Types of Smart Devices Used for Beekeeping, their Development and Possible Perspectives. An Overview

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Abstract
Honeybees are the most known managed social insect species with tremendous contributions to humankind. It is also a highly studied species. Despite extensive research, significant gaps remain in understanding its natural behaviour and survival mechanisms, particularly in the face of anthropogenic stressors such as climate change and intensive agricultural practices. In recent decades, advancements in digital monitoring technologies have facilitated real-time surveillance of colony health and behaviour, offering critical insights for improving hive productivity and reducing mortality. Modern sensor-based systems enable the continuous measurement of key hive parameters, with real-time data transmission to analytical platforms for in-depth processing. These non-invasive and cost-effective monitoring solutions have gained widespread adoption, providing beekeepers and researchers with unprecedented access to colony dynamics. This study presents a comprehensive review of current hive-monitoring technologies, evaluating their applications in assessing honeybee health, behaviour, and productivity. By leveraging these innovations, researchers can refine apicultural practices and develop strategies to enhance colony resilience in a rapidly changing environment.

Keywords: colony health, hive monitoring, honeybees, sensor technology

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1. Introduction

The honeybee (*Apis mellifera* L.) is a vital pollinator species that plays an essential role in sustaining diverse ecosystems worldwide. Valued by humans since ancient times, honeybees have been integral to apiculture due to the wide array of products their colonies produce. A honeybee colony exhibits a highly organised social structure, consisting of three castes: the queen, worker bees and drones. This division of labour is distinctly defined, with reproductive individuals (the queen and drones) and non-reproductive worker bees collectively maintaining colony function and survival within the hive [1]. The individuals within a honeybee colony cannot survive independently, collectively forming a unique eusocial biological unit [2–4]. In this context, the scientific literature defines the beehive as a superorganism [5–7].

Honeybee nests are naturally established in tree hollow cavities, rock crevices, and open spaces, while human-engineered hives have been developed using different materials to increase colony productivity and accessibility [4]. The internal architecture of the hive is built by worker bees, which secrete wax from their wax glands to form intricate comb structures [3,8]. These

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structures, called honeycombs, are composed of hexagonal cells that are used to store pollen and honey, as well as protection and development of the brood [9]. The transition from rudimentary hive structures to systematic horizontal or vertical became necessary for beekeepers as it was necessary to find new methods to increase the productivity of their colonies and facilitate access inside the hive for the beekeeper [3,10–12].

The health and physiology of bee colonies can be compromised by infectious diseases caused by bacteria, viruses, fungi, or parasites [3,13]. A notable example is *Varroa destructor*, an ectoparasite that feeds primarily on the honeybees' fat body and can devastate entire apiaries, leading to significant economic losses [14,15]. Monitoring devices aim to detect such threats early, enabling timely intervention and containment. For instance, the Purple Hive Project in Australia utilises cameras and artificial intelligence (AI) to identify *Varroa* infestations and prevent their spread. Additionally, Colony Collapse Disorder (CCD), first identified in 2006, remains a major concern, characterised by the sudden disappearance of worker bees despite the presence of a queen and healthy brood [16]. Beehive monitoring technologies are thus essential for diagnosing colony health, preventing losses, and advancing research on conditions such as CCD [17,18].

Technological advancements have enabled beekeepers to implement real-time monitoring systems and devices to detect and prevent pest infestations. These systems integrate wireless sensors within modern hives to continuously transmit internal data. This innovation marks a significant shift in apicultural monitoring and research. While the potential impact of sensor-emitted electromagnetic radiation has been investigated, such as studies exposing hives to varying frequencies, no consistent behavioural disruptions were found [19]. However, Alfonso Balmori [20] noted that frequencies between 50–60 Hz may alter colony behaviour, causing increased motor activity, hive weight loss, and reduced overwintering success. Notably, emissions from cell tower antennas (50 W) pose greater risks than the lower-power wireless routers (1–4 W) typically used in beekeeping [21].

The development of these devices and sensor integration in beehives is driven by the need to optimise honey production in remote areas, monitor nectar harvest periods, detect pathogens, and enable real-time monitoring. Technological advancements have also reduced sensor costs and enabled data collection from multiple beehives, including those distant from the beekeeper's residence.

2. Types of sensors and their evolution over time

Beekeeping has transitioned from the simple task of harvesting honey from wild hives to managing artificial hives with a focus on optimising production. While regular inspections are essential to monitor the development of the hive and their health, they can cause stress and may not address issues requiring prompt action. The implementation of monitoring systems facilitates precision beekeeping by reducing inspection frequency and enabling early detection of potential problems [21]. For example, weight changes detected by a scale can prompt an inspection to identify issues or confirm foraging activity [22,23]. Technology has advanced in this sector due to these insects' importance and contribution to maintaining the balance of ecosystems. Sensor advancements aim to minimise hive disturbances while rapidly identifying problems such as food shortages, pests, diseases, swarming, or queen absence [21].

The development of beekeeping equipment has advanced over time, particularly in temperature measurements. Initially reliant on thermometers, the industry progressed to thermocouples and other sensors for more precise temperature monitoring within the hive [24]. Similarly, weight measurement evolved from tensiometers to mechanical scales and later to electronic scales, with the current use of load cells [12]. The continuous flow of information provided by new and open-source technologies has expanded opportunities for device innovation. Depending on the sensor type, some devices allow the installation of additional sensors to measure specific parameters of interest. These sensors may include temperature and humidity sensors, weight sensors, gas exchange monitors, and video or audio recording devices. The collected data is then transmitted via technologies such as LoRa WAN or 4G networks [25]. These systems not only simplify the work of professional and hobbyist beekeepers but also hold significant potential for research. The data they collect can deepen our understanding of bee behaviour and communication mechanisms within the hive. This enhanced knowledge can inform the development of improved methods for bee care, survival, and overall well-being.

2.1. Temperature sensors

Honeybees are poikilothermic insects, meaning their body temperature is dependent on the surrounding environment; however, as a colony, they function as homeothermic, maintaining an internal hive temperature between 33 and 35°C [4,26]. This temperature range is crucial for brood development, as the brood is highly sensitive to both excessive heat and cold fluctuations [27,28]. The temperature inside the hive, when brood is present, is maintained by worker bees between 33 and 35 °C by forming a cluster; if the temperature rises above this range, the bees will break the cluster to ventilate the hive [11,29]. During winter, in the absence of brood, a cluster of bees can reach a core temperature between 15 and 20°C [30].

Temperature regulation within the hive is achieved through specific behavioural responses from the bees. When the temperature exceeds the upper threshold, worker bees engage in ventilation behaviour, such as fanning their wings and positioning themselves in various parts of the hive; they also place water droplets on the honeycombs, which, through evaporation, help to cool the hive [31,32]. In contrast, when the temperature drops too low, bees cluster together, a behaviour most commonly observed in winter when maintaining heat becomes a survival priority. Worker bees generate heat through the use of their thoracic flight muscles [28,33]. Additionally, bees may enter empty cells and vibrate their thorax, emitting heat (ranging from 34°C to 42.5°C) into the vacant spaces between brood cells, which facilitates heat transfer to the developing brood [27]. Drones can also play a role in temperature regulation by helping to maintain optimal temperatures on the honeycombs, particularly in the central hive area, which is essential for brood survival and development [3,34,27]. External temperature also plays a vital role in the welfare and productivity of honey bee colonies. A study by Abou-Shaara et al. [27] indicates that worker foraging behaviour is most active when external temperatures range between 10°C and 40°C, with an optimal temperature of around 20°C for efficient nectar collection. Temperatures outside of this range result in reduced colony activity and foraging efficiency [10].

Temperature sensors are essential in beekeeping as they provide critical information on the health and resilience of a honey bee colony. The health of the colony is reflected in the quality of the queen, the brood, and the population within the hive. Deviations from normal temperature ranges can offer insights into the impact of pathogens on the colony, as well as the status of honey and pollen reserves [35]. Moreover, the colony's resistance is indicated by the number of individuals, particularly the workers responsible for foraging, and the presence of both immature and mature brood, which ensures the continuity of the colony by replacing ageing bees [35].

The use of temperature measurement in beekeeping dates back to around 1914, when mercury thermometers were first employed, and beekeepers manually recorded temperature data every hour for several days [36]. Throughout the 20th century, thermocouples became more widely used [24], and by the end of the century, electronic sensors were adopted [36]. With advances in technology, real-time temperature monitoring became possible, with data now accessible either through wired connections or wirelessly. Many beekeepers have integrated sensors to monitor hive parameters such as temperature and humidity, often coupled with solar-powered panels to enhance device autonomy [37]. The automation of data collection has significantly reduced the need for frequent apiary visits, thereby lowering labour demands.

2.2. Weight sensors

Monitoring hive weight is a crucial tool that offers valuable insights into the health and dynamics of a honeybee colony and its interaction with the surrounding environment. Fluctuations in hive weight can be caused by factors such as population changes, food and water consumption, humidity, or external influences like pesticides, are key indicators of the colony's overall well-being [23,38].

Weight was one of the first parameters monitored by beekeepers. Early methods of weight measurement involved the use of tensiometers, which were placed under hives tilted to one side, assuming the weight was evenly distributed. The reading from the tensiometer was then doubled to estimate the total weight of the hive. However, this method had notable limitations, particularly in terms of accuracy under certain conditions [12]. A simple method for measuring hive weight involved using mechanical or electric scales adapted to be placed under the hive. However, this approach was labour-intensive, particularly in apiaries with many hives, as the scales required frequent checking, consuming a significant amount of time for the beekeeper. This challenge created an opportunity for researchers and entrepreneurs to develop new sensors and methods for recording and storing data, enabling the tracking of multiple factors beyond just food abundance or population size. The first recorded weight data, collected with an electric scale, is believed to have been entered into a database in 1990, specifically to monitor bee abandonment of the hive infested with the parasite *Acarapis woodi* [38]. The automation of weight monitoring began with the introduction of load cells in 2015, replacing traditional scales for hive monitoring [39]. Subsequent developments included precision beekeeping systems, such as a 4-load cell system introduced in 2017 [40] and a low-cost monitoring system with a single load cell in 2018 [41]. Load cells are typically mounted at the base of the hive on a frame, preferably made of aluminium, to ensure durability against weather conditions and to prevent deformation that may occur with wood. The frame is designed to fit the hive dimensions, ensuring even weight distribution [12,39].

2.3. Sound Monitoring

The sounds produced by honeybees are crucial for communication both within the hive and with the outside environment. By analysing these sounds, the state of the colony can be assessed, making sound analysis a valuable non-invasive technique for beekeepers [42]. Honeybees use various methods to produce vibroacoustic signals, including body and wing movements, high-frequency muscle contractions independent of wing motion, and pressing their thorax against surfaces or other bees [43–45]. There is a correlation between the frequency and amplitude of these signals inside the hive, which can help predict events such as swarming [42].

The historical significance of sound analysis in beekeeping dates back to the time of Aristotle. The evolution of equipment in the 20th century, marked by milestones such as the introduction of a standard wave analyser in 1959 [46] and the use of microphones and spectrographs in 1964 [42], contributed significantly to our understanding of bee communication. A practical method for detecting swarming colonies involved placing microphones along with humidity and temperature sensors in three hives [47], demonstrating the real-world application of this research.

The practical application of sound analysis in detecting swarming colonies are particularly evident in the identification of behaviours such as the sounds of new queens, workers and the performance of orientation dances. Swarming can be triggered by various factors, including queen loss, parasite infestation, pollutants, and external threats to the hive [48,49]. The onset of the swarming process is characterised by a sound frequency that begins at 110 Hz and increases to 500 Hz as the process progresses [47]. In the 21st century, advancements in digital processing and the use of smart devices for monitoring have further enhanced the utility of this non-invasive sound analysis technique [42].

Given its potential, sound analysis will be addressed in two distinct subchapters, as its functions can vary based on the location within the hive or apiary.

2.3.1 Sound monitoring inside the hive

Swarming is one of the most critical phenomena within the hive because, for professional beekeepers, it means a decrease in the yield of honey produced [47]. It serves as a natural mechanism for colony propagation, involving a sequence of collective behaviours aimed at dividing a strong colony into multiple viable units [50]. This process typically occurs from late spring to early summer and may repeat several times in robust colonies. During the primary swarm, the old queen departs with about half of the workers, leaving behind developing queen cells. Once mature, these new queens may also lead to subsequent swarms [50].

Vibroacoustic signals are key early indicators of swarming and are central to colony communication. Worker and queen-produced sounds such as "piping", "tooting" and "quacking" have been well-documented [48,50,51]. Understanding these signals can provide valuable insights into colonies' behaviour.

A newly emerged queen emits "tooting" at 0.5-second intervals, with frequencies ranging from 200 to 550 Hz, accompanied by comb vibrations via wing muscle activity [52]. This signal suppresses the emergence of rival queens [53]. In response, unhatched queens emit "quacking" every 0.2 seconds at around 350 Hz [44], with signals transmitted through the hive via specific vibrational patterns [54].

Workers also use "piping" and wing muscle vibrations for intra-colony communication and during foraging activities [51]. One example is the "DVAV" (Dorso-Ventral Abdominal Vibration) signal, described by Ramsey et al. [6], which conveys behavioural cues within the hive.

Queenless hives exhibit chaotic behaviour. Bees may expose their Nasonov glands and fan their wings, producing a distinctive sound indicating the queen's absence [55].

Sound monitoring also holds the potential to detect parasitic stress. For instance, studies comparing healthy and *Varroa*-infested colonies revealed distinct acoustic differences. Threat responses generate pulses ranging from 300 to 3600 Hz, while infestation causes a frequency shift from 100–300 Hz to 500–600 Hz [56,57]. These acoustic variations warrant further investigation to clarify the relationship between parasitism and vibroacoustic changes.

2.3.2 Sound monitoring at the entrance to the hive

In addition to detecting internal acoustic signals, microphones placed around the hive can alert beekeepers of external threats. Bees emit distinct sounds to deter predators during attacks [57,58]. For example, *Apis mellifera cypria* responds to *Vespa orientalis* with characteristic warning signals that mobilise colony defence [59]. External and internal microphones may also detect pest-specific noises. If these acoustic profiles are integrated into real-time alert systems, beekeepers can be notified early, before the infestation becomes severe [60,61]. Although such systems are still under development and face several technical challenges, expert consensus supports their potential for effective predator detection [61]. A notable example was recently demonstrated by Hall et al. [62], who showcased the capability to identify the predatory wasp *Vespa velutina* in real-time.

2.4. Gas monitoring sensors

CO_2 monitoring in hives was first documented in 1921 using metabolic chambers with controlled gas flow [36], later refined using "Tygon" tubing [63] and pipettes [64]. Advances in sensor technology have made real-time gas monitoring more accessible and led to their adoption in modern apiculture [36,65,66].

Carbon dioxide and humidity are important factors for colony health [65]. Excess CO_2 triggers ventilation behaviour, particularly in strong colonies, as part of thermoregulation [63,65,67,68]. Meikle et al. [66] demonstrated that increased hive ventilation raised CO_2 levels above 200 ppm without affecting temperature or weight. CO_2 concentration was found to be higher beneath the frames and lower above them.

Humidity, expressed as water vapour in the air, also plays a critical role [65]. Brood development requires relative humidity between 75–90% at 35°C [69]. This parameter varies with colony activity and environmental conditions, with higher internal moisture due to bee presence and nectar evaporation [31,32]. Historical humidity measurements used hygro-thermographs in empty hives or in compartments placed above the colony [70].

2.5. Video monitoring

Visual inspection of the bee colony is a necessary tool for beekeepers to assess colony status. However, the integration of video monitoring—both inside the hive using infrared cameras and outside using conventional setups—enhances observational capabilities by enabling real-time tracking of hive activity and foraging direction via wireless transmission [71]. This approach allows beekeepers to monitor colonies remotely, regardless of weather or time, reducing the need for on-site visits [71].

Infrared imaging offers a non-invasive method for internal hive assessment. Radiometrically calibrated thermal cameras provide signals directly proportional to the number of populated frames, with optimal results recorded before sunrise due to the thermal contrast between the hive and ambient conditions. This technique minimises colony disturbance and is especially valuable in applications requiring frequent assessment, such as using bees for mine detection [72].

Swarming, which negatively impacts honey production and operational efficiency, is more easily detected through frequent inspections. However, manual checks can stress bees and increase operational costs [73].

Automated systems continuously monitoring environmental and internal hive parameters—such as temperature and humidity—can detect behavioural cues indicating imminent swarming.

When integrated with video monitoring, these systems enable precise behavioural correlation and documentation [73]. Additionally, video systems have been used to monitor pollen inflow. Yang et al. [74] demonstrated a method using high-frame-rate video (50 fps) and image processing algorithms to identify returning foragers based on movement and colouration. Pollen loads were detected and differentiated, allowing for non-invasive estimates of colony food stores.

Table 1. Overview of key parameters reviewed in this study, including their recorded values, sensor types used for measurement, and corresponding references

Parameter	Recorded values	Reference	Type of sensor	Reference
Temperature (cold season)	15-20°C	[30]	Mercury thermometer	[24]
Temperature (active season)	35-36°C	[11,29]	Thermocouple	[24]
	33-35°C	[4,26]	Temperature sensors	[47]
Humidity	60-90%	[26]	Hygro-thermographs	[70]
	75-90%	[69]	HOBO H8 data loggers	[31]
Weight	Increase/decrease (Kg)		Tensiometer	[12]
			Mechanical/electronic scale	[36]
			Load cell	[39]
CO_2 concentration	200 –>11,000 ppm	[12,66,68]	Non-dispersive infra-red (NDIR) detectors	[65]
Sound	100-3600 Hz Combined with algorithms	[57]	Standard wave analyser	[46]
		[62]	Spectrograph	[42]
			Microphones	[47]
Video monitoring	Specific algorithms		Infrared camera	[71]
			Video camera	[73]

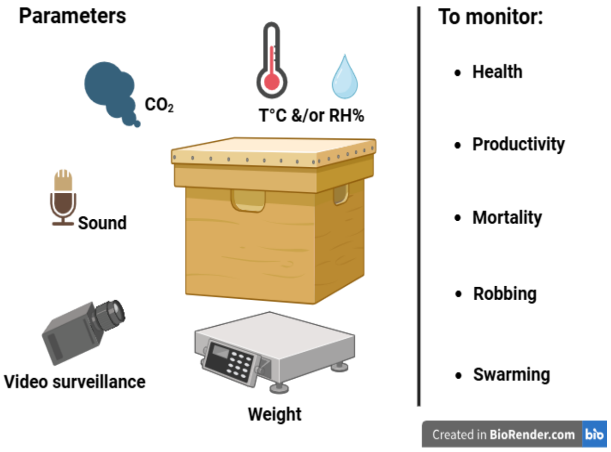

Figure 1. Types of parameters analysed and their purpose

3. Advanced Sensor-Integrated Systems for Comprehensive Hive Monitoring

Modern monitoring devices enable real-time tracking of key parameters for each colony within an apiary, allowing beekeepers to make informed management decisions and detect pest presence more efficiently [75,76]. A wide range of such technologies is now available, tailored to diverse apicultural needs [76].

The framework of "Precision Apiculture" has been established as a modern apiary management paradigm, characterised by continuous and automated monitoring designed to optimise resource allocation and maximise colony performance [77]. Central to this approach is the development of robust, intelligent systems capable of recording, storing, and analysing key indicators of colony viability [75]. Recent research highlights the integration of such datasets into predictive models, offering significant potential to enhance decision-making and colony management strategies [78].

For these systems to be broadly adopted, they must demonstrate economic sustainability, ease of deployment, operational simplicity, and minimal maintenance requirements [79]. Furthermore, given that many apiaries are located in remote areas, effective data transmission to the beekeeper in a user-friendly format is critical. In this regard, the Internet of Things ("IoT") presents the potential to transform traditional monitoring and decision-making processes in agriculture and apiculture into automated technologies. IoT brings different sensors with software and network connectivity, facilitating real-time communication and data exchange between devices, central hubs and databases [80]. Moreover, centralised data collection, storage, and the development of specific programs and algorithms can help beekeepers predict trends, detect issues, and make decisions on time. Through the integration of environmental and behavioural metrics, these technologies facilitate early detection and mitigation of critical stressors such as Colony Collapse Disorder (CCD), parasitic infestations, viral outbreaks, queen failure, and climate-induced disruptions. Widely used sensors include temperature and humidity sensors, visual and acoustic monitoring tools, gyroscopes, and GPS modules [81]. The subsequent section presents a selection of commercial and research-grade monitoring systems exemplifying these capabilities.

3.1. BEEP base

The BEEP monitoring system is designed to be user-friendly and effective, consisting of two main components: the BEEP base, an automatic measurement device that records key parameters such as temperature, hive weight, and acoustic signals, and the BEEP platform, a database where all collected data is uploaded and made readily accessible to beekeepers and researchers [82]. To enable real-time data visualisation, the BEEP base must be within the range of a LoRaWAN Gateway, which facilitates wireless data transmission from the hive to the cloud-based platform.

The development of the BEEP system has been closely tied to the B-GOOD project, a four-year European initiative aiming to enable comprehensive and standardised monitoring of honeybee health. The project seeks to record a broad range of parameters that reflect the physiological condition of the colony, including brood presence, honey production, pollination activity, resistance to diseases and pests, hive adaptability, and analysis of subspecies and ecotypes. These data are systematically gathered from multiple locations across Europe and centralised in a platform that supports both research and practical applications in beekeeping [83].

3.2. Purple Hive

The Purple Hive Project is an Australian initiative created to support the national honey production sector by developing an intelligent hive monitoring system. This solar-powered device is integrated into the beehive and designed to detect *Varroa destructor*, a highly destructive parasitic mite, directly on bees entering or exiting the hive. Detection is achieved using two 360-degree cameras placed at the hive entrance, paired with artificial intelligence algorithms capable of identifying infested bees. Upon detection, the system immediately alerts the beekeeper so appropriate measures can be taken to contain the threat [84]. Teams of experts are tasked with implementing these techniques in apiaries throughout Australia [85]. Previously, approved detection methods involved laborious techniques such as sugar shake or ethanol wash, both of which are invasive, require manual handling of bees and result in the loss of individuals from the colony. These approaches also depend heavily on trained personnel and are impractical for constant surveillance across large areas.

As part of its biosecurity framework, Australia has implemented a Sentinel Beehive Program since 2000. This initiative deploys hives in strategic maritime locations to act as early detection tools for a wide range of invasive pests. In a 2005 review, Pat Boland described the placement and monitoring of these hives, typically inspected every six months, and highlighted the risks posed by pests transported through international shipping routes [86]. The Australian government has proactively involved both professional and hobbyist beekeepers from urban and rural areas in a coordinated effort to mitigate the threat posed by *Varroa destructor*, which represents a serious risk to the national economy and agricultural systems [87]. The Purple Hive, still in the development phase, is being integrated into this sentinel network and deployed in high-risk zones. It aims to reduce costs, simplify monitoring efforts, save time, and increase detection accuracy [88,89].

Despite these efforts, in June 2022, sentinel hives in two regions of Australia confirmed *Varroa destructor* infestations. This prompted a large-scale eradication attempt. However, in September 2023, after considerable effort, the Australian federal government officially announced the end of eradication activities, opting instead for a new strategy focused on the long-term management of the parasite[90–93].

3.3. Eyes on Hives

For beekeepers, flight behaviour is a key indicator of a colony's health, strength, and resilience. Typically, visual inspection of bee traffic at the hive entrance serves as the first step in assessing colony status. Parameters such as bee volume, flight dynamics, and weather conditions offer insights into colony vitality [94].

Eyes on Hives is a solar- or 120V-powered system that employs image processing technology to monitor and record flight activity. The system includes a camera positioned in front of the hive, a central data storage unit, and an internet router to facilitate wireless data transmission [95].

The camera captures bee movements and transmits visual data to a cloud platform, which can then be accessed in real time via a dedicated mobile application. By analysing flight patterns and the number of bees entering and exiting the hive, the system allows daily colony monitoring through automated video analysis. Data are captured in 30-second video segments every two minutes, uploaded to the platform, and made available to users through the Eyes on Hives app [96]. The application also features automatic alerts, notifying beekeepers of significant behavioural anomalies such as swarming [97]. For optimal performance, the device must be placed directly in front of the hive and is programmed to operate from sunrise to sunset based on geolocation and date settings. A stable Wi-Fi connection is essential for continuous data transmission [97].

However, several environmental and physical factors, such as hive colour, background contrast, placement distance, and shadowing, can influence data quality [97]. A notable limitation is the high cost of the device, as reported by Souza et al. [98]. In response to this, the authors proposed a Doppler radar-based system as a non-invasive, cost-effective alternative. This technology detects bee movement via electromagnetic wave reflection and was found to outperform image-based systems in both efficiency and affordability[98].

3.4. IoBee EU

The Internet of Bees (IoBee) project, founded by the European Union, aims to support pollinator health and biodiversity through advanced monitoring solutions [99]. The initiative focuses on both in-hive and field-based data collection, supported by a centralised platform where beekeepers, data scientists, and researchers can share insights and findings. A significant outcome of the project is the development of a bee counter: a sensor system installed at hive entrances to track bee traffic, detect pests, and assess colony status [100]. IoBee also incorporates additional sensor modules to measure internal hive parameters such as temperature, humidity, weight, and acoustic signals. Despite these advancements, the precise monitoring of forager loss and foraging activity remains under development [101]. Another innovative aspect of the IoBee project is its use of satellite imagery in conjunction with in-field sensors. This integration allows the identification of phenological phases and land-use patterns, offering valuable data to environmental authorities and helping reduce manual labour while protecting insect populations [100].

3.5. Bee Hero

Bee Hero is an American initiative driven by a multidisciplinary team comprising experienced beekeepers, biologists, entrepreneurs, and data scientists. The project's objective is to support both ecological sustainability and agricultural productivity [102]. The core of BeeHero's system is a hive-integrated sensor array that continuously monitors parameters, including temperature, humidity, acoustics, and overall hive activity [102]. Particularly notable is its ability to track bee traffic, a key metric influenced by foraging resources and colony demographics. This information can yield valuable insights into the age structure and vitality of bee colonies [103].

3.6. Buzz Box

The BuzzBox system, developed by OSBeehives, is part of a broader initiative to build a global network of beekeepers and address common colony health issues. This solar-powered device is equipped with sensors that collect data on temperature, humidity, and hive acoustics, which are then analysed via an integrated AI platform. Additional features include an external weather station and theft detection alarms [104]. Data collected by the BuzzBox are transmitted via Wi-Fi directly to the beekeeper's smartphone. The system benefits from an extensive data foundation, with over 2 million data points gathered from thousands of hives, which enhances the accuracy of its predictive analytics and decision support tools [17].

4. Discussions

Honeybee colonies function as complex, cooperative systems, often described as superorganisms, due to their integrated social behaviour and interdependence among individuals. Investigating such systems through advanced monitoring technologies provides valuable insight into colony dynamics and opens new avenues for enhancing human–bee interactions.

In recent years, *A. mellifera* populations have faced a growing number of biotic and abiotic threats, including habitat degradation, pesticide exposure, climate change, and the spread of invasive species [105]. This escalating pressure underscores the urgent need for proactive monitoring strategies. Bees play a critical ecological and economic role, particularly in the pollination of entomophilous crops, which are essential to global food security [106]. Ensuring their protection is no longer optional; it is a necessity.

A central aim of modern apicultural monitoring is to reduce the disturbance caused by manual hive inspections. Repeatedly opening hives has been shown to stress colonies and disrupt their internal balance. In this context, recent advancements in remote sensing technologies, enabled by 4G and LoRaWAN communication networks, allow for real-time, minimally invasive monitoring [25]. These systems facilitate data transmission between the hive and digital platforms accessible via smartphones or computers, significantly reducing the need for direct interference with colonies.

Concerns have been raised regarding the potential impact of electromagnetic waves from such devices on bee health [19]. While current evidence suggests that the low power levels used in most monitoring systems do not harm bees, further investigation is warranted to establish long-term safety standards [20,21,25].

Technological advancements and the decreasing cost of digital components have made the development of sophisticated monitoring tools increasingly feasible. Current sensor technologies have evolved to track detailed hive parameters such as temperature, humidity, weight, acoustic profiles, and gas exchange. Additionally, some systems can detect the presence of pathogens and pests, most notably *Varroa destructor*, a mite linked to the widespread colony decline, or that can contribute to the early detection of *Vespa orientalis* or *V. velutina* [56,58–60,62].

Integrating sensors capable of monitoring a wide range of environmental and biological indicators offers considerable benefits for both professional and hobbyist beekeepers. These devices do not replace the beekeeper's expertise but rather serve as tools to optimise colony management. They can provide early warnings for swarming behaviour, detect the onset of nectar flow, or alert the user to the presence of disease, all while minimising physical inspections [21,48,50,51]. For hobbyist beekeepers, who may lack time, expertise, or easy access to their apiaries, automated monitoring offers a valuable solution. These tools deliver interpreted data via user-friendly platforms, bridging knowledge gaps and supporting better decision-making. This can be especially impactful for non-professionals, who may not possess the technical knowledge of veterinarians or commercial apiarists.

Several notable devices exemplify the current state of innovation in hive monitoring. The Eyes on Hives system offers visual analytics to monitor colony flight activity and detect anomalies such as *Varroa* infestations [95–97]. The Purple Hive project, developed in Australia, uses AI and visual recognition to identify *Varroa destructor* in real-time.[84,88] The BEEP base platform integrates sensors that measure hive temperature, weight, and sound, contributing valuable data to both practitioners and researchers [82]. These monitoring systems contribute not only to daily management but also to research. The data collected are archived in centralised databases that allow for retrospective analysis, model development, and cross-referencing among diverse regions and conditions. As these databases grow, they will enable the refinement of existing technologies and support the emergence of more accurate predictive tools. Looking forward, the accumulation of large-scale, high-quality data sets is vital for refining these technologies. Continued research efforts—supported by structured protocols for device maintenance and data interpretation—will be essential for improving performance and expanding functionality. The growing number of sensors used across agriculture and apiculture demonstrates the broader trend toward digital optimisation in the farming sector [107]. Ultimately, beekeepers and their managed colonies are at the core of this technological evolution. Their willingness to adopt and support these tools will be crucial for their widespread implementation. From the beekeeper's standpoint, beyond the initial financial investment, the success of any monitoring system will be judged by its practical utility, reliability, and contribution to improved colony health and productivity.

5. Conclusions

Integration of monitoring technologies in apiculture can offer significant benefits for both professional and hobbyist beekeepers. These devices are generally easy to install and use. The perspective for early detection helps optimize hive management while reducing the number of inspections. Although the initial investment may be high, maintenance costs are typically low, and the systems are designed to be minimally invasive, causing little to no negative impact on colony health. These technologies can improve productivity by enabling timely interventions for issues such as mite infestations or changes in nectar flow, and they help reduce colony losses by facilitating early detection of problems. Overall, monitoring devices enhance hive management, promote colony health, and ultimately contribute to more efficient and sustainable beekeeping practices.

Other potential applications by integrating monitoring devices can come to help the research sector. The biomonitoring sector can be optimised by placing monitoring devices on the hives that are used as bioindicators. This can facilitate the monitoring of specific areas to evaluate pollution levels, pesticide presence, and climate change's impact on the environment. Furthermore, if focused more on the colony, the use of monitoring devices can help researchers gain more insight into honey bee behaviour and colony dynamics. It could facilitate a better understanding of the mechanisms of interactions between individuals and their response to internal or external threats or environmental factors. A better insight into these areas can lead to the development of improved beekeeping practices.

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