Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 15 (1), June 2026, pp 141-148
ISSN 2147-3471 © 2026

IOT-Based Intelligent Beehive Monitoring System Using Acoustic and Environmental Analytics

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Accepted 30 May 2026

Abstract
In the article, an IOT-based intelligent beehive monitoring system is developed by integrating acoustic signal processing with environmental monitoring for non-invasive, continuous monitoring of the health and behavior of the beehive population. An ESP32 microcontroller is used to collect the acoustic signal from the beehive and environmental parameters such as microclimate, send the signals to the cloud server for feature extraction, and perform the required signal processing for feature extraction, such as FFT, MFCC, etc., and send the results to the cloud server for monitoring the beehive population and send alerts in case of any issues such as swarming, queen loss, disease-related stress, etc., in the beehive population. The results obtained by testing the proposed system in experimental beehives indicate that the proposed system is capable of monitoring the beehive population by identifying the acoustic signals and microclimate changes that occur in the beehive population before the actual issues arise, thereby reducing the need for invasive monitoring of the beehive population.

Keywords: *IOT, Intelligent Beehive Monitoring, Acoustic Analysis, Environmental Monitoring, Smart Agriculture, Precision Beekeeping, Machine Learning, FFT, Colony Health Detection, Real-Time Alert System.*

1. Introduction
The issue of beekeeping is significant to agriculture and environmental sustainability since honeybees play a significant role as pollinators and crop producers. Nevertheless, the manual observation of beehives is usually introduced in monitoring the health of the beehives, which is known to disrupt the bees in addition to failing to identify the early signs of issues in beehives, including swarming, queen bee loss, illnesses, or temperature variations[1-2]. In order to overcome these difficulties, the Intelligent Beehive Monitoring System based on the IOT and equipped with acoustic and environmental analytics is suggested. This system is deemed to be smart in the sense that it relies on sensors to gather environmental information like temperature and humidity, and microphones to gather the sounds that are made by honey bees [3]. It utilizes signal processing methods like FFT and machine learning methods to process the data and detect abnormal behavior of beehives. The information is then transferred to a cloud platform through the IOT technology which enables the real-time monitoring of the health of beehives and effective honey production [4-6].

The proposed system will be user friendly and easy to manage by the beekeeper. It is small and can be installed in the beehive or that of the bees and it does not cause a disturbance to the bees. The microcontroller upon completion of installation would automatically collect data and transmit them wirelessly on the Wi-Fi to the cloud server [7]. This is going to be displayed on the server in form of a dashboard with clear and graphic display. A computer or a smartphone will help the beekeeper to check the beehive wherever he or she goes [8-9]. Moreover, the system will automatically attract the attention of beekeeper in an event of abnormal temperatures detection, the humidity or sound pattern [10]. It is easy to maintain and will reduce the amount of manual intervention. It will overcome its need to have electricity to run as it will run on either battery or solar which will be applicable to remote rural areas.

2. IOT-Based Intelligent Beehive Monitoring System
The Internet of Things-Based Intelligent Beehive Monitoring System Using Acoustic and Environmental Analytics aims to monitor the health of honeybee colonies in a non-intrusive manner using

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intelligent methods. It uses Internet of Things devices such as temperature, humidity, gas sensors (CO_2), and a highly sensitive microphone to collect data from inside the beehive [11-12]. Audio data collected from the microphone is processed using signal processing techniques such as Fast Fourier Transform (FFT), which analyzes the variation in sound patterns that may indicate swarming, death of the queen bee, or any unusual behavior [13]. Environmental conditions, such as the temperature between 32-36°C and humidity between 50-70%, are also monitored to maintain the best conditions for the colony to thrive [15].

2.1. Abbreviations and Acronyms

AI (Artificial Intelligence), ML (Machine Learning), IOT (Internet of Things), FFT (Fast Fourier Transform), LSTM (Long Short-Term Memory), GCP (Google Cloud Platform).

2.2. Units

The system uses the International System of Units (SI) as a base for measurement.

- Temperature is measured in units of Celsius (°C).
- Relative humidity is measured in percentage (% RH.
- Sound frequency is measured in hertz (Hz).
- Gas concentration (CO_2) is measured in parts per million (ppm).
- Hive weight (if a load cell is used) is measured in kilograms (kg).
- English units may be provided in parentheses only .
- All numerical values are represented with a leading zero when decimal points are present (e.g., “0.25 Hz”).

2.3. Equations

The equations used in this system are related to acoustic signal processing and environmental monitoring.

Fast Fourier Transform:

$$X(f) = \Sigma\, x(n) * e^{(-j2\pi fn)}$$

Average Temperature:

$$T_{avg} = (T1 + T2 + \ldots + Tn) / n$$

Humidity Deviation:

$$\Delta H = H_{current} - H_{normal}$$

Acoustic Energy:

$$E = \Sigma\, |X(f)|^2$$

3. System Architecture

The system architecture of the beehive monitoring system is composed of many elements based on the IOT. These parts collect data and process them, sending it and giving an analysis of the information placed in the environment. It starts by having sensors which are mounted into the beehive or near the beehive. These are humidity sensors and temperature sensors. A microphone to record the sounds produced by the bees too.

These are the sensors that analyze the surroundings within the beehive on a constant basis. It is this minicomputer which constitutes the brain of the system. It processes the data slightly on the data collected by the sensors and translates the sounds of the bees into a digital format, thus capable of processing it further.

The little computer then sends the data through Wi-Fi to either a server or an internet of things platform. All the data that gets to the system is gathered in the cloud platform and analyzed with the assistance of such methods as Fast fourier Transform (FFT) and machine learning to figure out the patterns in the sounds of the bees and the environment that are not naturally occurring. This helps in determining what the bees are engaged in like whether they are about to swarm or whether the queen is missing or whether they are being harassed or something something that is wrong with the environment or whether the environment is okay.

The processed information is then shown in the site or a mobile app where persons that take care of the bees will have time to see what is happening in the beehive. They can see the temperature, the humidity and the bee activities. Upon detection of something abnormal by the system then it automatically sends a message to beekeeper. This would mean that the beekeeper has the benefit of checking up on the bees twenty four hours round the clock as well as not disturbing the bees in any way hence making the bees to be very healthy and easy to take care of. The smart beehive scanning system, which is based on the Internet of Things, does help in managing the health of the bee colonies and enhances the modern beekeeping.

3.1. Sensor Module

The sensor module captures the information of the beehive. It possesses such features as temperature sensors and humidity sensors to control the happenings in the hive. It also contains a microphone where one could hear the bees. These sensors will be used to monitor the hive and will not disturb the bees. They provide us with the news concerning bees healthiness, and their work.

3.2. Data Acquisition Module

The information is received in the data acquisition module in the sensor. It measures such variables as humidity and temperature. The sounds in the hive are captured in the microphone. Subsequently, it transforms this information into a digital form so that the system can make sense.

3.3. Processing Unit

The brain of the system is called processing unit. The sensors provide information which makes this thing cognizant of the fact that it is information and it is prepared to send. It ensures that the information of all the sensors is good and is good to be transported to the cloud.

3.4. Communication Module

Communication module assists the system to broadcast the information to a cloud or a server. It conveys the information in time via Wi-Fi. In this manner, persons who take care of the bees will be in a position to be aware of what is happening anywhere.

3.5. Cloud storage and Data analytics.

It is a module where the information in the hive is taken and embedded into a database. It employs a vehicle to study the noises produced by the bees. It even can be able to learn how to see whether the bees are behaving strangely. This assists in observing the issues such as the swarming of the bees, and the death of the queen bee.

3.6. Notification System and User Interface.

People who are serving the bees are the ones who observe what is happening in the user interface. They are able to utilize a web site or phone application. It informs them of what is going on in the hive at the time. When something goes wrong it gives them a signal to enable them assist the bees. They are depicted in the system by representing them with things, e.g. temperature and humidity in graphs. This shall cause them to take care of the bees.

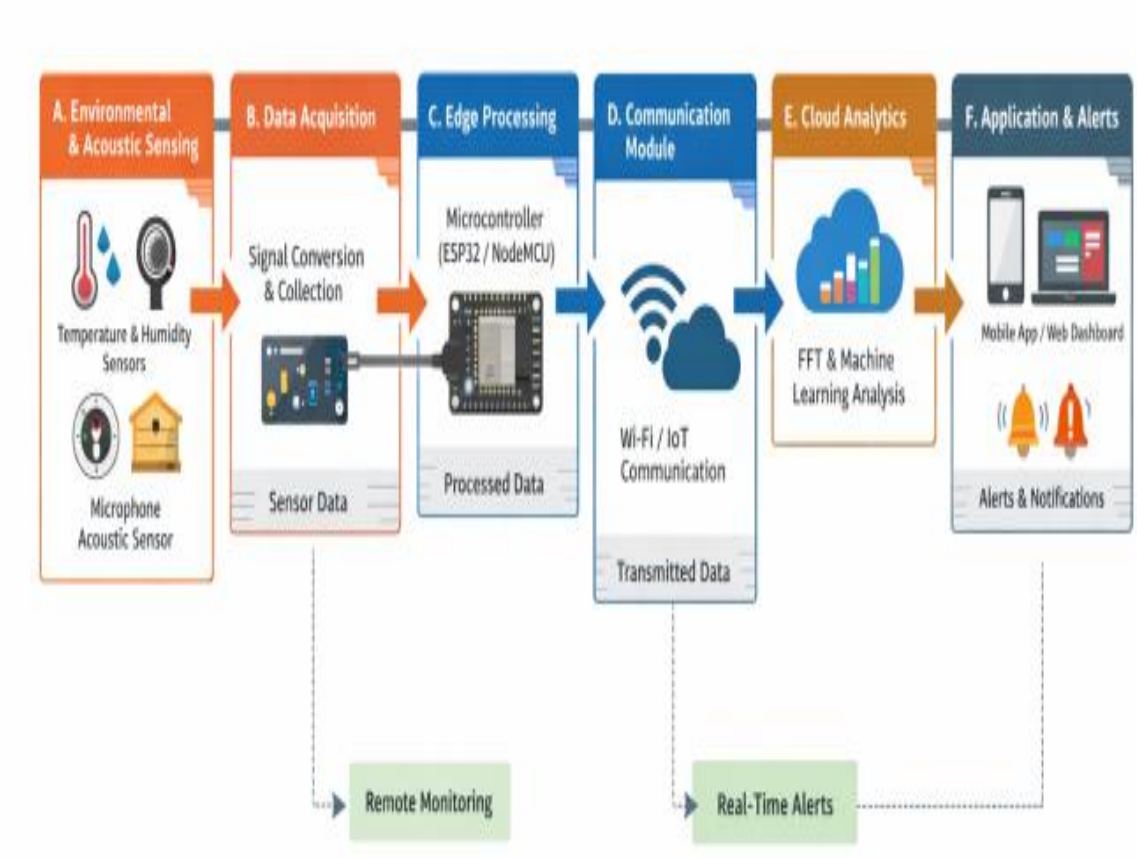

Figure.1: Architecture of IOT-Based Intelligent Beehive Monitoring System Using Acoustic and Environmental Analytics

Figure 1 (The Architecture of the IOT-Based Intelligent Beehive Monitoring System Using Acoustic and Environmental Analytics) demonstrates the space of the system of tracking the health and activity of a beehive with the help of sensors, data processing, and cloud technologies. The former has

environmental sensors, which can be used to gauge the temperature and the humidity of the surrounding of the hive and has a microphone sensor that has been captured to help in interpreting the buzzing of the bees. The sensor data acquired is then received and transformed to digital data to be processed. The information is filtered and formatted in a microcontroller such as ESP32 or NodeMCU which acts as the edge processing unit. The information under analysis is transmitted through the Wi-Fi and assisted by the IOT communication to the cloud system. More sophisticated algorithms, like Fast Fourier Transform (FFT) and machine learning, are used in the cloud to search acoustic and environmental data to detect the abnormal conditions of the hive like stress, swarming or temperature misbalance. Finally, the analyzed information is shown on a mobile application or a web dashboard, where beekeepers can observe the situation in the hives in real-time and receive an alert about some suspicious activity in the hive.

4. Methodology

4.1. Data Collection

The equipment like sensors is inserted or near the beehive. With such sensors we can have a clue of what is going on around us and how the bee sound like. We have temperature and humidity gauges which we check to check the activities in the hive. We are also equipped with a microphone sensor which we use to record the buzzing of the bees. These are continuously running sensors. Do not bother the bees.

4.2. Getting The Data Ready

We take the information from the sensors. Change it into a form that our system can understand. We organize the information about the environment and the sounds. This step makes sure that the information we get from the hive is correct and ready to use.

4.3. Making Sense of the Data

We use a computer like ESP32 or NodeMCU to process the information from the sensors. It does jobs like removing noise from the sounds and organizing the environmental information. This helps make the information better before we send it.

4.4. Sending the Data

After the small computer processes the information it sends it to a platform using Wi-Fi. This allows us to check the hive from using the internet.

4.5. Analyzing the Data

The hardware such as sensors will be placed or around the beehive. We are able to have an idea of what is happening around us and bee sound like with such sensors. We have temperature and humidity meters that we check so as to check what is going on in the hive. We also have a sensor of the microphone and we use it to record the buzzing of the bees. These are continuous running sensors. Do not bother the bees.

4.6. Watching and Getting Alerts

Lastly we present the information that was analyzed, in an application or web dashboard that the beekeeper can view the hive real time. In the event that the system detects something, it automatically sends notifications in order to allow the beekeeper to make appropriate interventions to ensure the survival of the bees and the hive. The bee data can enable the beekeeper to ensure that the bee colony is healthy and safe. The bee data are used with the system to assist the beekeeper in taking care of the bees.

5. Implementation and Results

5.1. Setting Up The Hardware

The temperature and humidity sensors are used to monitor the temperature and humidity in the hive. We also have a microphone sensor that we use to record the sounds that the bees make.We also use a microphone sensor to record the sounds the bees make. A small computer like ESP32 or NodeMCU. Controls all the sensors. We put the hardware together carefully so it does not bother the bees.

We make software to collect data from the sensors process it and send it to the internet. The small computer is programmed to read temperature, humidity and sound signals from the sensors. We use methods to remove noise from the sound signals. Then we send the cleaned up data to a cloud platform using Wi-Fi and communication rules.

We use a platform to store and manage the data from the beehive monitoring system. The temperature, humidity and sound data are sent to the cloud in time. We use math techniques like Fast Fourier Transform to analyze the sounds the bees make and see if the bees are behaving normally.

5.2. Testing Environment

We need to test the environment when we are working on the IOT-based beehive monitoring system. This is a step. We want to make sure that the sensors and devices that monitor the work correctly when they are actually in the beehive. So we attached sensors such as temperature sensor and humidity sensor in or around the beehive. These sensors are used to find out what is happening near the beehive. They send all the

information they receive to the microcontroller. Then it is uploaded to the cloud platform through a network.

Environment testing also enables us to view the functionality of the system in very hot or in very cold weather or in humid weather. We would like to know whether the system would be able to cope with such issues as noise of other objects that may influence it. We also wish to ensure that the wireless communication is stable and the sensors are working fast. We should also examine the power consumption of the devices. In case there is something wrong with the environment that the system is supposed to monitor, it should be able to provide the beekeeper with a warning. This testing ensures that the monitoring system is in good shape and provides us with information, concerning the environment. This assists us in caring about the beehive when the beehive is in actual use.

5.3. Results

- The beehive is always being watched by the system in time and it gives us the latest information about what is going on inside the hive. The system has sensors that get temperature, humidity and sound data from inside the beehive and all this information is shown on a dashboard that is easy to look at.
- When we listen to the sounds the bees make the system can find patterns in how the bees behave. These sound patterns help us figure out if the bees are doing okay. If they are stressed, getting ready to swarm or if something is wrong with the environment.
- The system is also linked to the internet which allows the beekeepers to monitor the beehive remotely with a phone or a computer. This also implies that the beekeepers do not need to visit the beehive frequently to inspect it and makes taking care of the beehive much easier.
- It also has a method to give warnings when anything was not right such as the sound the bees make was not normal or the environment was not favorable to the bees. These cautions assist the beekeepers to take immediate action to save the bees and ensure that the beehive is in good health. The beehive is extremely significant. The system enables us to take good care of the beehive and the bees, which are in the beehive.

5.4. Evaluation Metrics

- Evaluation metrics are used to observe the effectiveness of the beehive monitoring system we have based on intelligent means. These measures assist us in determining whether the system is effective in keeping track of what is transpiring in the surrounding and heed the hive sounds. Through observation, we can use the things to ascertain whether the system is effective in detecting bees that are not behaving normally changes in the environment, and the health of the entire colony. When we consider the system adequately then we can be certain that it provides the beekeepers with the information in good time.
- Accuracy: Evaluation metrics are used to observe the effectiveness of the beehive monitoring system we have based on intelligent means. These measures assist us in determining whether the system is effective in keeping track of what is transpiring in the surrounding and heed the hive sounds. Through observation, we can use the things to ascertain whether the system is effective in detecting bees that are not behaving normally changes in the environment, and the health of the entire colony
- Precision: This indicates whether the system is right when it discovers something that is out of the ordinary.
- Recall: This demonstrates whether the system is able to locate all the problems in the hive.
- F1-Score: This is a method of finding a compromise between precision and recall to know how much of what is occurring can be known by the system.
- Latency: This measure how long it takes for the sensor information to get from the hive to the cloud.
- Energy Efficiency: This examines the power consumption of the devices in the IOT so that we can be able to ensure that they are able to run on batteries or solar power
- Sensor Reliability: This checks if the sensors that measure things like temperature and humidity are working correctly and giving us the information.

All these evaluation metrics help us understand how well the intelligent beehive monitoring system works in life. We use these IOT-based beehives monitoring system metrics to make sure the system is working correctly and giving us the right information about the bees and the environment. The IOT-based intelligent beehive monitoring system is very important, for beekeepers.

Table 1. Table type styles

Parameter	Temperature Sensor	Humidity Sensor	Sound Sensor
Monitoring Type	Environmental	Environmental	Acoustic
Normal Range	32–36 °C	50–70 % RH	200–300 Hz
Purpose	Maintain hive temperature	Control hive moisture	Detect bee activity

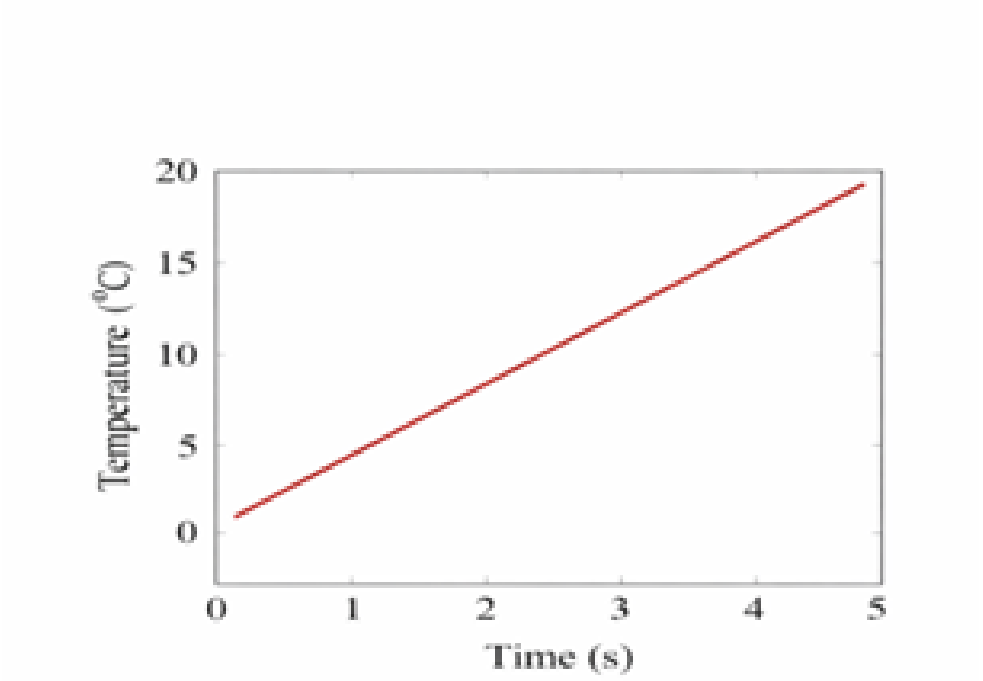

Figure 2. Example of a temperature measurement graph showing the relationship between Time (s) and Temperature (°C). The temperature increases linearly as time progresses.

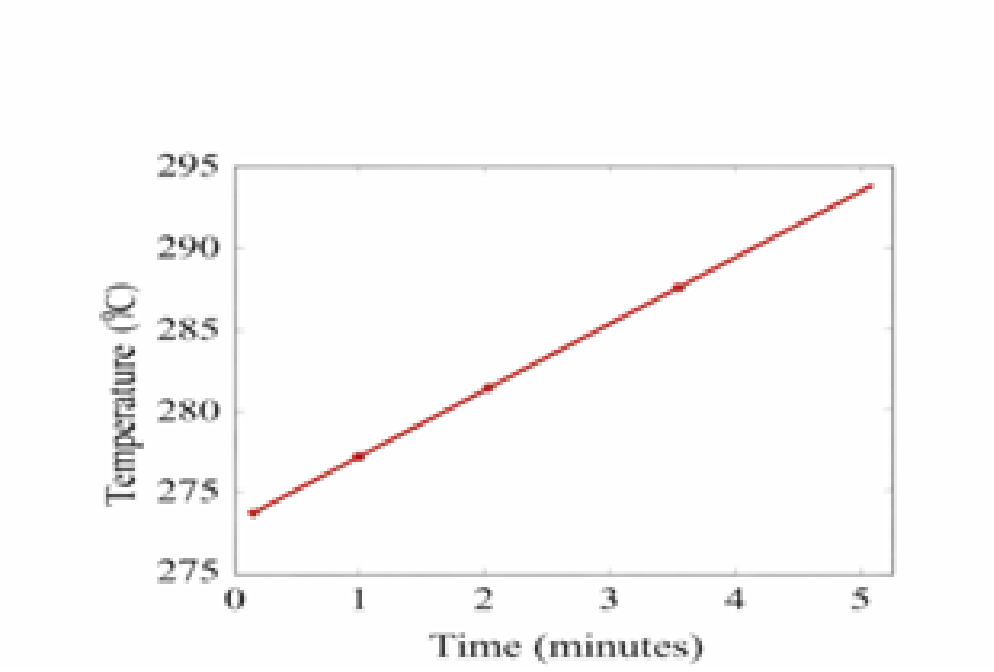

Figure 3. Real-Time Hive Temperature Data Visualization

6. Conclusions

6.1. Improvements over Conventional System

The Internet of Things based beehive monitoring system is a lot better than the old ways of taking care of bees. The old system mostly relies on people checking on the bees by hand which can bother the bees and might not find problems with the bees on. The new system is always watching what is going on in the hive and sends the information to the internet so the people who take care of the bees can check on them from away using a computer or a phone. The system also listens to the sounds the bees make to figure out if they're healthy or not. This way of watching the bees without disturbing them helps keep them healthy reduces the number of bees that die and helps the bees make honey.

6.2. Challenges Faced During Implementation

When we tried to make the system work we had some problems. A major issue was to ensure that the sensors were suitable even when it was hot or cold or when the hive was filled with a lot of dust. We could not hear the sound that the bees made as well since there were noises that interfered. We needed to learn how to make the system functionality without consuming a lot of power particularly where it was situated where power was not always available. Another thing we had to ensure was that the internet was performing well so that we could transfer the information to the computer. We had to adjust the sensors. How we approached the information in such a way that we were able to get the correct answers.

6.3. Future Enhancements

It is possible to complement the Internet of Things based beehive monitoring system with the addition of new technologies. There is a possibility that in the future we will have computer software which can learn and become better at understanding what the bees are up to and how healthy they are. It would also be possible to include sensors to obtain further information on what happens on the hive. Panels could be used to power the system hence it would be able to work even in a location where there is no power. Another thing we could do is create a phone application that transmits messages and pictures of what is happening in the hive and this would make the system easier to use by the people who attend to the bees. These modifications would enhance the system further and prove more useful, to people who are taking care of bees.

Acknowledgment

I would like to thank my project guide and the members of the faculty, who helped me a lot. They provided me with proper guidance and encouraged me throughout the working period on the project titled as IOT-Based Intelligent Beehive Monitoring System Using Acoustic and Environmental Analytics. I would also like to show my department and my institution that they provided me with the things that I required in order to complete the project of the IOT-Based Intelligent Beehive Monitoring System Using Acoustic and Environmental Analytics.

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