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RESEARCH ARTICLE - BEES

An IoT-Based Beehive Monitoring System for Real-Time Monitoring of *Apis cerana indica* Colonies

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Abstract

A study was conducted to monitor the bee activity in the colonies of different strengths in real time using an IoT-based device. The in-hive temperature and relative humidity were measured in the colonies of *Apis cerana indica* Fabricius of different strengths using the sensor-laden IoT device that was correlated with the movement of foragers into and out of the hive. A significantly higher movement of foragers was recorded at an in-hive temperature and relative humidity of 27.84 ºC and 61.47% at 5-6 p.m. with an observed activity of 9,638 bees/hive/hour in the strong colonies. In the weak colonies, the mean forager activity was 1,436.3 bees/hive/hour, which was recorded at an in-hive temperature of 26.52 ºC and 61.42% relative humidity. The mean honey area in the strong and weak colonies were 1,300.80±177.61 cm^2 and 508.80±156.84 cm^2, respectively. Pollen area in the strong and weak colonies were 447.60±112.08 cm^2 and 116.20±66.43 cm^2, respectively. In the strong and weak colonies, the area under egg brood was 470±53.06 cm^2 and 88.20±36.85 cm^2, larvae brood was 583.40±11.04 cm^2 and 80.00±24.67 cm^2 and sealed brood was 684.20±57.98 cm^2 and 102.80±16.59 cm^2, respectively. The real-time data on the movement of foragers in the colonies of different strengths enabled us to undertake timely intervention in the maintenance of the bee colonies.

Introduction

Honeybees belonging to the genus *Apis* are important pollinators of agricultural crops widely domesticated across the globe. Furthermore, honeybees have enormous economic importance due to the high value of apiculture products like honey, wax, and royal jelly (Klein et al., 2007; Hung et al., 2018). The strength and high honey productivity of a bee colony directly depend upon factors like the movement of foragers into and out of the hive that ensure a continuous resource flow (pollen/nectar) into the colony. Brood rearing and honey storage in a bee colony are largely dependent upon the quantum of resource flow that can be identified through the movement of the foragers (Gary, 1992).

In commercial apiaries with a greater number of bee colonies, monitoring the forager's movement in the colonies is a labor-intensive task that demands a constant engagement of trained manpower in the task (Cilia, 2019). In addition, physical hive inspection in apiaries causes frequent disturbances to the colony, and there are possibilities of the handling person getting stung by the bees if they are mishandled (Van Engelsdorp & Meixner, 2010). In addition to the bee sting, it is possible that there is a possibility of a few bees getting damaged in between the frames, killing the worker bees (Bencsik et al., 2015).

Colony division is an apiary management practice followed in commercial apiaries to increase the number of bee colonies for a productive and continuous harvest of hive products (Mythri et al., 2018). Newly divided bee colonies need utmost care and constant monitoring of comb health until complete establishment (Kastberger et al., 2009). As there is a lack of trained manpower in apiculture, there is an

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immense need to develop an automated system for monitoring the bee activity for the benefit of the beekeepers with a greater number of bee colonies in the apiary.

The need for beehive management innovation has attracted great attention to automated remote beehive monitoring research. For instance, beehive acoustic monitoring is emerging as a research field (Kulyukin, et al., 2018; Sharif et al., 2020; Abdolahi et al., 2022). The advent of the Internet of Things (IoT) has also prompted interest in exploring sensor-based beehive monitoring (Braga et. al., 2020; Cecchi et al., 2020; Hong et al., 2020). IoT-based beehive monitoring system is a remote sensing-based smart device that monitors in-hive parameters like colony strength, resource flow (pollen/honey) and bee movement could be monitored without the physical presence of the beekeeper in the apiary (Venkateswaran et al., 2019; Ntawuzumunsi et al., 2021). The system deploys in-hive sensors to deduct the physical parameters like prevailing temperature, relative humidity, and bee activity into and out of the hive (Cecchi et al., 2020). IoT-based beehive monitoring system is a concept of a new prototype proposed by the authors in this study that can directly benefit the beekeeping community. Automated monitoring of foragers' movement in the colonies can provide data that will aid the beekeepers in taking up timely hive management measures. With this background, the present study was proposed with an objective to develop an IoT-based bee-hive monitoring system, using sensor-based detection to facilitate automated monitoring of the bee movement in the colonies, inhive temperature, and relative humidity (parameters that influence the bee movement in colonies of different strengths), and to assess the stored reserves and brood area in the colonies based on real-time data, thus allowing timely interventions in the bee colonies.

Materials and Methods

Study Site

The experiment was conducted by placing the colonies of *Apis cerana* Fabricius in the farmers' fields in Bengaluru, Karnataka, India. The study was conducted during the months of January to April 2023. A uniform foraging source was maintained in the study site with the experimental colonies. The colonies were placed under the trees at about 0.5 km from agricultural fields planted with maize, *Zea mays* L. and pigeon pea, *Cajanus cajan* L. The common weed flora around the study location were *Alternanthera* sp, *Wedalia* sp, *Tridax procumbens* L., and *Parthenium hysterophorus* L.

Selection of bee colonies

Two treatments viz., strong colony and weak colony were selected. Five replicates/treatment were maintained. A bee colony having a brood chamber with all six frames filled with sufficient brood/pollen/nectar stored in the cells and hosting a high number of in-hive bees was considered a strong colony. On the other hand, a set of colonies having brood chambers with only two to three frames filled with brood/ pollen/nectar stored in the cells and hosting a comparatively lower number of in-hive bees was considered a weak colony.

Construction of IoT-based device

The proposed system block diagram for the IoT device is shown in Fig 1. The entire process was controlled by the ESP8266 controller with the help of a sensor connected to ports D5 and D6 (GPIO 14 and GPIO 12). The module used two types of sensors, one is the IR sensor and the other one is the DHT11 sensor. The IR sensor was used to sense the

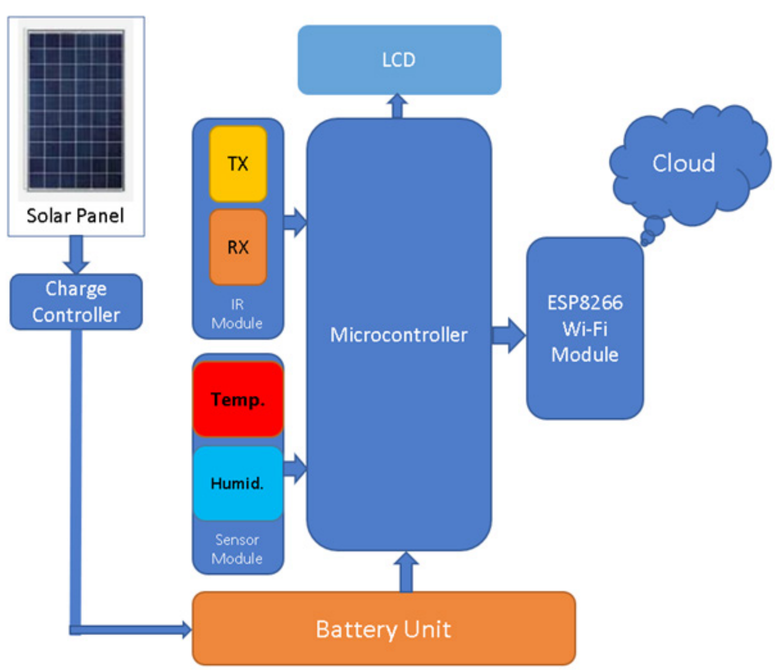

Fig 1. Block diagram of the IoT based system.

movement of the honeybees and record their count, whereas the DHT11 sensor was used to sense the temperature and humidity inside the beehive box.

The sensed data were converted from analog to digital using an ADC. An analog-to-digital converter (ADC) is a device that converts analog signals, such as voltage or current, into digital signals that can be processed by digital electronics. The process of converting an analog signal into a digital signal is called digitization, and it involves two main steps: sampling and quantization. The sensed data were sent to the cloud server using ThingSpeak software. ThingSpeak is open-source software written using Ruby programming language allowing users to enable IoT devices. ThingSpeak was launched by ioBridge Inc. in the year 2010 as a service of support in IoT Applications. It has integrated support with Matlab to analyze and visualize the data. ThingSpeak is a cross-platform operating system having a license version of GPL version 3. The entire unit was powered by Lithium-ion batteries. The batteries were charged using a 50 Watts solar panel.

The circuit diagram of the proposed system is given in Fig 2. The system was built on Atmega328P which was very popular with the Arduino series. Arduino was an open-source electronics platform based on easy-to-use hardware and software. It consists of a microcontroller board and a software development environment, which allows the user to create interactive electronic projects. The Arduino board serves as the brain of the project, and it can be programmed to perform various tasks based on the inputs it receives from sensors or other electronic components. The software development environment allows the user to write and upload code to the board, which can be written in C++ or a similar programming language.

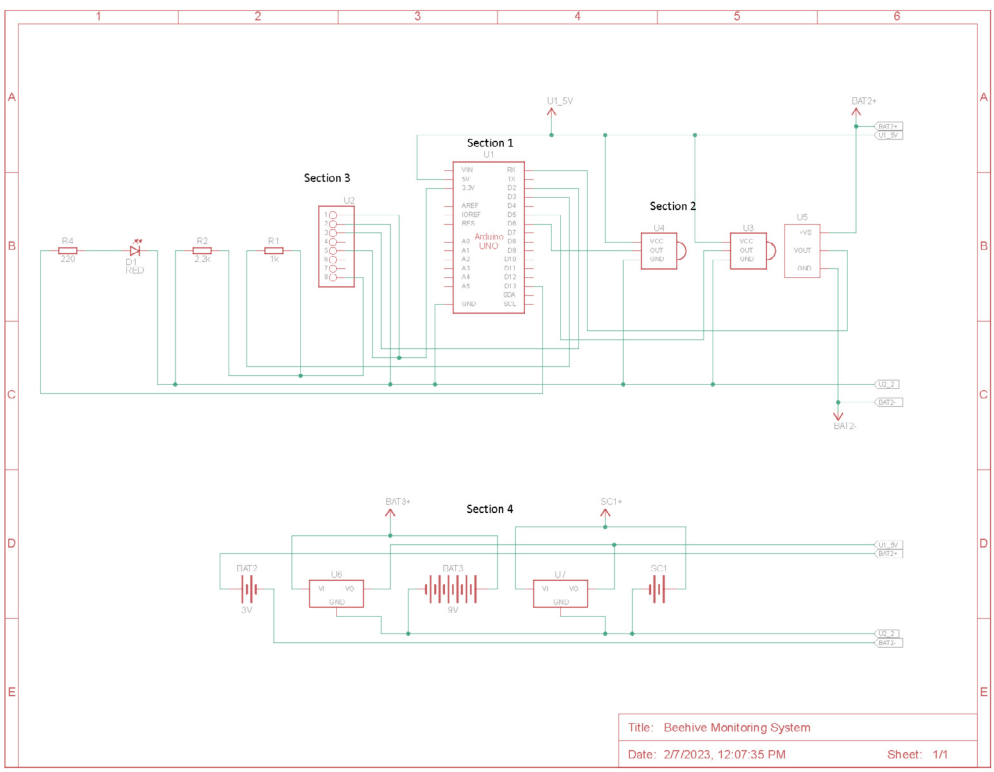

Fig 2. Circuit Diagram of the proposed experiment.

The system was connected to an infrared sensor to detect the events of bees entering and leaving the colony. Infrared sensors work by using a special detector, such as a thermopile or a photodiode, to sense the infrared radiation. The detector absorbed the radiation and produced an electrical signal proportional to the amount of radiation it received. This signal was then processed by the sensor's electronics to provide information about the presence or position of an object.

IoT-based observations on bee movement in the colonies

The IoT-based module was fitted at the nest entrance to facilitate the entry and exit of foragers into the colony. The integration of the IoT-based Beehive Monitoring System with the beehive box is given in Fig 3. After the integration of the prototype, the number of forager's movements (entry/exit) in strong and weak colonies was monitored. The physical parameters viz., in-hive temperature (ºC), and in-hive relative humidity (%) were also recorded. The activity of the foragers with respect to temperature and relative humidity in both the strong and weak colonies was monitored for a period of one month. We did a correlation between temperature and humidity parameters with respect to the bee activity.

Investigations on factors of bee health in the strong and weak colonies

In the colonies with lesser forager movement observed as per the output received from the IoT device, hive inspections were carried out to understand the cause for the lesser activity of the foragers. The frames were inspected for the presence of wax moth larvae or other pests' infestation. The brood area viz., egg, larvae, and sealed brood area (cm^2), the area covered by pollen cells, honey cells were quantified. The pollen and honey area in the combs was measured by placing a wire of 10 $inch^2$ on the top of the filled in cells on both sides of the comb. This was repeated in all the frames in the colony. The brood area viz., egg, larvae, and sealed brood in the combs were also measured in a similar way. The area measured in an inch square was converted into a centimeter square by making necessary conversions. After recording the hive parameters, necessary interventions were followed to revive the colony strength.

Fig 3. Integration of IoT based beehive monitoring system with bee hive box.

Fig 4. Bee entry and exit through the IoT device.

Data analysis

Analysis of variance (IBM SPSS Version 29) was used for data analysis. Data on bee activity was transformed to log 10 and the normalized values ranging from 0.90 to 3.99 were obtained. GLM univariate analysis was done using three factors (independent variables) Temperature (random factor), Humidity (random factor), and colony strength (fixed factor) to explain the bee foraging activity (dependent variable). The normality of residuals was checked using the Q-Q Plot analysis. Analysis of variance (IBM SPSS Version 29) was used to compare the honey, pollen area (cm^2), and brood area (egg, larvae, sealed brood in cm^2) in both the strong and weak colonies. Where significant difference was detected, treatment means were separated using Tukey's HSD Test (0.05%).

Results

IoT-based measurement of temperature and relative humidity vs. bee activity in strong and weak colonies

The foragers were observed to move freely without any hindrance into and out of the colony through the IoT device placed at the bee entrance in the hive (Figs 4 and 5). Fig 6 represents a linearity between the temperature with respect to bee foraging activity and the bee foraging activity gradually increasing with respect to the increase in temperature. The peak activity of the bees was recorded at a temperature between 26.1 ºC to 28.5 ºC. Bee foraging activity is optimal at moderate temperatures. With respect to relative humidity (Fig 7), linearity was observed between the humidity and bee foraging activity. Bee foraging activity gradually decreases with respect to an increase in humidity. Peak bee foraging activity was observed at a humidity level between 44%-63% followed by a sudden decrease in activity after 64% relative humidity. The bee foraging activity was more in the strong colony compared to the weak colony (Fig 8). In the weak colonies, the bee foraging activity decreased with a rise in relative humidity (67%) and low temperature (31 ºC). In the strong colonies, a similar trend of decreased bee foraging activity with the rise in humidity was observed but the bee activity increased at moderate to high-temperature conditions (26.7 ºC to 28.5 ºC) (Figs 9-12).

Fig 5. Forager carrying pollen resource entering the hive.

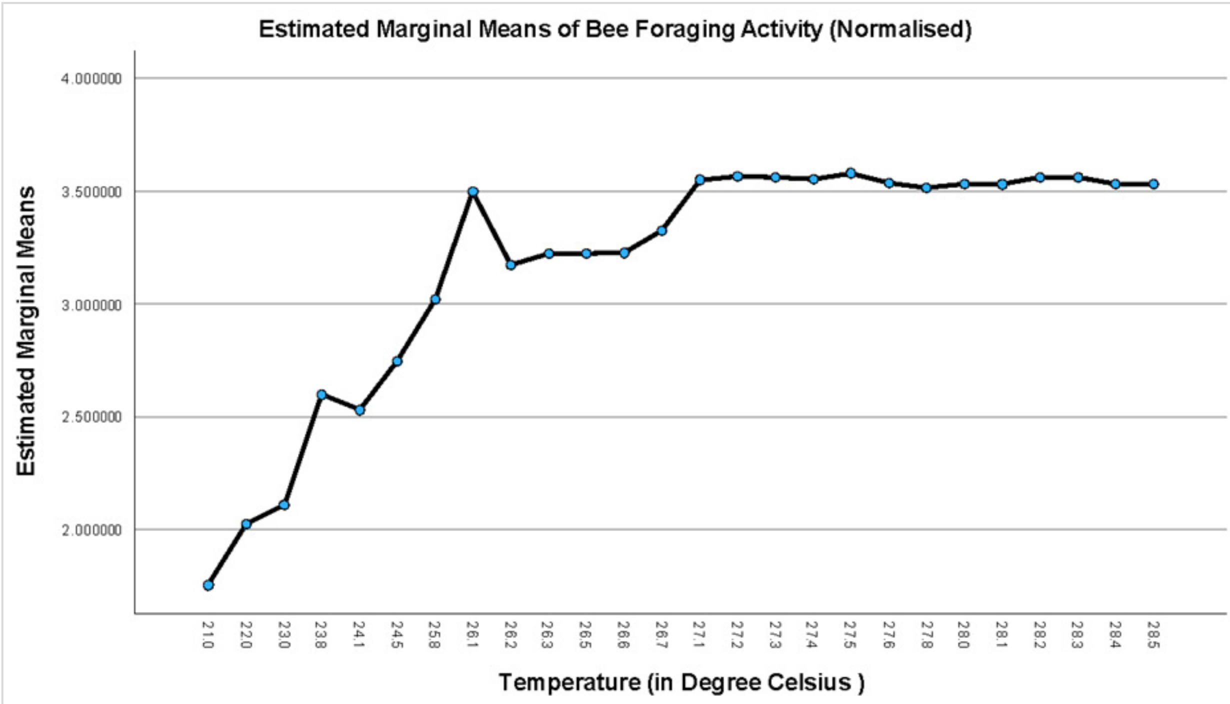

Fig 6. Estimated means of bee foraging activity with respect to temperature.

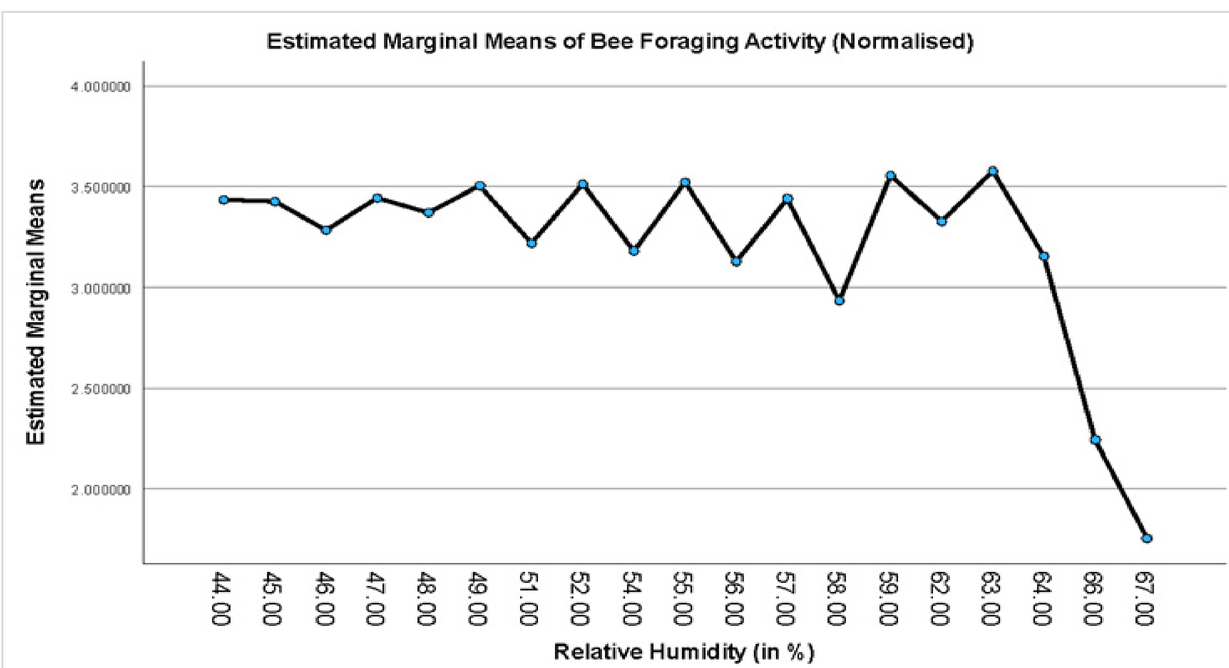

Fig 7. Estimated means of Bee Foraging Activity with respect to Relative Humidity.

In the present study, there was a significant variance between the predictors (colony strength, relative humidity, temperature) variance for the dependent variable foraging activity and the regression model was significant and the F value (3,1442) under degrees of freedom for regression and residual is 2.61 and the observed F value for the same is 10,395.32 which shows the model was statistically significant. From the model summary table, R^2 value is 0.956, once again showing that the overall regression analysis was statistically significant. The normality check for the bee foraging activity is given in Fig 13 e 14.

Investigations on factors of bee health in the strong and weak colonies

There was a significant difference in the honey area (cm^2) between the strong and weak colonies (F value = 51.57; P < 0.0001) (Fig 15). The mean honey area in the strong and weak colonies were 1300.80 ± 177.61 cm^2 and 508.80 ± 156.84 cm^2 respectively. The pollen area in the brood chamber differed significantly between the two colonies ie. strong and weak colonies (F value = 45.43; $P < 0.0001$). The pollen area in the strong and weak colonies were 447.60 ± 112.08 cm^2 and 116.20 ± 66.43 cm^2, respectively. There was a significant difference in the quantum of sealed brood between the strong and weak colonies (F value = 38.78; $P < 0.0001$). In the strong and weak colonies, the sealed brood area was 684.20 ± 57.98 cm^2 and 102.80 ± 16.59 cm^2 respectively.

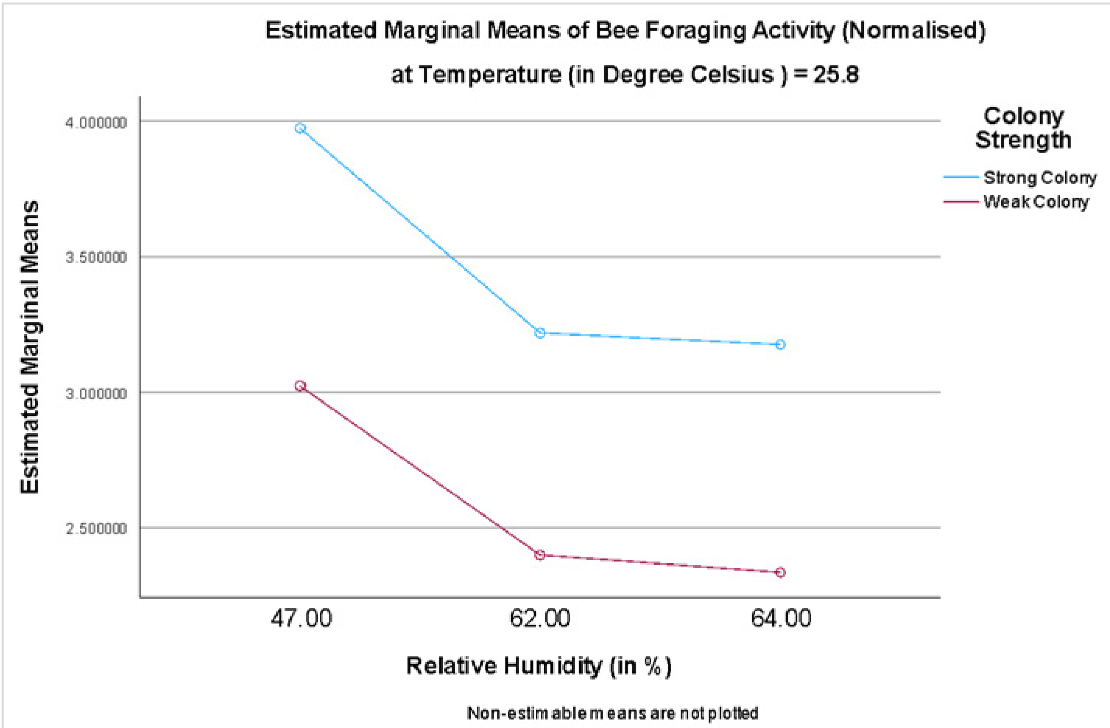

Fig 8. Relative Humidity Vs Estimated Marginal Means Vs Colony strength.

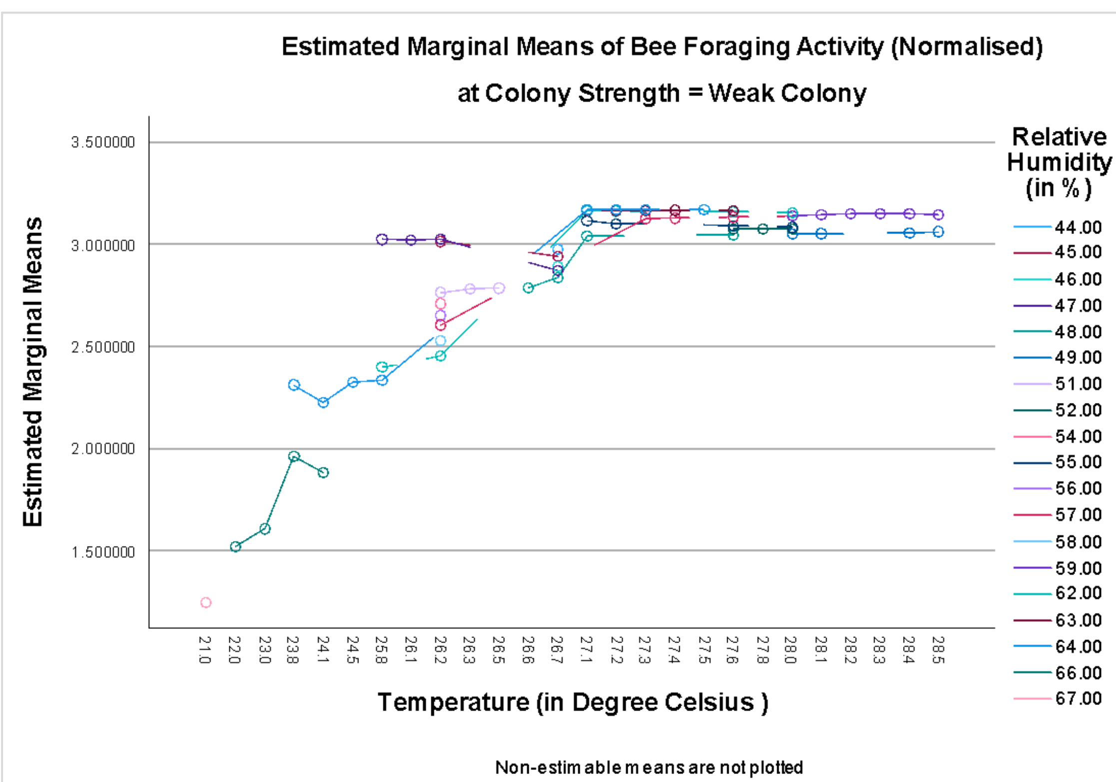

Fig 9. Estimated Marginal Means of Bee activity Vs Temperature Vs Humidity in Weak colony.

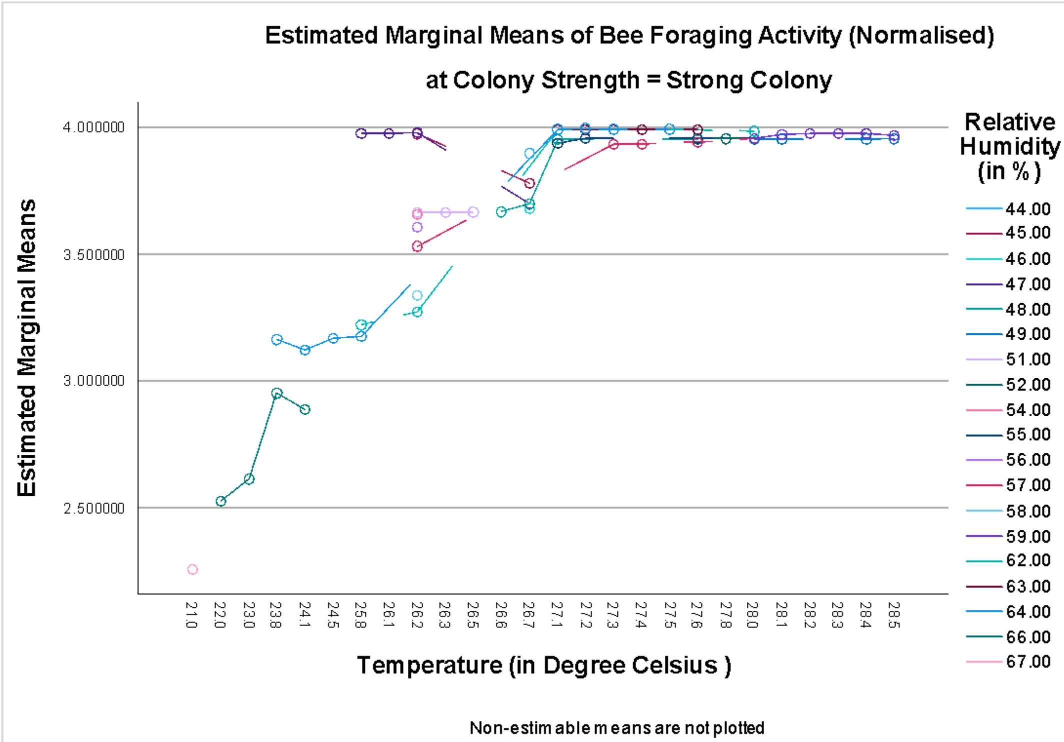

Fig 10. Estimated Marginal Means of Bee activity Vs Temperature Vs Humidity in Strong colony.

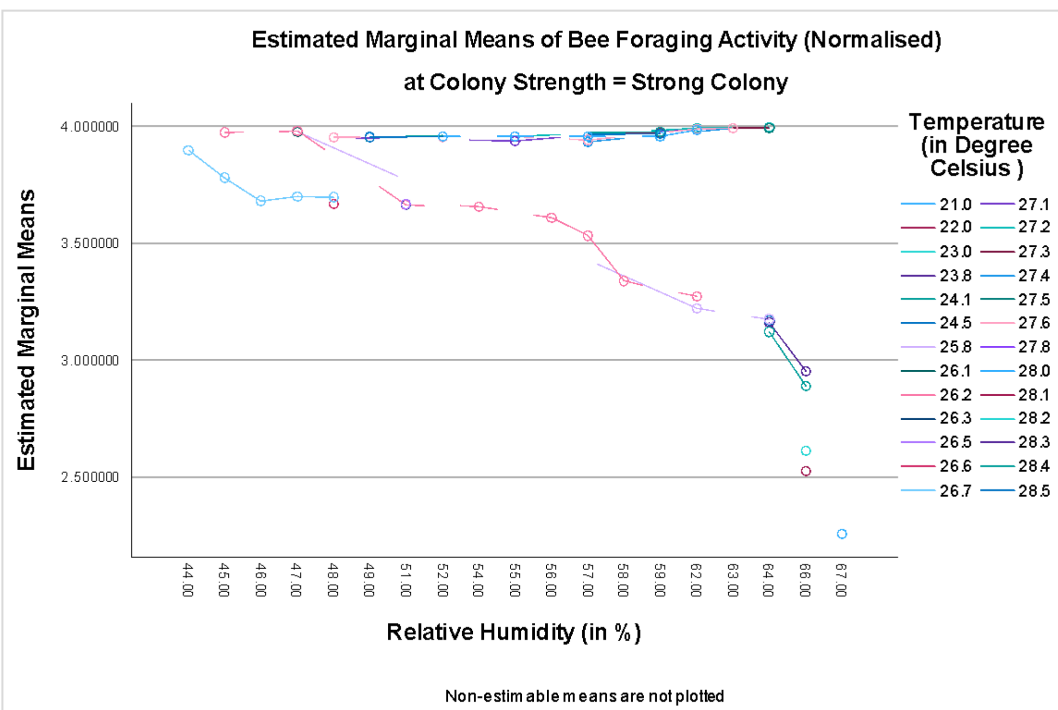

Fig 11. Estimated Marginal Means of Bee foraging activity Vs Humidity Vs Temperature in Weak colony.

A significant difference in the proportion of comb area under egg (F value = 69.47; P < 0.0001) and larvae (F value = 81.87; P < 0.0001) was observed between the strong and weak colonies (Fig 16). The mean comb area with egg in the strong and weak colonies were 470 ± 53.06 cm^2 and 88.20 ± 36.85 cm^2, respectively. In the strong and weak colonies, the mean larval brood area was 583.4 ± 11.04 cm^2 and 80 ± 24.67 cm^2, respectively.

Discussion

In the current study, the forager movement into and out of the strong as well as the weak colony with respect to temperature and relative humidity levels were monitored. In the current study, the maximum bee activity was recorded at an in-hive temperature above 25 ºC in both the strong and weak colonies.

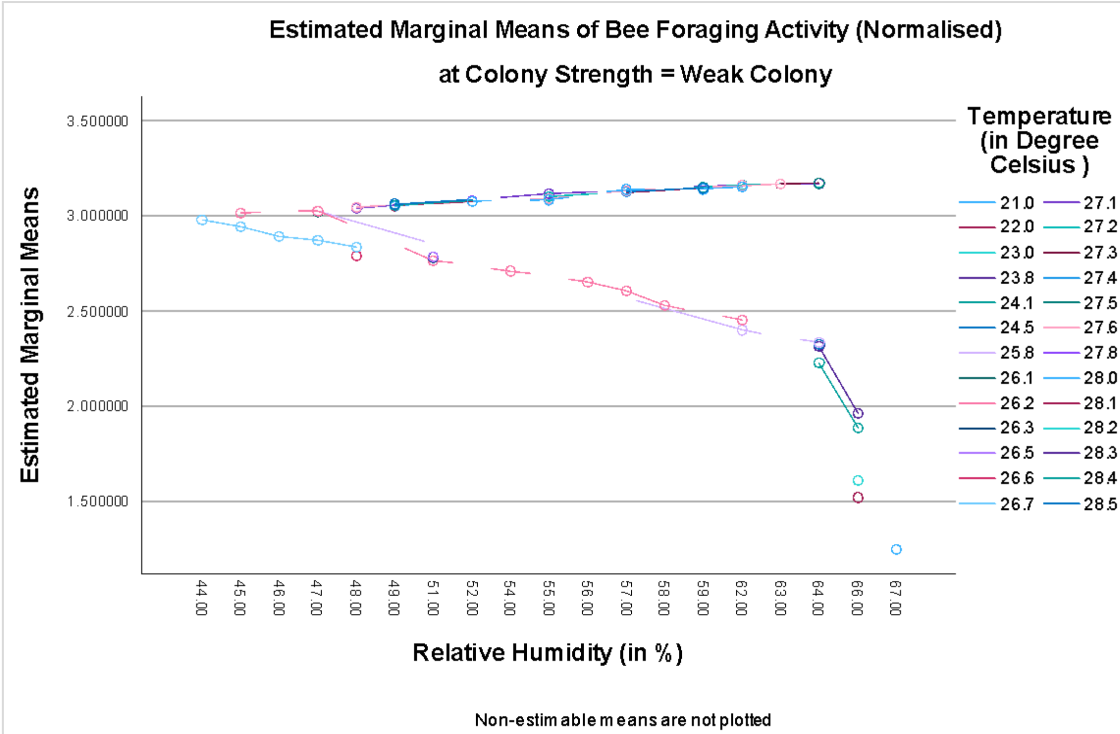

Fig 12. Estimated Marginal Means of Bee foraging activity Vs Humidity Vs Temperature in Week colony.

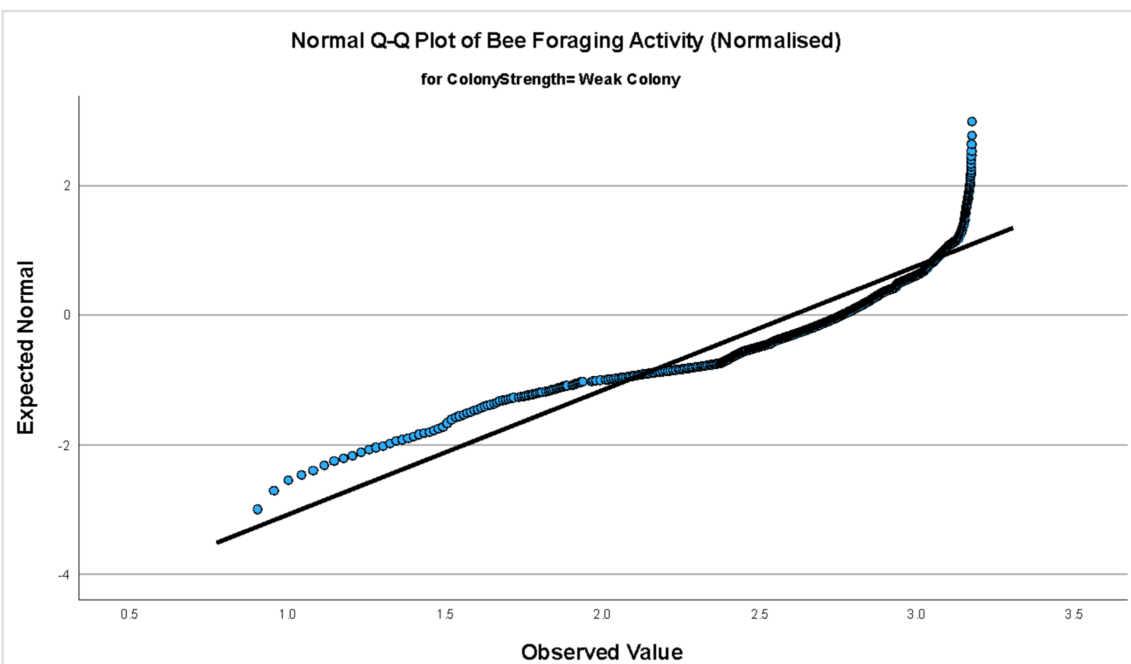

Fig 13. Q-Q Plot of bee foraging activity in weak colony.

The maximum in-hive temperature in the present study was 27 ºC in the strong colonies and 30 ºC in the weak colonies which recorded the maximum activity of the foragers. The results slightly differed from the observations recorded by Morammazi (2019) who reported that the maximum flight of *Apis mellifera* was recorded at an in-hive temperature of 35-36 ºC. The reason might be due to the in-hive temperature, foraging flights might vary with respect to the fanning ability of the bee species, location, and forage source. *A. mellifera* being a robust species of bee compared to *A. cerana* could also be a reason for the tolerance for a relatively higher range of in-hive temperatures during the foraging period. Seeley (1985) reported that 20-28 ºC was observed to be optimum for foraging of pollen and honey in *Apis* sp. Under higher in-hive temperatures, the percentage of bees devoted to foraging tasks will be relatively lesser as the majority of the workers will be engaged in the hive cooling task to maintain the inside hive temperature (Jarimi et al., 2020).

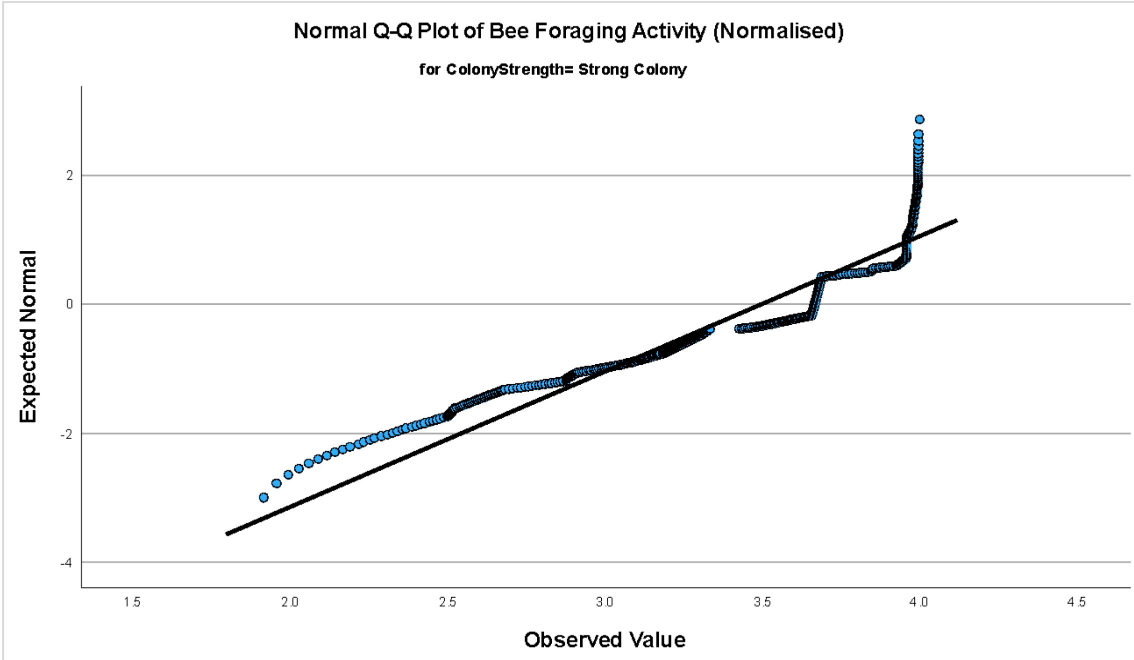

Fig 14. Q-Q Plot of bee foraging activity in strong colony.

With respect to the relative humidity, the movement of foragers was observed to be significantly greater between 48 to 60% RH in both the strong and weak colonies. Several abiotic factors like temperature, relative humidity, rainfall, and wind speed have a direct influence on the foraging activity and colony development of honeybees (Kovac & Stabentheiner, 2011). Relative humidity could be easily maintained by the worker bees in the hive. The humidity factor is very important for the rearing of the brood, and at times of low RH water evaporation in the stored honey cells gets accelerated which results in more water foraging by the bees (Human et al., 2006). In the strong colony, the number of foragers in the foraging task was significantly higher compared to the weak colonies. This might be due to the availability of a lesser number of bees that were taking up the in-hive duties like tending the broods, hive cleaning, etc., compared to the quantum of bees devoted to the foraging activity. The movement of foragers is an important factor that

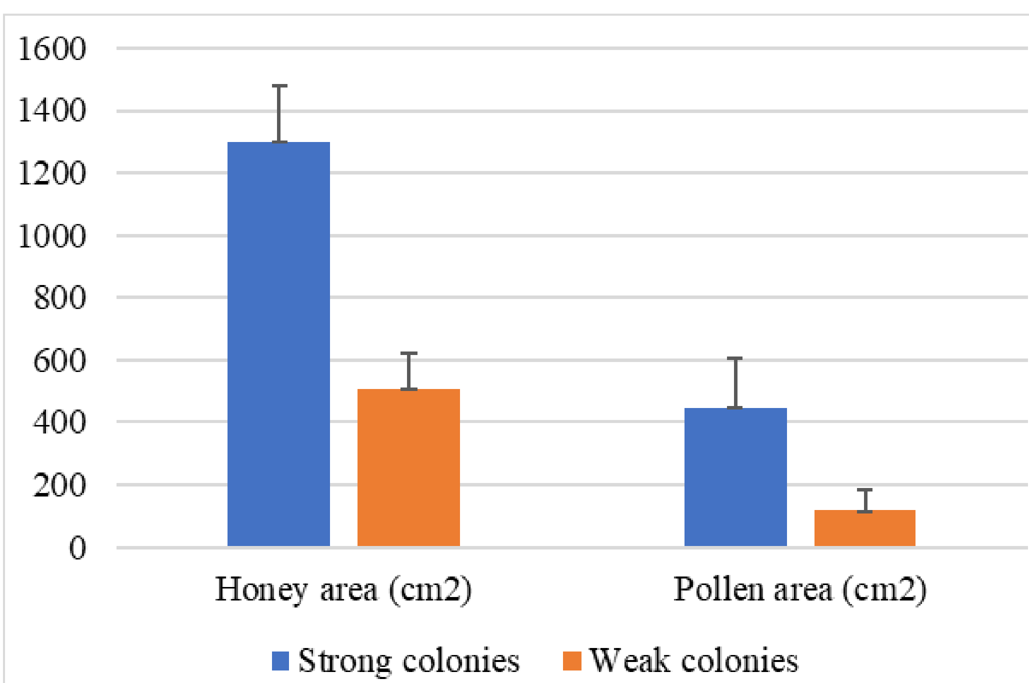

Fig 15. Storage reserve in the strong and weak colonies.

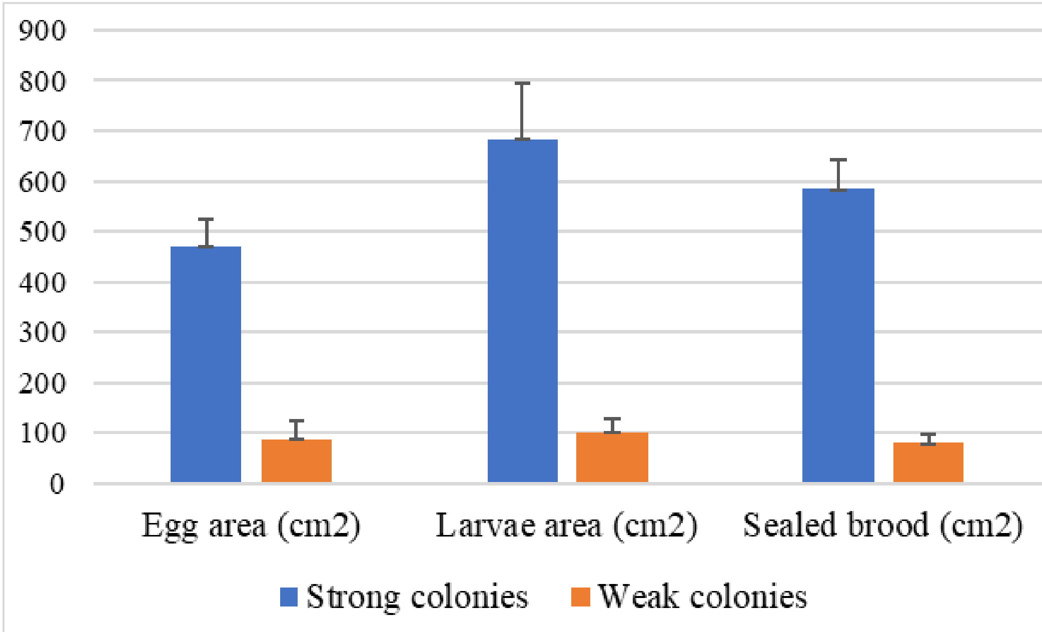

Fig16. Brood area (cm^2) in the strong and weak colonies.

dictates the strength of the bee colony which is influenced by parameters like pollen and nectar availability and climatic factors in the locality (Gregorc & Lokar, 2010).

The stored reserves (pollen/honey) and brood area in the colonies were less in the colonies with the relatively lesser movement of foragers indicating the authors to watch and ward the colonies on a regular basis. The reason for the low stored reserves in the weak colonies could be directly due to the lower number of resources carrying foragers inside the colony. The mean area of brood, honey, and pollen in the strong colonies was significantly higher compared to the weak colonies. On the other hand, the strong colonies with fairly a great number of forager's movement had larger quantities of storage reserve and mixed brood stages coupled with honey filling in the super chambers. Brood-rearing activity is a direct measure of comb area under egg, larvae, and pupae in addition to pollen and honey-filled cells which is a vital factor of colony development (Manoj et al., 2017). Regular monitoring of the weak bee colonies for movement of foragers is of vital importance as *Apis cerana indica* is a species more prone to absconding during times of less resources in the colony and at times of pest infestation in the colony (Kafle, 1985). Frequent physical disturbances, lack of pollen/nectar resources in the colony, and pest and disease attacks are the crucial factors attributed to the absconding behavior in the colonies of *Apis cerana* (Pokhrel et al., 2006). Based on the data on less activity of the foragers, the colonies with less brood were physically inspected and examined for the volume of the brood in the colonies. The colonies with the lowest volume of brood were supplied with additional frames with mixed stages of egg, larvae, and sealed brood to encourage more pollen foragers in the colonies. Honey syrup feeding was given as supplementation to weak colonies to encourage the foragers for pollen collection and build up the rearing of broods in the comb. Feeding sugar syrup in the bee colonies to encourage the pollen foragers as a measure to manage the bee colonies was reported by Goodwin (2015).

Conclusion

The present study is a first-ever attempt to monitor the bee-hive parameters through an automated IoT-based module in India. Using the device, the bee activity was successfully studied on a real-time basis without physical hive inspection. The influence of the abiotic parameters viz., inhive temperature and relative humidity over the bee activity were precisely measured using the IoT-based hive monitoring device. The bee movement measured through the IoT-based device aided the authors in inspecting the stored reserves and brood area in the colonies and undertaking needed interventions for the maintenance of the colonies.

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Authors' Contributions

VNK: conceptualization, methodology, investigation, formal analysis, writing - original draft.
SN: Resources (designed the IoT device and conducted the calibrations), writing: review & editing.
NL: Resources (designed the IoT device and conducted the calibrations). writing: review & editing.

Competing Interests

Authors hereby declare no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

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