Chapter 15

Artificial Intelligence-Based Beehive Monitoring Systems in Modern Beekeeping

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Abstract

Honeybees play a vital role in maintaining the balance of ecosystems and supporting human life. Their primary contribution is pollination, which enhances agricultural productivity and biodiversity. Additionally, they produce valuable natural products such as honey, royal jelly, and propolis, which have nutritional and medicinal benefits. In recent years, increasing threats to bee populations have emphasized the need for improved beekeeping practices that ensure both the conservation of bees and the efficiency of hive management. Traditional beekeeping methods, while effective, are often labor-intensive and time-consuming. In contrast, precision beekeeping also known as smart beekeeping integrates technology to monitor and manage hives more efficiently. Artificial intelligence (AI)-based hive monitoring systems have emerged as powerful tools in this field. These systems use sensors and AI algorithms to collect and analyze data on temperature, humidity, bee activity, sound, and other environmental factors. They enable early detection of diseases, swarming, or other threats, allowing beekeepers to take timely action. Over the past decade, many studies have explored the use of machine learning and deep learning techniques in these systems. This chapter aims to provide a comprehensive overview of recent advancements and emerging trends in AI-supported hive monitoring, offering valuable insights to guide future research and technological innovation in modern beekeeping practices.

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1. Introduction

Honeybees are among the important living groups that maintain balance in the ecosystem. These bees are primary pollinators among plant species. Moreover, honeybees hold a significant position economically, socially, and culturally because they contribute positively to food security, production, and pollination (Kayişoğlu & Türksoy, 2023). Honeybees naturally live in colonies. Bee colonies produce beneficial nutrients such as honey, propolis, royal jelly, beeswax, and pollen (Mutlu, Akbulut, Aydın, & Mutlu, 2023). Honey is highly beneficial for health because it contains valuable minerals like calcium and magnesium (Budak, 2023). Therefore, the demand for bees and bee products is increasing worldwide, leading to a rapidly growing business sector in this field (Çalışan, Balat, & Yavuz, 2022).

Beekeeping has always been one of the most important agricultural activities contributing to the economy. According to data from the Food and Agriculture Organization of the United Nations (FAO, 2024), our country ranks among the top in the world in honey production. Beekeeping is practiced commercially in our country, but also as a hobby to meet natural food needs. The beekeeping sector has important advantages such as being able to operate with small capital and generating income within one year. The amount of honey produced in beekeeping is not solely related to the number of colonies. For example, although Turkey ranks among the top countries in terms of bee colonies and honey production, it does not show the same success in honey yield per colony. The main reasons for this failure are unconscious production processes, environmental effects, and various diseases in the colonies (Kutlu & Kılıç, 2020). In this area, productivity can be increased by methods such as controlling knowledge, experience, and environmental conditions.

Bee species conservation can be done by classical or modern beekeeping methods. Classical methods require high labor and costs. Modern beekeeping methods aim to increase productivity and quality while reducing costs. Modern beekeeping methods also appear as precision beekeeping technology. Precision beekeeping involves the electronic monitoring and tracking of honeybees' roles and functions in nature, such as honey production and life cycles. The most commonly used methods in precision beekeeping are bee hive monitoring systems that include artificial intelligence-based machine learning and deep learning methods.

Hive monitoring systems and machine learning algorithms are becoming increasingly important for bee production and behavior. Hive monitoring systems consist of data collection and data analysis sections. Bee monitoring and tracking systems are important for assessing colony health and increasing production efficiency. Sensors, cameras, and Global Positioning System (GPS) devices are used to collect data on bee behaviors. Machine learning algorithms are used to define bee behavior patterns and detect anomalies. For example, image processing algorithms can detect abnormalities on bees' bodies. Machine learning algorithms can be used to increase hive efficiency. Additionally, data analysis can be performed to determine the timing of nectar collection and the most productive areas. By using machine learning algorithms, relationships can be established between bee movement data inside the hive and colony health and production performance (Zacepins, Brusbardis, Meitalovs, & Stalidzans, 2015).

To ensure quality and efficient honey production, regular inspection of hives is necessary. Environmental factors such as temperature, humidity, wind, wild animal attacks, and parasites like varroa negatively affect hives and reduce yield. Regular monitoring of hives against these factors can be easily achieved using information technology-based devices. Data can be collected to evaluate some conditions occurring in hives and analyzed using machine learning methods. Images can be collected to detect diseases such as varroa. In this way, information about the most productive conditions for honey production can be obtained. With the development of Internet of Things (IoT) technology, the number of sensors is increasing, enabling more data collection and more accurate analyses.

Bees produce sounds at different frequency ranges depending on various activities (Hadjur, Ammar, & Lefèvre, 2022). Classification studies can be performed using machine learning methods based on these sound frequencies. The number of bees or the status of the hive can be monitored by images taken from around or the entrance of the hive. AI-based applications are important in beekeeping, allowing the examination of many characteristics affecting the basic structure of the hive such as the queen bee, nectar level, feeding, and swarming (Güler; Zacepins et al., 2015). Bee colonies face environmental factors, parasites, and problems like Colony Collapse Disorder (CCD) that negatively affect their survival. Important threats to bees include CCD, varroa parasite, habitat degradation, and genetic species factors (Dimitrijević & Zogović, 2022). These problems in bees cause reduced production in the food chain, negatively impacting global economies. Today, beekeepers develop various methods such as bee hive monitoring to combat negative situations like hive theft, colony health problems (CCD, parasites), and weather conditions (Meikle & Holst, 2015). To accurately determine the parasite load of bee colonies, it is statistically necessary to test at least 300 bee individuals (Lee, Moon, Burkness, Hutchison, & Spivak, 2010). Manual performance of these processes is prone to error and time-consuming. Technology-based applications can perform these processes in a shorter time.

Nowadays, problems that were previously difficult to solve, such as classification and pattern recognition, are solved more easily. Time and economic savings in analyses are also highlighted. Artificial intelligence applications provide significant savings in this regard. Classification applications are used in tasks such as counting bees, determining pollen status, detecting pests and diseases like varroa, and providing suitable environmental conditions for bees.

Artificial intelligence includes many subfields. Machine learning is a subfield of artificial intelligence, and deep learning is a subfield of machine learning. Machine learning automates the model creation process by enabling systems to learn from training data to solve tasks in computer science. It is also described as imparting learning ability to computers. There is no single best algorithm to solve a problem. The algorithm's performance is affected positively or negatively by many features such as problem type, number, and variable ratio (Mahesh, 2020). Large amounts of input data are not necessarily required to perform analysis with machine learning. Data are labeled by experts according to their class. Preprocessing such as rotation, scaling, and filtering may be necessary to handle missing or inconsistent data. Data augmentation techniques increase data quantity and improve learning outcomes, thereby enhancing model robustness. Adequate knowledge about observed data is essential.

Deep learning consists of neural networks with many layers and parameters (Shinde & Shah, 2018). It is a concept within machine learning based on Artificial Neural Networks (ANN) methods (Janiesch, Zschech, & Heinrich, 2021). In many studies, deep learning approaches produce better results than traditional machine learning methods. Its greatest advantage is good performance with high-dimensional data. The biggest disadvantage of deep learning is the high computational requirement. Today, improvements in Graphics Processing Unit (GPU) performance largely eliminate this disadvantage.

Traditional machine learning approaches are less universal and more complex than Convolutional Neural Network (CNN)-based architectures, which are a type of deep learning. In traditional methods, object detection or classification is divided into individual stages. The first stage is computer vision, and the second is the machine learning algorithm. CNN is a special type of supervised machine learning algorithm. Its use increased in computer vision after its performance in the 2012 ImageNet competition (Bilik et al., 2024). It can easily classify objects without requiring preprocessing. It allows the use of pre-trained networks for general problems.

One of the important fields enabling the increased use of AI-based applications in the beekeeping sector is IoT technology. IoT technology is defined as the exchange of data between objects over the internet. It enables machine-to-machine communication (M2M) (Zikria, Ali, Afzal, & Kim, 2021). In beekeeping, IoT technology allows data collection from hives such as temperature, humidity, and images through sensors, enabling AI-supported analysis or real-time control systems.

Nowadays, modern beekeeping applications have become an important area for monitoring hive conditions automatically, thereby increasing production and yield. However, beekeepers often lack sufficient knowledge about automatic hive monitoring systems. This section aims to inform beekeepers about modern beekeeping and discuss studies in this field. Examples are provided regarding the use of IoT sensors in monitoring bee behavior and how data collected from hives via these sensors are analyzed using AI-based algorithms.

2. Literature Review

Precision beekeeping is an advanced agricultural field that optimizes hive productivity using digital infrastructure. At both hive and colony levels, it aims to maximize efficiency while minimizing resource consumption. The digitalization of the beekeeping sector began with the development of sensors in the field of IoT and the collection of data. In studies related to beekeeping, the most commonly used data come from sensors related to image (Tashakkori, Hamza, & Crawford, 2021; Wachowicz, Pytlik, Małysiak-Mrozek, Tokarz, & Mrozek, 2022), sound (Nolasco & Benetos, 2018), and temperature (Mahamud et al., 2019; Zacepins, Kviesis, Pecka, & Osadcuks, 2017). These are valuable because bees within the hive produce different sound frequencies depending on conditions such as the absence of a queen, swarming, or emergence of a new queen (Truong et al., 2023). In addition, high temperatures and humidity inside hives adversely affect honey production and yield. Therefore, determining optimal environmental conditions based on this data is essential (Wardhany, Hidayat, & Jhoswanda, 2020).

According to the literature, a study on smart bee health monitoring systems for improving honey production emphasized the importance of maintaining hives in good condition for bee activity (Yusof, Billah, Kadir, Ali, & Ahmad, 2019). Stingless bees are very sensitive to environmental changes. In the study, hives were monitored using sensors measuring temperature, humidity, carbon dioxide (CO_2) levels, and hive weight. These were tracked in real-time via IoT technology.

According to a study in the literature, significant challenges have been identified in automatically detecting the status and health of bee colonies within the scope of precision beekeeping (Robles-Guerrero, Saucedo-Anaya, Guerrero-Mendez, Gómez-Jiménez, & Navarro-Solís, 2023). The study aimed to reduce power consumption in automated monitoring systems, extend battery life, and monitor colony stress to prevent yield losses. Since many hives are located in remote areas with limited access to electricity, solar energy is needed. The choice of power model positively affected battery life. Machine learning methods including Logistic Regression (LR), Support Vector Machines (SVM), Random Forest (RF), K-Nearest Neighbors (KNN), and Neural Networks (NN) were evaluated for computational requirements and execution performance. Model performance was assessed using confusion matrix, accuracy, precision, recall, F1 score, and ROC curve. Acoustic samples were collected from five carniolan bee colonies using an Raspberry Pi 2-based omnidirectional monitoring system powered by a 10 Ah power bank and a 10 W solar panel. Data were recorded every 10 minutes in 30-second intervals. For feature extraction, the classical Mel-Frequency Cepstral Coefficients (MFCC) method was used. 70% of the 504 samples were used for training and 30% 216 samples for testing. SVM and NN achieved the best performance with faster classification.

In a study for detecting varroa mite infestations, image analysis and machine learning techniques were applied to visuals captured at hive entrances (Schurischuster, Remeseiro, Radeva, & Kampel, 2018). A homogeneous background was established and image patches containing individual bees were extracted. Raw images were converted to RGB format, and processing used brightness information separated from color using CIELab and HSV color spaces. Each frame of video footage 1920 x 1080 pixels, 30 fps was extracted and analyzed. From 12 videos, 1300 image patches were obtained. Due to the small number of varroa samples, the dataset was balanced. 80% of data 163 samples was used for training, 20% 43 samples for testing. Classification results using Naive Bayes, SVM, and RF were evaluated for accuracy and F1 score, with RF performing best.

In a study explained that varroa mites were initially seen in Eastern honeybees (Apis cerana) and later spread to Western honeybees (Apis mellifera), posing a significant threat to their health (Picek, Novozamsky, Frydrychova, Zitova, & Mach, 2022). In Western bees, varroa reproduces in worker brood. The study used 400 images from 100 hives taken with a mobile phone. If the varroa size was less than 12x12 pixels, detection was not possible. A shallow CNN architecture called VarroaNet achieved 96% and 93% accuracy in fall and winter, respectively. The model was evaluated using sensitivity and specificity metrics. Advantages of the proposed model include low cost, real-time detection, and sufficient data provision on infestation.

In a study proposed a system for monitoring varroa infestation levels using deep learning with video images (Bjerge et al., 2019). The model achieved an F1 score of 97% for counting bees and 91% for counting mites using a CNN architecture with fixed-size images of varroa mites. Figure 1 shows images of varroa and other objects from the study.

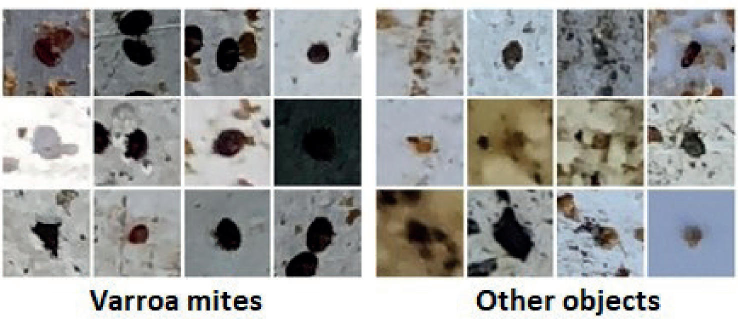

Figure 1. Visualization of varroa and other objects (Bjerge et al., 2019)

AI and IoT applications in beekeeping generally involve data collection through devices such as sensors or cameras. These data are automatically analyzed using machine learning and deep learning methods.

3. Artificial Intelligence-Based Applications and Internet of Things Technology in Beekeeping

Honeybees play a critical role in ecosystems, especially through pollination. Bee health is evaluated at the colony level, not individually. In recent years, the investigation of colony losses in Apis mellifera has become an important agricultural issue. Correct practices in beekeeping positively affect colony health. Beekeepers play a key role in colony management, especially when faced with threats. Physical or chemical interventions can help prevent dangers. Conditions affecting bee health and survival are shown in Figure 2.

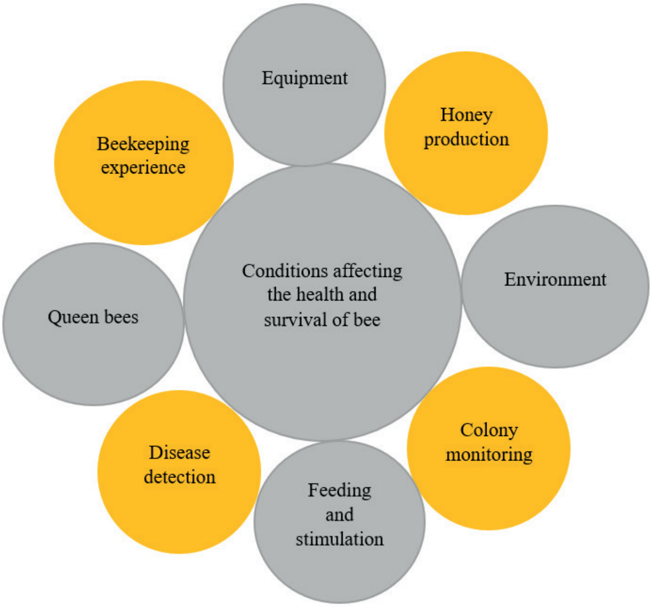

Figure 2. Bee health and survival conditions (El Agrebi et al., 2021)

Simultaneous monitoring of hives was previously costly and difficult. Today, technologies like IoT provide remote access to hive data. Real-time data access has brought significant convenience. Automatic data transfer has also greatly facilitated analysis. When sufficient data is not available, data augmentation with machine learning and deep learning methods can enhance analysis.

Analyzing honeybee images is increasingly important. Human eyes may fail to distinguish parasites on bees. Deep learning methods, especially CNNs, are effective for image-based analyses.

In beekeeping, classification methods commonly include RF (Albayrak, Çeven, & Bayır, 2021), SVM (Rahman, Lee, Venkatesan, Lim, & Shin, 2022), Decision Trees (DT) (Çukur & Çukur, 2022), KNN (Rafael Braga, G Gomes, M Freitas, & A Cazier, 2020), and LR. Deep learning methods include CNN (Braga, Madureira, Scotti, Piuri, & Abraham, 2021), Deep Neural Networks (DNN) (Zgank, 2021), and Feedforward Neural Networks (FNN) (Dimitrijević & Zogović, 2022).

3.1. Evaluation of Classification Results in Artificial Intelligence-Based Applications

Analyses conducted using machine learning and deep learning methods are generally evaluated based on the ROC curve or the confusion matrix (Lasko, Bhagwat, Zou, & Ohno-Machado, 2005; Sokolova & Lapalme, 2009). The confusion matrix consists of four different outcomes (Handelman et al., 2019):

- TP (True Positive): The number of correctly classified and actually correct values,
- TN (True Negative): The number of incorrectly classified and actually incorrect values,
- FP (False Positive): The number of correctly classified but actually incorrect values,
- FN (False Negative): The number of incorrectly classified but actually correct values.

In beekeeping-related classification studies, metrics such as accuracy, precision, recall, and F1 score are commonly used for analysis.

3.2. Machine Learning and Deep Learning Studies in Beekeeping

Deep learning is essentially formed by increasing the number of layers in ANN models, which are a type of machine learning method. In the field of precision beekeeping, image data has been increasingly utilized in recent years. Deep learning methods, which are based on machine learning, offer higher performance in this area. Example classification results from machine learning and deep learning-based approaches in precision beekeeping are presented in Table 1.

Table 1. Machine learning- and deep learning-based approaches in beekeeping

Reference	Implementation	Method	Performance (%)
(Kaur, Ardekani, Sharifzadeh, & Varastehpour, 2022)	Varroa detection	CLAHE + DCGAN + CNN	F1: 99.9
(Bjerge et al., 2019)	Bee counting Varroa detection	CNN	F1: 97.0 F1:91.0
(Schurischuster & Kampel, 2020)	Varroa detection	DeepLabv3	F1: 95.0
(Yoo, Siddiqua, Liu, Ahmed, & Hossain, 2023)	Bee counting Varroa detection Pollen recognition	BeeNet	Acc: 92.45 Acc: 94.50 Acc: 99.18
(Ngo, Rustia, Yang, & Lin, 2021)	Pollen recognition	YOLOv3-tiny	Pre: 91.0 Rec: 99.0 F1: 94.0
(Berkaya, Gunal, & Gunal, 2021)	Varroa detection	Pre-trained DNN	Acc: 93.22 Pre: 94.99 Rec: 97.24 F1: 95.34

In deep learning, the success of classification results largely depends on the quantity and quality of the available data. In cases where the dataset is limited, the outcomes often tend to be ambiguous or suboptimal. However, by applying data augmentation techniques to expand and diversify the training data prior to classification, significant improvements in accuracy and model performance can be achieved.

4. Artificial Intelligence in Beekeeping: Evaluation and Future Vision

In the field of precision beekeeping, studies are conducted on tracking pollen-carrying bees, obtaining additional information about subspecies, distinguishing bee species, and analyzing their health status (infected or healthy). These studies are generally conducted using electronic systems mounted on the hives. This paper reviewed methods (deep learning and machine learning) and targeted applications (pollen recognition, varroa detection, bee traffic monitoring) used in automatic hive monitoring systems. Furthermore, articles published in the last 10 years on this topic were analyzed.

The analysis revealed that deep learning-based approaches are increasingly preferred due to their deeper architectures and better performance on large datasets. Therefore, the usage of deep learning has significantly surpassed that of traditional machine learning methods. Based on the reviewed studies, it is anticipated that the use of AI-based hive monitoring systems in precision beekeeping will continue to grow, particularly due to advantages in speed and cost.

5. Conclusion

Honeybees are affected by adverse conditions such as colony collapse disorder, varroa mites (parasites), and unfavorable environmental factors. Early detection of problems within beehives is essential to protect bee populations and ensure stable production levels. Identifying hive issues manually is often time-consuming and costly. Precision beekeeping systems offer advantages in terms of cost and labor, making beekeeping more efficient.

AI-supported systems used in precision beekeeping can rapidly detect unfavorable conditions and potential problems within beehives. However, such smart monitoring systems are not yet widely adopted due to factors like lack of training and limited access to technology. This section aims to contribute to the proliferation of AI-supported hive monitoring systems. It is expected that in the future, the adoption of AI-based applications in beekeeping will become more widespread. As a result of this expansion, more informed production practices will emerge, leading to increased yield and quality per hive.

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