Precision Beekeeping Technologies: Current Trends and Prospects for Sustainable Apiary Management

Hussain Ali

Entomology Section Agriculture Research Institute Mingora Swat, Pakistan
Corresponding author: agrihassanba@gmail.com

ABSTRACT

Precision beekeeping is an emerging field that applies sensor technologies, data analytics, and automation to enhance hive monitoring, optimize management decisions, and promote sustainable apiculture. This review explores the core components and current applications of precision tools, including temperature, humidity, weight, acoustic, and traffic sensors, and how they enable real-time monitoring of colony health, productivity, and behavior. The integration of machine learning and cloud-based platforms allows early detection of stressors and facilitates predictive management, especially in large-scale operations. Challenges such as high implementation costs, lack of standardization, and limited accessibility for smallholders are critically examined, alongside environmental concerns and ethical questions surrounding bee welfare and data governance. The article concludes by identifying future opportunities in miniaturization, open-source innovation, and the alignment of precision apiculture with broader sustainability goals. This synthesis underscores the potential of precision beekeeping to support resilient, efficient, and ethically informed apiary management systems.

Keywords: beekeeping; sensors; hive monitoring; apiculture; sustainability.

INTRODUCTION

Beekeeping plays a vital role in both agricultural productivity and ecological resilience. Honey bees (Apis mellifera) are not only valued for their honey and wax but, more importantly, for their role as pollinators in natural and cultivated ecosystems. An estimated 75% of globally important crops benefit from animal pollination, and honey bees are responsible for a substantial portion of that service (Klein et al., 2007; Potts et al., 2016). However, global beekeeping practices face mounting challenges due to environmental stressors, emerging diseases, declining floral resources, and the increasing complexity of apiary management. These stressors have contributed to declining colony health and have highlighted the limitations of conventional beekeeping, which often relies on manual inspections, infrequent data collection, and reactive management decisions. In this context, the emergence of precision beekeeping technologies represents a transformative step toward more efficient, data-informed, and sustainable apiculture.

Precision beekeeping, often considered a subset of precision livestock farming, involves the application of sensor technologies, real-time monitoring, and data analytics to manage bee colonies with greater accuracy and minimal disturbance (Zacepins et al., 2015). The approach is grounded in the idea of optimizing management at the level of individual hives by continuously tracking variables such as hive temperature, humidity, weight, sound patterns, and bee activity. These technologies enable beekeepers to make timely and evidence-based decisions, reduce labor costs, detect health issues before clinical symptoms appear, and improve overall colony welfare. The proliferation of wireless sensors, Internet of Things (IoT) devices, and machine learning algorithms has made it increasingly feasible to monitor beehives remotely and at scale (Bencsik et al., 2011; Cecchi et al., 2020). By digitizing beekeeping practices, these innovations contribute not only to production efficiency but also to ecological monitoring and biodiversity conservation.

The growing interest in precision beekeeping coincides with broader transformations in agriculture driven by digitalization and sustainability imperatives. Across the agricultural sector, precision technologies are being adopted to reduce waste, improve traceability, and respond more adaptively to environmental variability. In beekeeping, this trend is manifest in the use of integrated platforms that combine sensor data with weather forecasts, geolocation

systems, and disease alerts to support decision-making. However, the adoption of such technologies remains uneven, with high implementation costs, lack of technical skills, and device interoperability issues posing significant barriers, especially for small-scale and traditional beekeepers (Zacepins et al., 2022). Moreover, there are ongoing debates regarding the ethical boundaries of technology use in animal-based systems, including concerns about over-monitoring, loss of beekeeper intuition, and potential stress effects on bees caused by sensors or electromagnetic exposure.

This review explores the emerging landscape of precision beekeeping with an emphasis on current technological applications, underlying sensor systems, and their potential to reshape sustainable apiary management. It begins with an overview of the conceptual foundations and core components of precision beekeeping, followed by a detailed analysis of existing use cases and innovations. The integration of artificial intelligence and big data analytics is examined, particularly in relation to colony health monitoring and decision support. Environmental and socio-economic considerations are also addressed, with special attention to energy consumption, data ownership, and accessibility for smallholders. The review concludes with a discussion of future prospects, research gaps, and the role of precision beekeeping in a digitized, sustainability-oriented food system. By synthesizing interdisciplinary insights, this article aims to provide researchers, technologists, and beekeeping practitioners with a comprehensive understanding of precision beekeeping as a tool for modern apiary resilience.

Core Concepts and Components of Precision Beekeeping

Precision beekeeping is conceptually grounded in the broader paradigm of precision livestock farming, which emphasizes individualized management through continuous monitoring, sensor integration, and data-driven decision-making. In the context of apiculture, the unique challenges of monitoring free-flying, densely populated insect colonies necessitate specialized approaches that combine miniaturized sensors, remote data acquisition systems, and intelligent analysis tools. The central aim is to manage each hive as a distinct biological unit, enabling early detection of stressors, behavioral changes, or health issues while minimizing physical interventions that might disrupt colony dynamics (Zacepins et al., 2015). Unlike traditional management practices that rely heavily on manual inspections and subjective judgment, precision beekeeping leverages objective, real-time data to inform and optimize interventions.

The core technological architecture of precision beekeeping typically includes a network of environmental and hive-specific sensors designed to monitor internal and external variables relevant to colony health. Temperature sensors are among the most widely used, given that consistent internal hive temperature is a key indicator of brood rearing activity and colony vitality. A drop in internal temperature, particularly below 32°C, may suggest queen failure, brood absence, or colony collapse (Meikle et al., 2006). Humidity sensors provide complementary insights into brood condition, wax integrity, and the microclimate within the hive, which can affect disease susceptibility and ventilation efficiency. Weight sensors mounted under hives detect changes in colony mass associated with nectar flow, food stores, swarming, or depopulation events. These load cells, when monitored continuously, can also help identify the onset of foraging or robbing behavior by tracking daily gain and loss patterns (Cejrowska et al., 2023).

Another critical component of precision beekeeping is the use of acoustic and vibration sensors to capture colony sound signatures. Changes in sound frequency and amplitude have been correlated with various colony states, including queenlessness, swarming preparations, and forager return rates (Bencsik et al., 2011). These bioacoustic signals are particularly valuable because they offer non-invasive insight into internal colony behavior without the need to open hives or physically handle bees. Microphones or piezoelectric sensors embedded in hive walls or frames continuously record vibrations, which are then analyzed using signal processing algorithms to detect anomalous patterns or stress indicators. This passive monitoring method reduces labor, enhances early detection, and preserves colony integrity during sensitive periods.

GPS and RFID technologies also contribute significantly to tracking bee activity beyond the hive. GPS systems are used to geo-reference hives in mobile apiary operations, support spatial analysis of foraging behavior, and correlate hive health with landscape features such as pesticide exposure or floral availability. RFID (Radio Frequency Identification), when applied to individual bees, allows researchers to monitor foraging trips, lifespan, and social interaction patterns within the colony. Although RFID is more commonly used in research contexts due to its technical complexity and cost, it has opened new avenues for understanding bee behavior at the individual level (Streit et al., 2003).

Data acquisition and transmission systems form the connective tissue of precision beekeeping infrastructures. Most hive sensors are integrated into wireless sensor networks that use protocols such as ZigBee, LoRaWAN, or Wi-Fi to transmit data to centralized databases or cloud-based platforms. These systems are often solar-powered and designed for low energy consumption to ensure long-term operation in remote apiaries. Data are typically collected at regular intervals and either stored locally or uploaded to servers for real-time visualization and analysis. User interfaces range from mobile apps for individual beekeepers to advanced dashboards for researchers and commercial operations. These platforms allow users to monitor multiple hives simultaneously, receive alerts about abnormal conditions, and generate reports for seasonal trend analysis or health forecasting (Zacepins et al., 2022).

Together, these components establish a digital framework that transforms the beehive into a data-rich ecosystem capable of autonomous reporting and intelligent response (Fig. 1). The integration of multiple sensor types provides a holistic view of colony dynamics, bridging the gap between manual observation and automated diagnostics. However, the effectiveness of this approach depends not only on the precision of individual sensors but also on their interoperability, calibration, and integration into cohesive systems that align with the practical needs of beekeepers. As such, the success of precision beekeeping hinges on both technological sophistication and usability, with careful attention to cost, durability, and adaptability across diverse environmental conditions and management scales.
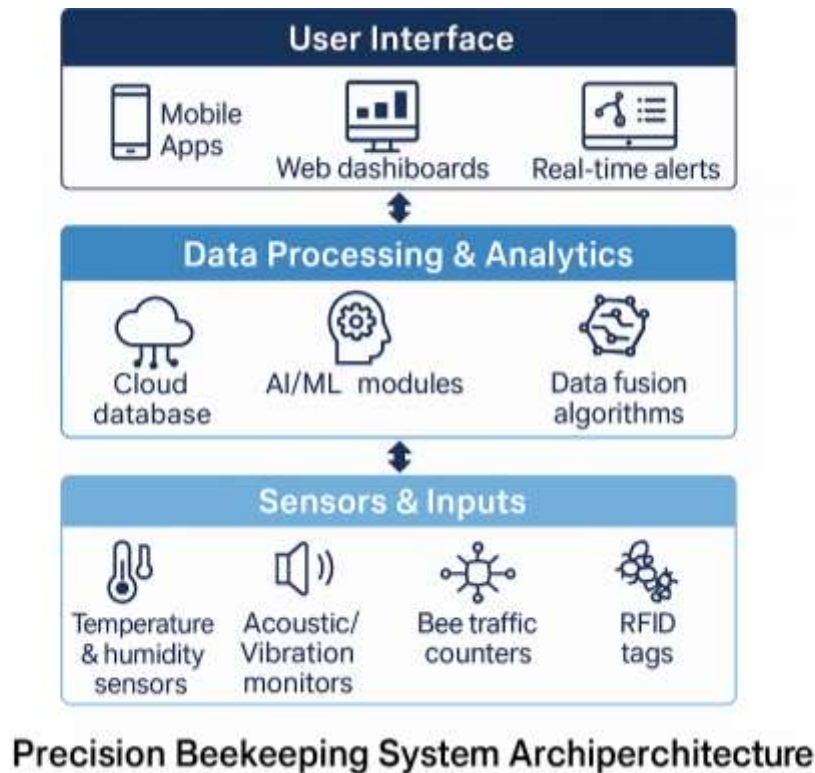

Fig. 1: Precision Beekeeping System Architecture.

Current Applications in Apiary Management

The integration of precision technologies into beekeeping has opened new possibilities for monitoring, decision-making, and intervention, significantly enhancing the ability of beekeepers to manage colony health and productivity in real time. One of the most valuable applications of precision beekeeping lies in the early detection and continuous tracking of colony health. Through the use of temperature and humidity sensors, beekeepers can assess brood rearing status, identify abnormal thermal regulation that may signal queen loss, and detect early signs of colony stress or disease. Temperature anomalies, especially a sustained drop in brood nest temperature, are often the earliest indicator of queen failure or collapsing colony strength (Meikle et al., 2006). By monitoring these internal conditions continuously, interventions such as requeening or feeding can be applied with minimal delay, reducing colony mortality and improving seasonal outcomes.

Colony weight monitoring through load cells offers further insights into hive dynamics and nectar flow. Changes in hive mass over 24-hour periods allow beekeepers to quantify foraging activity, evaluate resource availability in the environment, and make timely decisions about supplemental feeding or honey harvesting. A sudden weight loss can indicate robbing or absconding, while weight gain suggests a strong nectar flow, allowing optimized timing for adding supers or relocating hives to target crops (Cejrowska et al., 2023). These metrics are particularly useful in migratory beekeeping, where real-time feedback on forage availability can improve site selection and reduce transport costs.

Acoustic monitoring represents another frontier in hive diagnostics. Using microphones or accelerometers embedded within hive walls, researchers have developed models to correlate sound frequency and vibration patterns with brood presence, forager return rates, and swarming preparations. Swarming, one of the most significant causes of colony division and production loss, can be predicted through characteristic sound signatures days in advance (Bencsik et al., 2011). By identifying this signal, beekeepers can apply swarm control measures proactively, reducing colony losses and preserving queen productivity. Similarly, unusual acoustic activity during off-hours may suggest predator attacks, mechanical disturbance, or behavioral stress, all of which can be logged and addressed using remotely accessible monitoring platforms.

Precision beekeeping tools also enable detailed assessments of queen performance. Prolonged queen failure, poor egg-laying patterns, or inconsistencies in brood development can be inferred from deviations in temperature cycles, reduction in foraging rates, or decreased hive weight gain. Advanced systems may integrate multiple sensor types to infer queen vitality without physically opening the hive, thus minimizing disruption and preserving thermal homeostasis. In breeding operations or queen-rearing enterprises, such technologies allow for non-invasive screening of queen quality, aiding in selection and record-keeping.

Pest and disease detection is another critical application. While most pathogens cannot be directly identified through sensor data, certain conditions associated with Varroa mite infestations, chalkbrood, or colony collapse disorder can produce observable changes in hive metrics. Declining internal temperature, erratic weight changes, or reductions in bee flight activity have been correlated with parasitic stress and immune suppression (Zacepins et al., 2015). When these patterns are integrated into machine learning models, the resulting predictive algorithms can generate early warnings, triggering interventions such as miticide application, queen replacement, or hive isolation before overt symptoms arise.

In addition to health monitoring, precision tools are increasingly used to optimize feeding strategies. Real-time data on hive mass and ambient weather can inform the decision to provide supplemental sugar syrup, protein patties, or pollen substitutes. This targeted feeding approach ensures that colonies receive resources when they are most needed—such as during nectar deaths or pre-wintering periods—while avoiding overfeeding or waste. Feeding interventions can be precisely timed and customized for each hive, improving resource use efficiency and reducing operating costs.

Some advanced systems also incorporate hive traffic analysis, using optical sensors or infrared counters at hive entrances to record the number of foraging bees exiting and returning (Table 1). These data can be used to estimate colony size, forager mortality, or the presence of drift behavior, all of which impact hive productivity and health. Traffic analysis has also been proposed as a method to monitor pesticide exposure, as sudden declines in returning foragers may signal field-level toxicity that warrants investigation (Colin et al., 2019).

Table 1: Sensor Technologies in Precision Beekeeping: Functions, Indicators, and Limitations

Sensor Type	Primary Function	Indicators Monitored	Use Cases	Limitations
Temperature Sensor	Brood health, hive vitality	Internal temperature fluctuations	Detect queen loss, colony collapse	Affected by seasonal variation
Humidity Sensor	Wax integrity, disease risk	Hive RH levels	Brood health, fungal risk monitoring	Less stable in outdoor setups
Weight Scale (Load Cell)	Foraging, nectar flow, robbing	Daily weight gain/loss	Harvest timing, feeding needs	Wind/rain interference
Acoustic Sensor	Swarming, queen loss, colony behavior	Frequency & amplitude of hive vibrations	Predict swarming, queen performance	Requires calibration, sound overlap
Bee Traffic Sensor	Activity and exposure monitoring	In/out bee counts	Colony strength, pesticide exposure tracking	Light & thermal interference
RFID Tags	Individual bee tracking	Bee lifespan, foraging pattern	Research on bee social behavior	Expensive, invasive, short lifespan

Altogether, these applications demonstrate how precision beekeeping technologies not only improve observation and record-keeping but fundamentally alter the management paradigm from reactive to predictive. By transforming raw sensor data into actionable insights, precision systems empower beekeepers to intervene early, personalize management, and support colony welfare with minimal disturbance. The continuous and non-invasive nature of these systems also aligns with animal welfare principles by reducing hive disruptions and allowing bees to maintain their natural rhythms. As these tools become more accessible and affordable, they are likely to shift from experimental to mainstream use, particularly in commercial and semi-professional operations seeking both sustainability and productivity gains.

Technological Integration and Data Analytics

The value of precision beekeeping lies not only in the deployment of isolated sensors but in the integration of these devices into cohesive, intelligent systems that enable predictive management and automated decision-making. As sensor arrays generate massive volumes of time-series data on temperature, humidity, weight, acoustic patterns, and bee traffic, there is a growing need for advanced analytical frameworks to convert raw data into actionable insights. This transformation is made possible through the use of machine learning, artificial intelligence (AI), and big data platforms, which collectively represent the analytical backbone of precision apiculture. These technologies allow beekeepers to detect trends, recognize anomalies, and anticipate future risks with far greater accuracy than traditional methods alone.

Machine learning algorithms have been employed to classify hive conditions based on sensor data, particularly for identifying brood presence, predicting swarming events, and detecting colony collapse. Supervised learning models, such as support vector machines and decision trees, can be trained on historical hive data to recognize patterns associated with specific health states or behavioral transitions. For example, temperature fluctuation profiles combined with acoustic signatures can distinguish between healthy, queenless, and pre-swarming colonies

(Meikle et al., 2018). Unsupervised learning methods, such as clustering algorithms, are useful for anomaly detection in large datasets where labeled data may be unavailable. These approaches are particularly promising for early-warning systems that flag unusual sensor combinations before visible symptoms appear.

Data fusion techniques are also essential to precision beekeeping because they allow multiple sensor streams to be analyzed collectively rather than in isolation. A single metric, such as weight loss, may have ambiguous implications unless it is contextualized by other indicators such as reduced bee traffic or declining internal temperature. By combining these variables through data fusion, AI systems can provide more nuanced interpretations of hive conditions, minimizing false positives and improving management recommendations. In commercial operations with hundreds or thousands of hives, automated analytics platforms reduce the cognitive burden on beekeepers and make large-scale monitoring feasible.

Cloud computing and remote access interfaces further enhance the utility of precision technologies by enabling real-time monitoring and multi-user collaboration. Many modern precision beekeeping systems are linked to cloud-based dashboards that display live sensor feeds, send push notifications for abnormal readings, and generate visual reports for seasonal analysis. These platforms often feature customizable thresholds, allowing users to set alerts based on species, climate, or management objectives. Some systems also offer integration with weather data, pesticide alerts, and flowering calendars, further contextualizing hive conditions in relation to broader environmental factors (Zacepins et al., 2022). As connectivity infrastructure improves, these tools are becoming increasingly viable even in remote or mobile apiary settings.

Despite these advancements, the effective application of data analytics in beekeeping faces several challenges. One key issue is the lack of standardization in sensor hardware and data formats, which makes it difficult to aggregate and compare data across systems or vendors. Proprietary software and closed architectures hinder interoperability and limit the scalability of precision solutions. Addressing this challenge requires the development of open-source platforms and standardized data protocols that facilitate cross-platform integration and long-term data storage. Another concern is data reliability, as sensor drift, power loss, or communication errors can result in gaps or inaccuracies that reduce trust in automated systems. Quality assurance protocols and periodic calibration of sensors are necessary to maintain data integrity.

There are also user-centric challenges, especially for small-scale beekeepers who may lack the technical expertise to interpret complex analytics or customize digital platforms. Simplifying user interfaces, providing training modules, and incorporating decision-support systems that offer clear, actionable guidance are essential steps toward broader adoption. Incorporating feedback mechanisms into platforms—where users can validate or dispute AI-generated diagnoses—can also help refine models over time and build user confidence in automated systems. Accessibility and affordability remain critical considerations, and efforts are underway to develop low-cost kits and open-hardware solutions that democratize access to precision tools.

Privacy, data ownership, and ethical concerns are emerging themes as precision technologies become more embedded in apicultural practice. Questions arise about who owns the data collected from hives, especially when commercial service providers or third-party platforms are involved. Additionally, as AI systems gain influence over management decisions, there is a risk of displacing beekeeper intuition and traditional ecological knowledge. Balancing the insights offered by machine learning with the experience of human caretakers will be crucial for ensuring that technology serves as a complement rather than a replacement.

In sum, the integration of sensor networks with data analytics transforms the role of technology in beekeeping from passive monitoring to intelligent management. Machine learning, cloud platforms, and decision-support systems enable early detection of stressors, reduce manual labor, and support evidence-based interventions. However, realizing the full potential of these tools requires overcoming interoperability challenges, ensuring data reliability, and designing user-friendly systems that align with the diverse realities of beekeeping worldwide. As the field matures, collaborative efforts between engineers, computer scientists, and beekeepers will be essential to ensure that technological innovation is both scientifically robust and practically impactful.

Environmental, Economic, and Ethical Considerations

The widespread adoption of precision beekeeping technologies raises important questions about environmental sustainability, economic accessibility, and the ethical treatment of honey bees. While these technologies promise improved efficiency and early problem detection, their deployment must be evaluated in the broader context of resource use, equity of access, and the potential for unintended consequences. A key environmental consideration is the energy consumption associated with sensor operation, wireless data transmission, and data storage in cloud servers. Although many precision beekeeping systems are designed to be energy-efficient and solar-powered, the cumulative footprint of hundreds or thousands of devices operating continuously should not be overlooked. The materials used in sensors, batteries, and communication hardware also introduce environmental concerns related to electronic waste, rare metal extraction, and system disposal, particularly in regions without robust recycling infrastructure (Tosi et al., 2022).

Despite these concerns, the environmental benefits of precision beekeeping may outweigh the costs if the technology enables more sustainable management. Early detection of colony stress, reduced need for chemical treatments, and more efficient feeding practices can minimize resource inputs and pesticide use, thereby reducing

environmental contamination. Furthermore, by allowing for more targeted and timely interventions, precision tools may reduce the total number of hive inspections, which lowers fuel usage and human-induced stress on bees, especially in large-scale migratory operations. These benefits are especially important in the context of global pollinator decline, where more informed and responsive management could support healthier colonies and improved ecosystem services (Potts et al., 2016).

From an economic standpoint, precision technologies present a double-edged sword. On one hand, they offer long-term savings by improving colony survival, optimizing harvest timing, and reducing labor costs. On the other hand, the initial investment in equipment, training, and maintenance may be prohibitive for smallholders, hobbyists, or beekeepers in low-resource settings. Many commercially available systems remain priced beyond the reach of the majority of the world's beekeepers, leading to a digital divide that could exacerbate existing inequalities in access to knowledge and profitability. Additionally, maintenance of such systems may require technical expertise and periodic replacement of components, which further adds to operational costs and complexity.

To address these issues, efforts have been made to develop low-cost, open-source alternatives that rely on off-the-shelf components and community-developed software. Initiatives focused on frugal innovation, particularly in Latin America, Asia, and Africa, have demonstrated the feasibility of DIY sensor kits that provide basic hive temperature or weight data at a fraction of the cost of commercial systems (Nicodemo et al., 2020). These innovations contribute to democratizing technology and fostering local adaptation but often lack the technical robustness or support services needed for broader adoption. Collaborations between research institutions, extension services, and grassroots organizations are critical to scaling these solutions, improving usability, and building trust among beekeeping communities.

Ethically, the growing reliance on technology in managing living organisms invites scrutiny regarding the boundaries of intervention. Honey bees are eusocial insects with complex communication systems and environmental sensitivities. While precision tools can help minimize unnecessary disruption, there is concern that continuous surveillance and over-optimization could prioritize productivity at the expense of natural behaviors and colony autonomy. For example, automated systems that trigger interventions based solely on algorithmic thresholds may override intuitive observations made by experienced beekeepers or fail to account for the unique dynamics of individual hives. Additionally, the use of tracking devices such as RFID tags on individual bees has raised questions about invasiveness and the potential stress caused by long-term sensor attachment (Leonhardt et al., 2019).

There are also broader ethical debates about data ownership and digital sovereignty. As sensor-equipped hives become data sources for commercial platforms, questions arise about who controls the data, how it is used, and whether beekeepers benefit fairly from insights derived from their operations. Transparency in data policies, fair pricing models, and open access to analytics outputs are important principles for ensuring that precision technologies empower rather than exploit their users. Furthermore, developers of these systems must engage with the ethical implications of datafication in agriculture and promote technologies that support sustainability, animal welfare, and user autonomy.

In conclusion, while precision beekeeping offers clear advantages in terms of monitoring accuracy, productivity gains, and reduced colony stress, it must be implemented thoughtfully to avoid creating new challenges in sustainability, equity, and ethics (Fig. 2). Environmental concerns about energy use and waste should be addressed through durable, modular, and energy-efficient designs. Economic barriers must be overcome through inclusive innovation and public–private partnerships that lower costs and build capacity. Ethical dilemmas surrounding bee welfare, technological dependency, and data governance require ongoing dialogue among stakeholders, including scientists, beekeepers, policymakers, and consumers. By embedding these considerations into the design and dissemination of precision beekeeping tools, the sector can evolve toward a future that is not only technologically advanced but also socially responsible and ecologically sound.

Conclusion and Future Directions

Precision beekeeping represents a promising evolution in the management of honey bee colonies, offering a path toward enhanced productivity, early problem detection, and improved welfare through the integration of sensor technologies, data analytics, and automated decision-making. By enabling real-time monitoring of internal hive conditions, foraging activity, and behavioral patterns, these technologies allow beekeepers to intervene more precisely, reduce colony stress, and optimize resource use. As global challenges such as climate variability, disease pressure, and pollinator decline continue to intensify, the capacity for predictive, data-driven management will become increasingly vital in ensuring both the viability of commercial beekeeping and the broader ecosystem services that honey bees provide.

Despite the technical advances, several challenges must be addressed for precision beekeeping to achieve widespread, equitable impact. Economic barriers remain a significant obstacle, particularly for small-scale or resource-limited beekeepers who lack access to capital or technical support. Open-source innovation, capacity-building initiatives, and public-sector investment will be crucial in democratizing these tools and ensuring they contribute to global pollinator health, not just commercial gain. Environmental sustainability must also remain a central design criterion, with emphasis on low-power, modular, and recyclable systems that reduce ecological

burden. Moreover, the sector must continue to explore ways of integrating sensor networks with other agricultural technologies, such as precision crop monitoring and landscape-level biodiversity assessments, to support a more interconnected and ecologically informed model of land management.
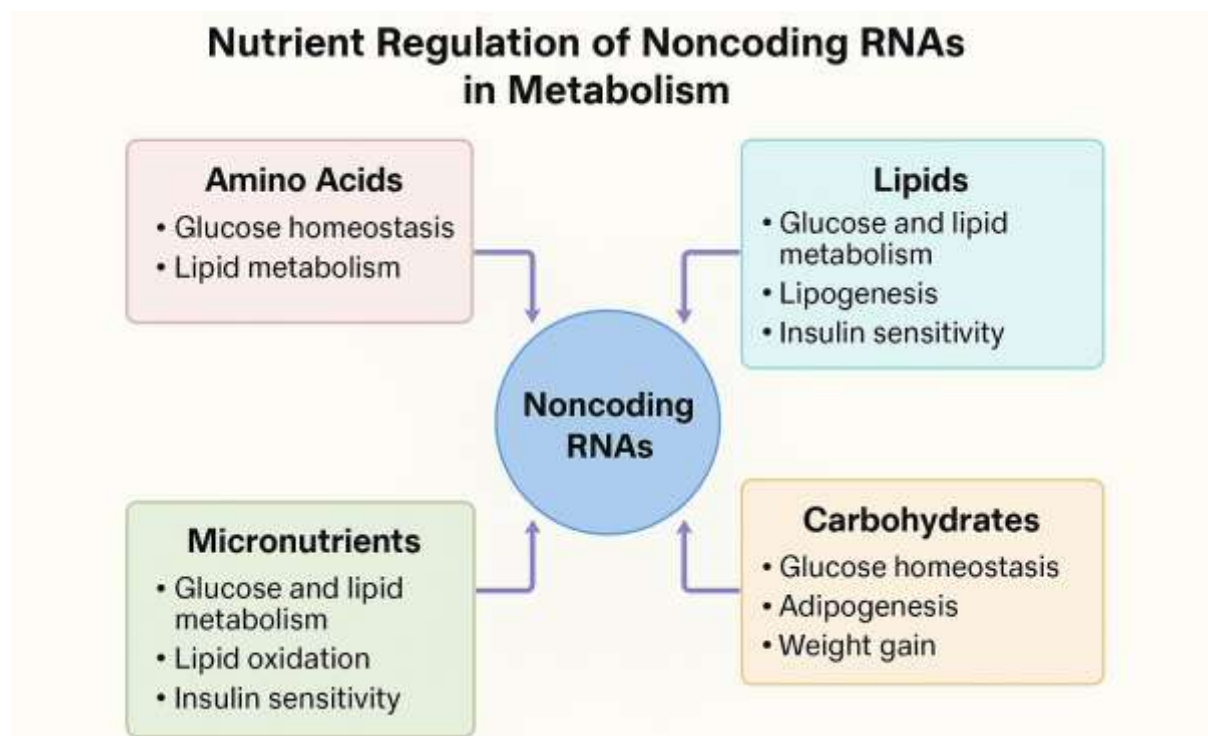

Fig. 2: Ethical-Ecological Tradeoffs in Precision Beekeeping.

Looking forward, the future of precision beekeeping lies in further miniaturization of sensors, longer battery life, and greater device interoperability to support scalable and user-friendly systems. The integration of artificial intelligence with increasingly rich datasets will enable more refined diagnostics and predictive models that account for hive individuality, seasonal variation, and landscape context. Emerging research into behavioral analytics and bee-level biometrics could open new possibilities for understanding social dynamics and stress responses within colonies. At the same time, ethical frameworks will be necessary to guide the development of technologies that respect the biological autonomy of bees and the cultural knowledge of beekeepers, ensuring that innovation does not outpace reflection.

In conclusion, precision beekeeping is not merely a set of digital tools but a reimagining of the relationship between humans and bees—one rooted in observation, responsiveness, and ecological stewardship. With careful attention to sustainability, inclusivity, and ethics, these technologies can help transition apiculture toward a more resilient, knowledge-driven future. Continued collaboration among researchers, engineers, beekeepers, and policymakers will be essential in shaping that future in ways that are not only technologically effective but also socially and environmentally responsible.

Conflict of Interest: The authors declare no conflict of interest.

Data Availability: Not applicable

Ethics Statement: Not applicable

Author's Contribution: HA conceived the idea and the review scheme and drafted the manuscript.

Generative AI Statements: The authors confirm that no generative-AI tools (including DeepSeek) were used in the writing or preparation of this manuscript.

Publisher's Note: The views and claims presented are solely those of the authors and do not necessarily reflect the

positions of their institutions, the publisher, editors, or reviewers. References to any products or manufacturers are for identification only and are neither guaranteed nor endorsed by the publisher/editors.

REFERENCES

Bencsik, M., Bencsik, J., Baxter, M., Lucian, A., Romieu, J., & Millet, M. (2011). Identification of the honey bee swarming process by analysing the time course of hive vibrations. *Computers and Electronics in Agriculture*, 76(1), 44–50. https://doi.org/10.1016/j.compag.2011.01.004

Cecchi, S., Zampella, M., Rossi, G., Cossu, R., & Longo, D. (2020). Internet of Things and Artificial Intelligence for sustainable beekeeping. *Computers and Electronics in Agriculture*, 170, 105254. https://doi.org/10.1016/j.compag.2020.105254

Cejrowska, M., Romaniuk, R., & Kosior, A. (2023). Beehive weight dynamics and its application in monitoring colony activity. *Sensors*, 23(4), 2141. https://doi.org/10.3390/s23042141

Colin, T., Meikle, W. G., Paten, A. M., & Barron, A. B. (2019). Long-term dynamics of honey bee colonies following exposure to chemical stress. *Science of the Total Environment*, 677, 660–670. https://doi.org/10.1016/j.scitotenv.2019.04.272

Klein, A. M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, 274(1608), 303–313. https://doi.org/10.1098/rspb.2006.3721

Leonhardt, S. D., Gallai, N., Garibaldi, L. A., Kuhlmann, M., & Klein, A. M. (2019). Economic gain, stability of pollination and bee diversity decrease from southern to northern Europe. *Biology Letters*, 15(1), 20180698. https://doi.org/10.1098/rsbl.2018.0698

Meikle, W. G., Holst, N., & Mercadier, G. (2006). Using within-day hive weight changes to measure environmental effects on honey bees. *Apidologie*, 37(1), 77–85. https://doi.org/10.1051/apido:2005058

Meikle, W. G., Holst, N., Colin, T., Weiss, M., Carroll, M., & McDermott, E. (2018). Combining continuous hive weight data and hive temperature to identify swarming and queen events in honey bee colonies. *Computers and Electronics in Agriculture*, 150, 489–496. https://doi.org/10.1016/j.compag.2018.05.031

Nicodemo, D., Oliveira, D. L., Couto, R. H. N., & Malaspina, O. (2020). Sustainable beekeeping technologies: Trends and prospects for smallholders. *Journal of Apicultural Research*, 59(5), 851–861. https://doi.org/10.1080/00218839.2020.1759068

Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., ... & Viana, B. F. (2016). Safeguarding pollinators and their values to human well-being. *Nature*, 540(7632), 220–229. https://doi.org/10.1038/nature20588

Streit, S., Bock, F., Pirk, C. W. W., & Tautz, J. (2003). Automatic life-long monitoring of individual insect behaviour now possible. *Zoology*, 106(3), 169–171. https://doi.org/10.1078/0944-2006-00107

Tosi, S., Nieh, J. C., Sgolastra, F., Cabbri, R., & Medrzycki, P. (2022). Neonicotinoid pesticides and pollinators: Insights from recent research and implications for future risk assessments. *Ecotoxicology*, 31, 781–795. https://doi.org/10.1007/s10646-021-02483-4

Zacepins, A., Brusbardis, V., Meitalovs, J., & Stalidzans, E. (2015). Challenges in the development of precision beekeeping. *Biosystems Engineering*, 130, 60–71.

Zacepins, A., Kviesis, A., Stalidzans, E., & Liepins, A. (2022). The development of precision apiculture and IoT-based beekeeping systems: A review. *Agronomy*, 12(2), 488.