natural settings. Furthermore, honey bees are the only pollinator for about 5% of plant species worldwide. Because of their function in pollination, honeybees are essential to both global agriculture and biodiversity. Therefore, maintaining beehive health is essential for agricultural output and environmental stability [1]. However, conventional monitoring systems typically use a small number of sensor types and are primarily concerned with a single parameter, such as humidity or temperature. The system's ability to quickly identify different external stresses impacting hive health may be jeopardized by such limitations [2]. This work uses a Raspberry Pi as the central processing unit to create a multi-sensor beehive monitoring system in order to overcome these constraints. This device combines sensors for weight, sound, humidity, and air quality, enabling a more thorough evaluation of hive conditions. The Raspberry Pi makes it possible to process data in real time, which lessens the need for cloud processing and gives beekeepers instant feedback. With the help of machine learning any abnormal sound can be identified. By providing beekeepers with accurate and timely information on colony health, our multi-sensor setup seeks to improve early intervention capabilities. Related works

Literature Review

Beehive monitoring systems have significantly improved over the last ten years because to developments in data processing using machine learning and the data transmission using Internet of Things (IoT). The contributions and limits of recent studies on single-sensor, multi-sensor, and Internet of Things-based monitoring systems are reviewed in this section.

Single sensor-based monitoring

Single-sensor based Bee-hive monitoring and tracking methods are easier to deploy and operate and reasonably priced, they have been widely adopted. For example, Aumann et al. [2] recorded bee activity within hives using a radar and a piezoelectric vibration sensor to detect robbing and swarming behaviors. Single-sensor systems are useful for identifying certain behaviors, but they frequently don't provide a whole picture of hive health since they can't record several environmental

stresses at once. Similarly, Sakova et al. [3] used a convolutional neural network (CNN) with auditory monitoring to categories noises that indicated hive circumstances like queen death or swarming. The system's dependability in a variety of environments may be limited by false positives brought on by background noise, even while sound data may identify specific hive activities.

IoT-integrated multi-Sensor Methods

More thorough monitoring capabilities have been made possible by the integration of several sensors and IoT frameworks. Using temperature, humidity, and sound sensors, Tashakkori et al. [4] created the Beemon IoT system, which relays data to a cloud server for analysis. Despite its effectiveness, this method needs consistent internet connectivity, which might not be possible in isolated locations. A low-cost multi-modal sensor network comprising temperature, sound, and humidity sensors that are wirelessly coupled to a central unit was proposed by Howard et al. [5]. The usefulness of the multi-sensor strategy in identifying contaminants that impact hive health was restricted because to the omission of important parameters like as air quality, even if it yielded new insights. Furthermore, the intricacy of on-site data analysis was limited by microcontrollers' low computing power.

On board computing and processing

A more recent development is the usage of Raspberry Pi as a central processing unit in beehive monitoring systems. Compared to conventional microcontrollers, the Raspberry Pi has some noteworthy benefits, such as more processing power, multi-threading capabilities, and machine learning model compatibility. Diogo et al. [6] used machine learning for anomaly detection in a Raspberry Pi-based system that analyses environmental and activity data to assess hive health. This approach marked a shift toward more autonomous and adaptive monitoring systems. In a different research, Imoize et al. [7] used a Raspberry Pi for local data processing to create a temperature and sound monitoring system. Although it was still restricted to a few environmental parameters, this configuration lessened reliance on other servers. Incorporating sensors into monitoring systems improves data durability and dependability. When Braga et al. [8] used industrial temperature and humidity sensors, they were more accurate than ordinary sensors, especially in harsh environments. However, their study lacked a comprehensive strategy to hive monitoring and instead concentrated mostly on individual characteristics. Misirli et al. [9] used a Raspberry Pi in conjunction with sound and air quality sensors to identify pollutants and track bee activity. Despite showing promise, their

method needed to be further modified to take into consideration colony circumstances that were always changing.

Methods

Fig. 1 illustrates the block diagram of the Beehive condition monitoring and health tracking System. The system proposes an Internet of Things-based sensor data collection and raspberry pi assisted data processing for keeping an eye on and controlling a beehive's interior environment to promote the productivity and well-being of bee colonies. The Raspberry Pi Pico controller, which manages data gathering, processing, inferencing machine learning model and transmission, is the central component of the system. The KY-037 Sound Sensor records acoustic information from inside the hive, and the DHT11 Temperature and Humidity Sensor continually checks all the important environmental factors required for bee health and the environmental pressure data is collected by BMP 180 pressure sensor. In order to identify typical or anomalous bee activity patterns that alert the beekeeper to potential disruption, sound data is used to infer a machine learning model made for Raspberry Pi Pico. Additionally, an Air Quality Sensor keeps an eye on the air quality to identify pollutants or ventilation issues.

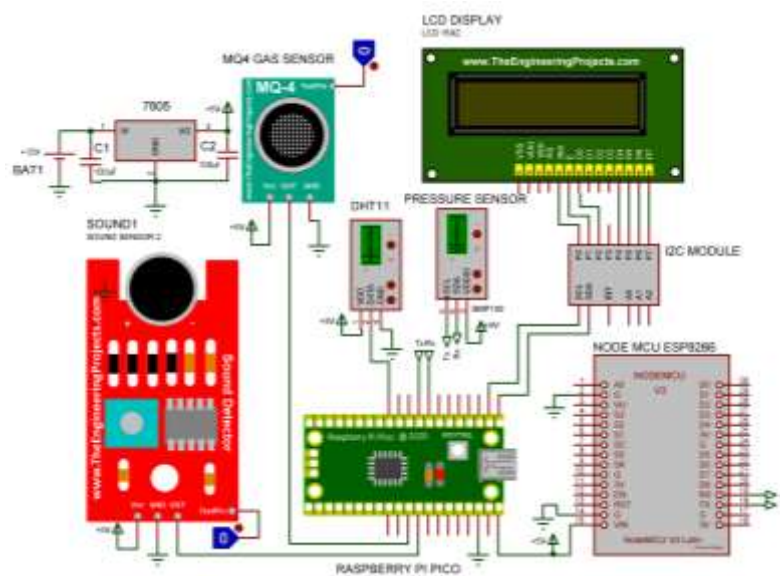


Fig. 1: Elements of Real time bee hive monitoring system.

After that, the ESP32 NodeMCU receives this data and sends it over the air to the Blynk Cloud. Then, using the Blynk app on a computer or smartphone, beekeepers can see in real time the current conditions of each hive in terms of temperature, humidity, sound, and air quality. This program offers a very user-friendly user interface for monitoring purposes, notifying users of any significant changes that call for prompt action. This will be an inexpensive, readily expandable technology that supports sustainable beekeeping by providing proactive, data-driven colony management to ensure ideal circumstances for bee production and health.

System Architecture

Multiple sensors are integrated into the proposed system, which uses an NodeMCU ESP to transfer the data to the cloud for remote monitoring and a Raspberry Pi-Pico for real-time data processing and analysis. The circuit diagram of the bee hive monitoring system is illustrated in Fig. 1. and Fig. 2. The experimental setup of real time bee monitoring system is shown in Fig. 3.

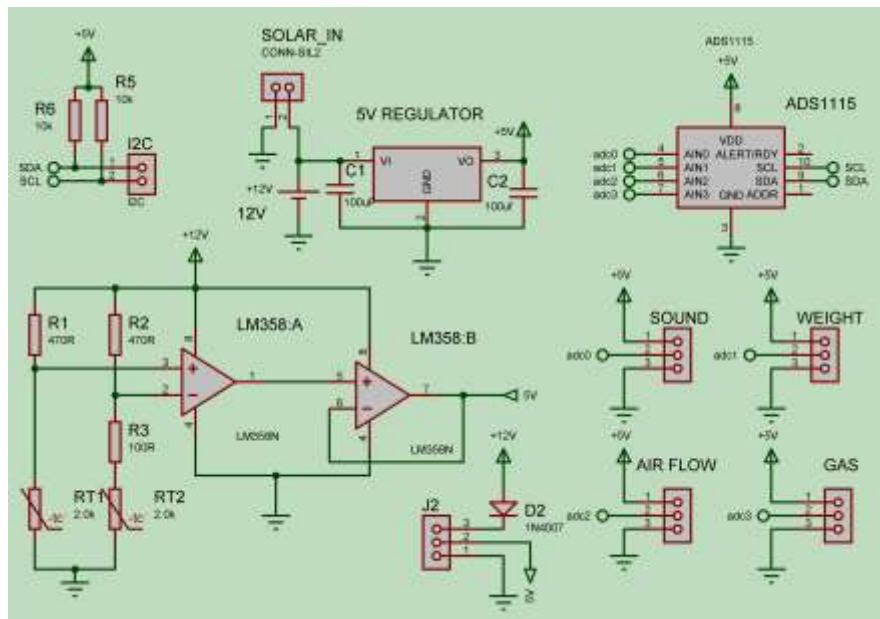


Fig. 2: Circuit diagram of Bee hive monitoring system.

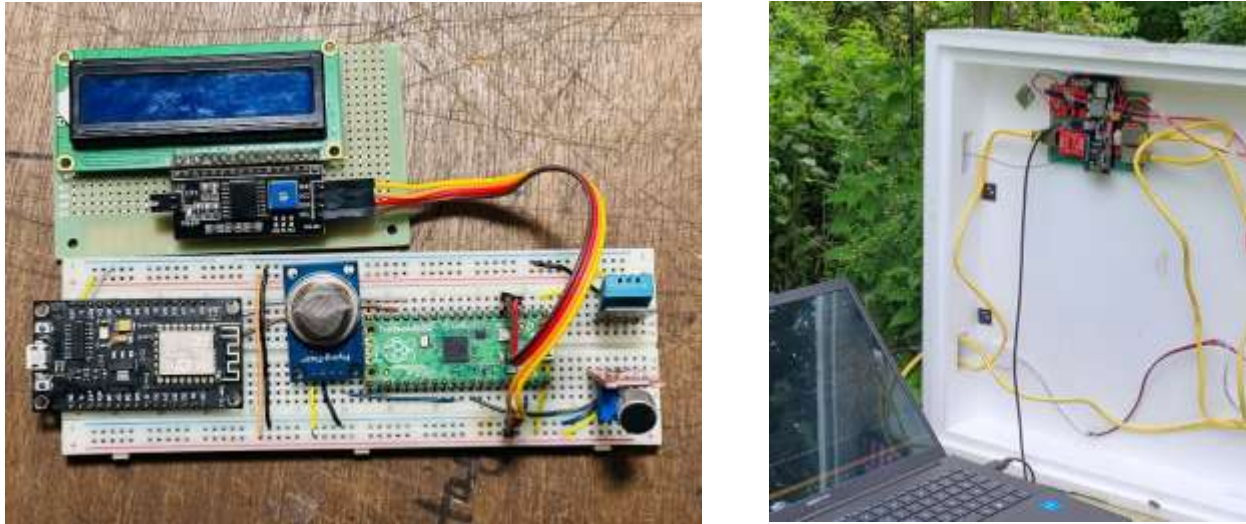


Fig. 3. Experimental setup in a local bee farming hive. Left side contains the components, right side is the hive data collection setup. Testing of Bee hive monitoring system. Real-time on-board Data collection using sensors and on-board computing ML with raspberry pi-Pico.

Sensor Selection and Integration

The hive monitoring system incorporates several sensors to collect hive data as well as data from outer side of a hive. To collect hive's surroundings temperature and humidity data a low cost yet accurate sensor DHT-11 is used. This sensor, which can detect changes in temperature and humidity, is one of the key environmental regulators inside the hive. Because excessive humidity can lead to stress, illnesses, or reduced production, and because extremes of temperature can have negative impacts, these factors are critical to bee health. By keeping the hive within reasonable bounds that support health and colony expansion, ongoing monitoring stops harmful circumstances from taking root.

Hive's air quality is captured by MQ-4 and MG811 precision gas molecule detection sensor. These gas detection sensors are chosen because of their low cost but accurate gas detection ability. This sensor keeps an eye on the hive's levels of CO₂, VOC, and other potential pollutants. The sensor's detection of poor ventilation or the presence of toxins may enable early treatments that might prevent the emergence of circumstances that could negatively impact bee health or behavior.

Maintaining a clean and secure environment in the hive depends heavily on effective air quality monitoring.

Sound detection of Queens presence as well as other factors that are dependent to sound of environment is captured by microphone-based digital sound sensor. To record and capture the noises of the hive, this sensor has a very sensitive array of microphones. Raspberry Pi takes the noise data from the sensor and inference the machine learning model which was trained using convolutional neural network (CNN).

Data Processing and Analysis on Raspberry Pi

In addition to handling raw data from sensors that monitor temperature, humidity, sound, and air quality in real time, the Raspberry Pi serves as the system's central processing unit and is responsible for gathering and evaluating data from each sensor. This list of noteworthy occurrences—which indicates the existence of significant variations with respect to typical environmental parameters—is recorded and saved in a local MySQL database on the Raspberry Pi. With this storage arrangement, a beekeeper will be able to monitor hive conditions over time and identify reoccurring problems by observing trends. Additionally, models may be improved using the stored data, allowing the system to learn from the past and adjust and enhance its detecting skills. Because local processing and storage make data available even in the event of sporadic connectivity problems, they also improve system resilience.

For Internet of Things applications, the ESP32 is a low-cost, low-power microcontroller with Bluetooth and Wi-Fi built in. It may be expanded for a variety of tasks because to its dual-core processor, large memory, and numerous I/O ports. The ESP32's built-in Wi-Fi capabilities enables wireless data transfer, enabling direct connections to local networks or cloud platforms for distant access. Data processed by the Raspberry Pi Pico is sent to the cloud for remote monitoring via the ESP32/NodeMCU in this beehive monitoring system. The view is made possible in real-time by sending data to the Blynk Cloud via a Blynk application, which gives beekeepers a way to keep an eye on the temperature, humidity, sound, and air quality within the hive from any location in the globe. Because of this connectedness, beekeepers can maintain colonies of healthy and productive bees by reacting quickly to changes in the hive environment.

Sound Classification and analysis using CNN

The overall health of the colony is reflected in the noises produced by honey bees. A sound trail, for instance, may be connected to queen identification or swarm preparation. Table 1. lists the classification and feature with effect of such sound which carry important information of a bee-hive [12].

TABLE I. BEE-HIVE SOUND CLASSIFICATION WITH SIGNIFICANT EFFECTS

Signal type	Frequency [Hz]	Source	Signal Pattern	Effect
Recruit	190 – 340	Forager	Pulse Sequence	Quality food exists
Tooting	290 – 500	Queen	Pulse Sequence	Hatching prevention
Quacking	290 – 350	Queen	Pulse Sequence	Viability of mature queen
Piping	290 – 500	Scout	Single Pulse	Prepare to swarm
Hissing	290 – 3500	Colony	Single Pulse	Hive attacks or adverse situations.

Certain sound patterns can be used to identify pest infestation in honey bee hives. The majority of these noises are in the 200–600 Hz fundamental frequency range. An overview of bee noises is given in Table I, together with information on their sources, frequency ranges, and importance. By examining their internal sound patterns, researchers were able to detect queen-less colonies in investigations [13] and [14]. Their spectrogram study showed that colonies without queens had much greater amplitudes and different frequency components. Notably, new frequencies that were absent while a queen bee was present around 400 Hz and 130 Hz—emerged when one was not. On the other hand, while a queen was present, frequencies close to 100 Hz, 250 Hz, and 500 Hz displayed smaller amplitudes; however, when the queen was not there, the amplitudes and peaks were larger. Similar to setups used in earlier investigations [15,16], the audio collecting system used in this study made use of micro-controller sensors and a microphone enclosed in a protective box. Accelerometers that record vibration data directly attached on the hive frame provide an additional means of sound monitoring [17].

Machine Learning in EDGE Impulse

Using a Convolutional Neural Network (CNN) with Edge Impulse is a common approach for deploying machine learning models on edge devices like Raspberry Pi Pico or other microcontrollers or low-power IoT boards.

After choosing data type as audio Edge Impulse data acquisition tool is selected for Raspberry Pi Pico. Data set from Kaggle is uploaded in WAV format which is supported by API. Edge Impulse uses Keras, which is a very high level for building and training Neural Network (NN). After labeling data an Impulse is created. A preprocessing block and a CNN are created for learning. In the next step, Neural Network (NN) Classifier block is created

At the beginning of NN layer, non-speech audio data which is Mel-Frequency Energy (MFE) data from Bee colony is employed in signal processing blocks for extracting meaningful features like presence of bee Queen or absence of Bee queen. This is the preprocessing part. To optimize performance on resource-constrained devices, Edge Impulse incorporates several techniques such as Quantization, Model Pruning and Transfer Learning. Quantization: Lowers the precision of model weights to reduce memory usage and accelerate inference. Model Pruning eliminates unnecessary neurons and connections to simplify the network. Transfer Learning utilizes existing pre-trained models and adapts them for new, specific tasks. After input following information to Edge Impulse 1. Number of layers, 2. Filter sizes 3. Epochs, 4. Learning rate the start Learning button is pressed.

To identify occurrences like swarming or robbery, a CNN model categorizes sound patterns. This approach reduces response time by operating locally on the Raspberry Pi. Edge Impulse was used to develop a machine learning model for identifying normal and abnormal sound inside the hive. Edge impulse provides a complete platform for recording, training and deploying machine learning models in low power devices and microcontrollers. The data collection was the most laborious part where around 18mins of normal beehive sound and 18mins of abnormal sound (swarming, absence of queen, varroa mites' infection) was recorded. The whole recording was then segmented into 1 second window. The segmented audio samples were then partitioned to 80% training and 20% test set.

The model was trained using neural network consists of multiple layers, each containing of a set of neurons. The first layer receives raw data as input, and subsequent layers process and transform this data into increasingly complex representations until reaching the output layer that produces the result. The trained model is shown in figure below that is used to predict the normal and abnormal beehive sound in real time.

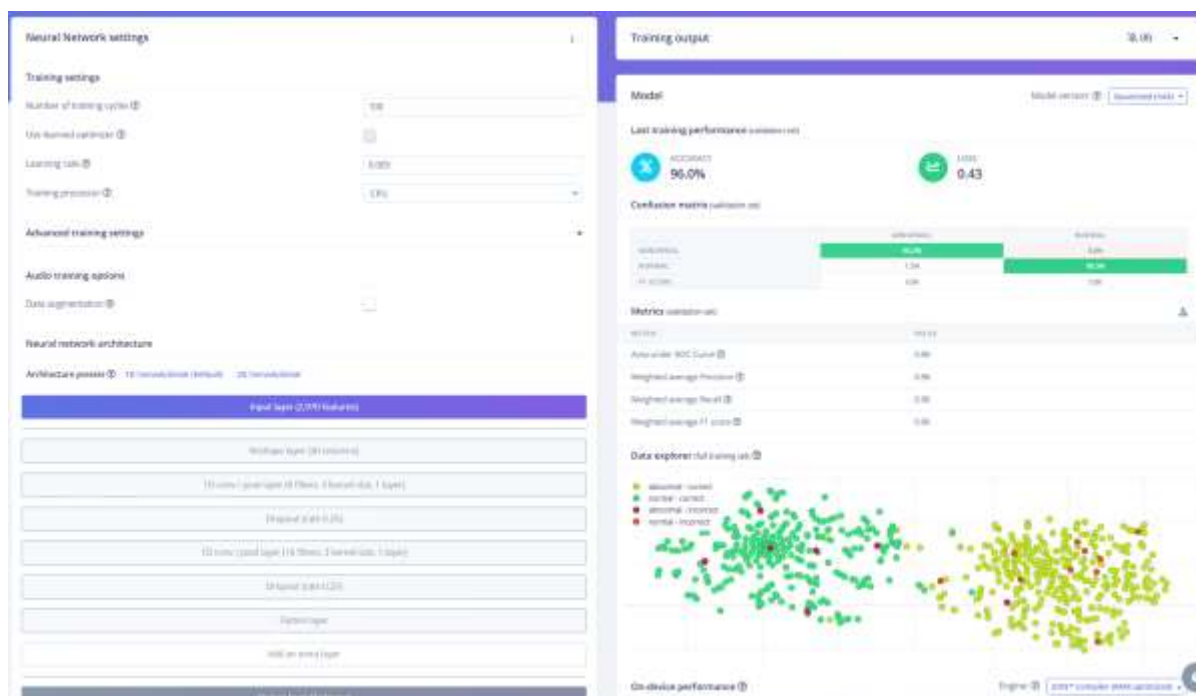


Fig. 4: Neural Network using Edge-Impulse

The Neural Network Settings and training output is shown in the figure below. The proposed model acquires 96% accuracy as shown in above Fig. 4. The collected temperature data is shown in Fig. 5 Graphs are plotted using GraphPad prism 8. The average temperature difference of hive internal and external temperature is 12.65%.

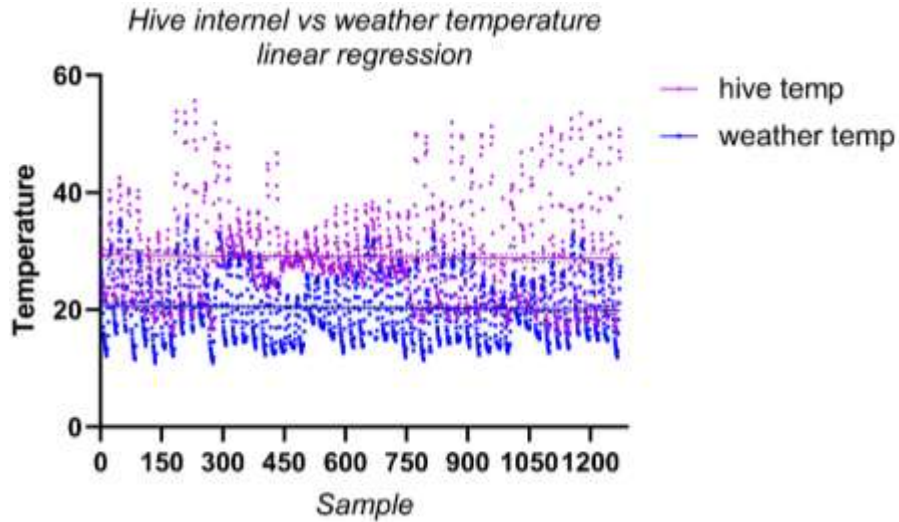


Fig. 5: Hive internal and external temperature data collected using IoT system and sensors.

Humidity of Hives internal and external data is plotted and shown in Fig. 6.

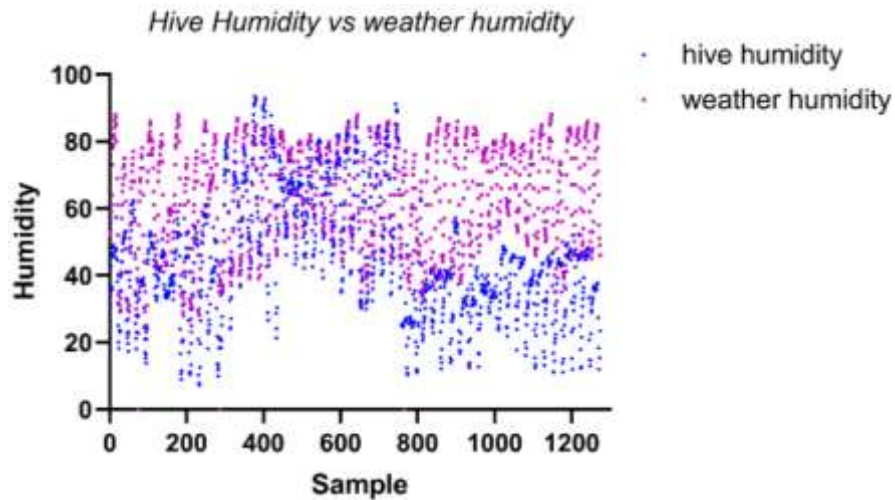


Fig. 6: Hive internal and external humidity data collected using IoT system and sensors

Result and Discussion

The monitoring of acquired data is performed by creating a dashboard accessible via Wi-Fi which allows remote monitoring. Current dashboard to visualize data includes Temperature,

Humidity, AQI index and Sound level. Another important parameter which is pressure level in the surrounding environment will be performed in next update.



Fig. 7: Dashboard of Sensor data on Blynk. One incident data of Bee hive monitoring system.

The experimental results strongly validate the effectiveness of the multi-sensor approach in achieving comprehensive hive monitoring. By integrating a diverse array of sensors and leveraging the computational capabilities of the Raspberry Pi, the system significantly enhances the accuracy, reliability, and timeliness of the collected data.

This integration ensures that beekeepers receive precise and actionable insights into hive conditions, which are critical for maintaining bee health and optimizing hive management practices. Furthermore, the incorporation of machine learning algorithms introduces a dynamic element to the system, enabling it to adapt and refine its predictive capabilities over time. This adaptability not only improves the system's ability to forecast potential issues but also minimizes the occurrence of false alarms, thereby increasing the overall efficiency and trustworthiness of the

monitoring process. The combination of advanced sensor technology, real-time data processing, and adaptive machine learning creates a robust and scalable solution that addresses the challenges of modern beekeeping, paving the way for more sustainable and data-driven apiculture practices.

Conclusion and Future work

The Beehive Condition Monitoring System offers a comprehensive Internet of Things solution for contemporary beekeeping. The beekeeper responds promptly to hive developments and keeps an eye on the beehive's vital environmental factors. Temperature, humidity, air quality, and sound sensors are all integrated into this system to monitor important real-time data about the productivity and well-being of the bee colonies. The Raspberry Pi Pico is the central component of the system; it processes data from those sensors, identifies significant occurrences, and initiates event recording in a MySQL database that is locally located to monitor trends and history. This would improve the potential capacity to discover patterns in such a system, provide a better understanding of the hive's long-term environment, and allow for the adjustment of reactions accordingly. By moving the processed data to the Blynk Cloud, the ESP32 microcontroller expands the capability. Beekeepers may view the data remotely using the Blynk application on their PCs or cellphones. An app may provide real-time updates on these changes, data trend analysis, and alerts for crucial circumstances, such temperature imbalances or strange bee noises that can indicate swarming or queen problems. In order to provide optimal circumstances for the hive, the beekeepers will be able to take proactive, data-driven measures. All things considered, the Beehive Condition Monitoring System offers a scalable and reasonably priced way to support sustainable beekeeping for improved colony production and health through effective bee population control.

The sensors that are implemented in current experimental setup does not include environmental pressure sensor. In future update it will be implemented. Also, the next update of the research will include the natural Bee hives of mangroves which definitely help natural hive eco-system to become free from any unusual natural occurrences and environmental hazards.

Author contribution

Conceptualization, methodology, software, Data curation, Writing original draft: Sakhawat Hossen Rakib. Review ML-based Bee data analysis: Md. Khairul Alam, all authors contributed to the article and approved the submitted version.

Funding source

No funds are received for this study.

Declaration of Competing Interest

The authors state that they have no known financial interests or personal relationships that could have influenced this study.

Ethics statements

The authors stated no ethical statement is required for this review article. The authors also declared no conflict of interest and none of the animal and/or human trials were included.

Acknowledgment

This study was supported by IRID of University of Asia Pacific. IEERD provided necessary software and research space. Real time bee hive setup was done in UAP rooftop.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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