

near-term direction is multimodal sensing linked to predictive decision support. Reviews indicate that single parameters are informative but that simultaneous monitoring of multiple variables gives a fuller picture of colony status, and smart-beehive research is now moving from basic reporting toward predictive analytics and behavioral inference. Future systems are therefore expected to combine multiple sensor types with embedded machine learning, anomaly detection, and open benchmarking datasets to improve real-time forecasting across seasons.

Field studies already show that digital monitoring can translate into production-relevant decisions. Precision apiculture platforms have linked drops in honey production to lower external temperature and strong wind events, and they can identify the start and end of production, guide supering decisions, and warn of swarming risk. Broader IoT syntheses similarly conclude that continuous remote data streams support early problem detection, more targeted interventions, and better resource efficiency than routine inspection alone. The main barriers are no longer proof of concept, but deployment and usability. Current reviews emphasize the need for real-world validation, beekeeper-centered design, cost-effectiveness, and stronger collaboration between engineers and domain experts if smart hive systems are to scale beyond fragmented pilot studies (Šabić et al., 2025). Adoption will also depend on solving implementation costs, data security, and beekeeper training, since these remain recognized obstacles to integrating IoT tools into conventional practice.

The main conclusion across this literature is that sustainable honey production will depend on integrated seasonal management, not isolated practices, because colony health and productivity reflect interacting effects of climate, forage, pests, and beekeeper decisions. Large observational datasets further show that better overall management is associated with lower winter losses, even though no set of practices eliminates all risk (Steinhauer et al., 2021).

A clear research priority is improving evidence for region-specific forage resilience. Recent African work shows that forage availability is shaped by both season and land use, with agricultural lowlands offering fewer and less diverse resources during dry periods, while exotic plants now dominate much of the recorded diet. Future work should therefore compare the nutritional value of native and exotic forage across seasons and test how forage design can support colony productivity under climate change. Another priority is building more robust evidence pipelines for management innovation. Existing practice reviews show that most field interventions have focused on Varroa and late-season management, while also identifying major regional research gaps that limit evidence-based advisory services. Research infrastructure itself also needs attention, because methods that extend winter experimentation can alter learning and thermoregulation, making validation under realistic colony conditions essential.

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