Impact of Wireless Network Electromagnetic Fields on Navigation Abilities and Homing of Honey Bees

[1] **Aleksei Seto**
[1] Atlantic Breeze Group, LLC Founder, CEO Bainbridge, GA, United States

Received: 23th Nov 2025 | Received Revised Version: 29th Dec 2025 | Accepted: 17th Jan 2026 | Published: 07th Feb 2026

Volume 08 Issue 02 2026 | Crossref DOI: 10.37547/tajet/Volume08Issue02-05

Abstract

The article examines the influence of radiofrequency electromagnetic fields (RF-EMF) produced by wireless infrastructure on the navigation abilities and homing success of the Western honey bee Apis mellifera. The relevance of this work is determined by the fact that pollination is an economically and ecosystemically significant service, while the density of RF-EMF sources in landscapes is rapidly increasing and transforming previously local impacts into a quasi-permanent background. This review aims to integrate data on bee orientation mechanisms, exposure metrics, and regimes (ranging from electric field strength and power density to SAR/surface-averaged absorbed power density), as well as behavioral protocols that enable the detection of hive-return disruptions under realistic conditions. Scientific novelty lies in a cognitive-ecological interpretation of navigation as a multichannel ensemble (solar compass with circadian compensation, polarization cues, landscape memory, and potential magnetic sensitivity), within which RF-EMF are considered not as an off-switch for orientation but as a factor that shifts channel weights and increases the probability of errors. Additionally, the necessity of linking field dosimetry with the modeling of energy absorption by the bee body is emphasized, because the frequency structure of the environment can alter absorbed power disproportionately to the mean background. The main conclusions can be summarized as a fundamental distinction between short-term and chronic exposure: in a particular field test at frequencies typical of Wi-Fi, a reduction in the return proportion was observed under prolonged exposure, whereas short irradiation before release did not demonstrate a comparable effect. Practically, this supports a precautionary approach (reasonable hive placement and minimization of unnecessary transmitters near colonies) alongside standardized recording of context and behavioral indicators. The article will be helpful for researchers of insect behavior, specialists in radiobiology/ecotoxicology, as well as practitioners of beekeeping and agroecology who assess the risks associated with the anthropogenic background.

Keywords: honey bee, navigation, homing, radiofrequency electromagnetic fields, Wi-Fi, 5G

Cite This Article: Seto, A. (2026). Impact of Wireless Network Electromagnetic Fields on Navigation Abilities and Homing of Honey Bees. The American Journal of Engineering and Technology, 8(2), 34–43. https://doi.org/10.37547/tajet/Volume08Issue02-05

Introduction

Insect pollination remains one of those ecosystem services that are rarely noticeable in everyday life, yet are continuously embedded in food security and the stability of natural communities. The honey bee is used as a managed pollinator in agroecosystems. She simultaneously serves as a convenient model for assessing how external factors affect foraging, learning, and return to the hive. The contribution of pollination is manifested not only through production quantity but also through its quality: a global meta-analysis across 48 crops showed that, in the presence of pollinators, aggregate quality indicators increase on average by 23% (confidence interval 16–30%), with the effect being especially pronounced for traits associated with fruit marketability and storage life (Gazzea et al., 2023). At the macroeconomic scale, dependence is also tangible: according to an estimate for the global market, approximately 17% of the value of the worldwide harvest is attributable to crops that depend on pollination, and their share in international trade reaches 28% (Feuerbacher, 2025). Monetary valuations of the pollination service itself, aggregated across major crops, vary widely (approximately $195–387 billion per year; under alternative assumptions, the range expands to $267–657 billion), reflecting both methodological differences and unequal crop vulnerability to pollination deficits (Porto et al., 2020).

Against this background, the physical environment in which bees perform flights is changing rapidly: wireless communication infrastructure is becoming denser, and radiofrequency electromagnetic fields are shifting from a rare local factor to a continuously present background. Field measurements in ten European countries show that exposure levels differ by environment type and usage scenario: in a no data transmission mode, country means lie within 0.33–1.72 mW/m², and under artificially induced intensive data transmission, they increased, with a notable contribution from the fifth-generation band around 3.5 GHz (Veludo et al., 2025). The question is therefore formulated not abstractly but applied: can such a background, especially under prolonged exposure, interfere with mechanisms of orientation and return to the hive, given that even in a controlled field experiment at 2.4 and 5.8 GHz (typical of Wi-Fi) a decrease in homing success was observed specifically after prolonged rather than short-term irradiation (Treder et al., 2023).

Materials and Methodology

The work is constructed as an integrative review with elements of comparative and content analysis, based on a corpus of 17 selected sources, academic articles, regulatory-methodological documents, and technical specifications, that jointly describe (i) the significance of pollination and its economic-ecosystem context, (ii) the physics and exposure metrics of radiofrequency electromagnetic fields (RF-EMF), and (iii) behavioral and biophysical protocols for assessing navigation and homing in Apis mellifera.

At the level of the theoretical framework, a cognitive-ecological view of navigation as a multichannel ensemble is used (solar compass with circadian compensation, polarization cues, landscape memory, and potentially auxiliary magnetic sensitivity), which provides a basis for interpreting RF effects not as an off switch for orientation but as a factor capable of shifting channel weights and increasing the probability of return errors; this block relies on a synthesis of navigation mechanisms and the role of learning/memory (Doussot et al., 2023; Menzel, 2023), experimental validation of the polarization channel under controlled conditions (Kobayashi et al., 2020), as well as data on transfer/generalization of navigation memory (Bullinger et al., 2023) and physicochemical evidence for magnetite presence in tissues (Dandy et al., 2024).

The exposure component of the methodology is implemented by comparing the technical frequency map of wireless environments (Wi-Fi band families and their evolution: IEEE Standards Association, 2023; delineation of 5G user equipment frequency domains: ETSI, 2025) with regulatory definitions of measurable quantities and dose-averaging principles (incident electric field strength/incident power density; SAR and surface-averaged absorbed power density; temporal averaging windows: ICNIRP, 2020). Thereafter, as empirical anchors for realistic field levels and frequency structure, multi-country microenvironment measurements with emphasis on the 5G contribution around 3.5 GHz (Veludo et al., 2025) are used together with linking in situ measurements at hives to computational modeling of energy absorption by the bee body, demonstrating that frequency redistribution can change absorbed power disproportionately to mean background (Thielens et al., 2020).

The behavioral component of the methodology is defined through comparative analysis of experimental assays in which endpoints % returned and return time are treated as an integral indicator of navigation-system functioning, while distinguishing short-term and chronic exposure is fixed as a key design factor; the central empirical basis here is a field experiment with defined exposure at frequencies typical of wireless networks, showing reduced homing success under prolonged irradiation in the absence of an effect for short irradiation before release (Treder et al., 2023).

To localize where the route breaks and to increase observability of individual trajectories and returns, the methodological review is supplemented with technologies for automatic registration at the hive entrance (RFID monitoring) and trajectory tracking (harmonic radar), which are interpreted as tools for decomposing the integral outcome into departure/arrival patterns and search geometry (Alburaki et al., 2021; Woodgate et al., 2021). Finally, to avoid reducing RF-EMF effects exclusively to compass hypotheses, the framework includes a layer of indirect physiological-behavioral markers of stress response under long-term field exposure (oxidative stress as a possible accompanying mechanism/mediator of behavioral change: Vilić et al., 2024), and the macroecological context of the importance of possible navigation shifts is consolidated through data on pollinator effects on crop quality and economic valuations of pollination (Gazzea et al., 2023; Porto et al., 2020) and through estimates of the contribution of pollination-dependent crops to global food security and trade (Feuerbacher, 2025).

Results and Discussion

Honey bee navigation is organized as a multichannel system, in which several information sources mutually support each other. Under cue conflicts, the cue weight is reweighted depending on flight conditions and experience. A foraging bee solves the problem of search and return at distances of several kilometers while maintaining attachment to the hive and learned foraging sites; therefore, orientation cannot be reduced to a single compass or a single type of memory (Doussot et al., 2023). A 2023 review emphasizes that the backbone of this system is a solar compass with circadian compensation: the direction of the Sun is interpreted via internal clocks, which allows for the correction of the diurnal azimuth shift and the maintenance of a stable metric route scheme (Menzel, 2023). For this reason, any external influences that distort sensory inputs or disrupt alignment between compass information and landscape memory can potentially affect return accuracy, even if each channel remains almost functional.

The sky provides not only the position of the Sun but also a polarization pattern, which becomes especially valuable when the Sun is partially obscured and when direct landmarks are unreliable. Flight-simulator experiments demonstrated that bees adjust their direction in response to the rotation of the polarization angle. When the dorsal rim area of the eye is bilaterally covered, the characteristic response disappears, indicating specialized visual input to the compass subsystem (Kobayashi et al., 2020). At the same time, the road home is not built solely on celestial cues: bees form long-term landscape memory in which visual structures are linked with compass direction and can be retrieved by individual cues or their combinations. A 2023 review describes landscape memory as a set of elements associated with directions, emphasizing the role of exploratory flights in its formation (Menzel, 2023). A 2023 field approach further demonstrates that learned cues can generalize to new test conditions, indicating that memory is not limited to mechanical picture recognition. Still, it allows the transfer of orientation rules (Bullinger et al., 2023).

Possible magnetic sensitivity in bees is traditionally considered an auxiliary channel proper under optical information deficits. Still, it remains the most controversial in its mechanism and in its fundamental role during routine flight. Contemporary physicochemical evidence supports the possibility of magnetic input: a 2024 study reports biogenic magnetite nanoparticles in the abdomen and, for the first time, in antennae, and the authors explicitly link these findings to the need for new experiments to confirm or refute functional participation of these structures in magnetic field perception (Dandy et al., 2024). It is essential to distinguish between the presence of a substrate and its contribution to navigation: even if a magnetic channel exists, it likely operates in conjunction with solar and visual compasses. It can be masked by other cues or expressed only under specific conditions. This ensemble nature makes the topic of RF-EMF fundamentally complex: exposure may not disable navigation entirely but may shift the balance between channels and thereby increase the probability of return errors when the environment already demands high coherence among memory, compass, and current sensory signals (Menzel, 2023). Honeybee Navigation Challenges are shown in Figure 1.

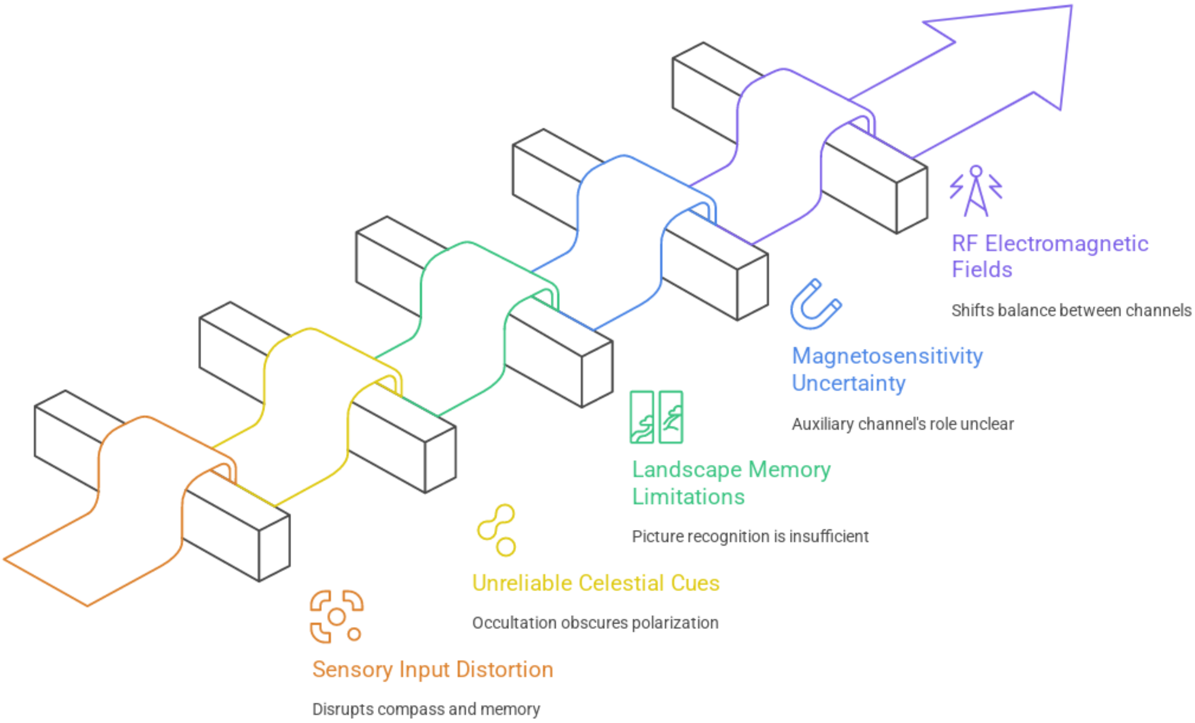

Fig. 1. Honeybee Navigation Challenges

To discuss whether anthropogenic radiofrequency background can interfere with the navigation cues described above, it is necessary to specify what is meant by electromagnetic fields of wireless networks and in which ranges they arise. In household wireless local area networks, the most common bands are around 2.4 and 5 GHz, which have been historically established within families of data transmission standards (IEEE Standards Association, 2023). For cellular communications, the frequency geography is broader and formalized through operational frequency domains: in the specification for user equipment, the range below 7.125 GHz is assigned to the first domain (410–7125 MHz), while higher frequencies are placed in the second domain, within which subranges 24.25–52.6 GHz and 52.6–71 GHz are allocated (ETSI, 2025). This is biophysically important: as frequency increases, wavelength, tissue penetration depth, and energy absorption regimes change, and therefore the way the field can interact with an insect organism also changes, not necessarily by destroying a single sensory channel, but by shifting the overall signal balance on which hive return relies.

Exposure is a set of parameters defining the dose pattern. In practical measurements, electric field strength and incident power density are often used; in the International Commission on Non-Ionizing Radiation Protection guidelines these appear as incident electric field strength and incident power density, while for absorption assessment in the organism restrictions are introduced on specific energy absorption rate (for the range up to 6 GHz) and surface-averaged absorbed power density (for higher frequencies) (ICNIRP, 2020). The relationship with distance is fundamental: in the far field, power decreases with the square of the distance. However, in real-world conditions, reflections, shielding, and antenna directivity also play a role, so that the same source can create very different field levels at nearby points. It is also important that even the mean background in natural settings is measurable and can be small: near hives in Belgium, the mean measured value was about 0.06 V/m, while the estimate of realistically absorbed power for bee models of different castes and stages was approximately 0.1–0.7 nW (Thielens et al., 2020). These estimates serve as reference numbers; without them, the discussion of influence inevitably becomes a dispute over words.

The distinction between short-term and chronic exposure is defined not only by duration but also by how energy is averaged over time and how the organism has time to adjust. In regulatory logic, this is reflected directly: for example, in the same guidelines, whole-body averaging is considered over 30 minutes, while local restrictions are considered over 6 minutes, with both continuous and intermittent regimes separately specified (ICNIRP, 2020). In biological logic, chronic exposure differs in that it encompasses periods of development, maturation, and learning, meaning it can become embedded in the formation of those very navigation strategies and landscape memory, whereas short-term exposure more often tests only the instantaneous robustness of an already tuned system. The observation that reduced return success was manifested under long-term irradiation at 2.4 and 5.8 GHz but was not detected after short exposure illustrates this difference and suggests why subsequent sections must separate effects at the level of flight from impact at the level of long-term behavioral tuning (Treder et al., 2023).

Field homing tests are based on a simple idea: if navigation is an ensemble of solar compass, polarization cues, and landscape memory, then the overall functionality of the system will be expressed in how many bees and how quickly they return after forced displacement to an unfamiliar point. For this, foraging bees are typically collected at the entrance, individually marked, transported a fixed distance, and their return flight and return time are recorded. This indicator simultaneously assesses orientation, memory, wing-muscle work, and energy metabolism, and is therefore often used as an integral endpoint. In RF-EMF studies, this approach is beneficial because it allows testing not the hypothesis that something changed in the nervous system, but the practical question of whether the ability to return to the hive is disrupted under realistic flight conditions (Treder et al., 2023).

When the return flight alone is insufficient, and it is necessary to understand where the route breaks, trajectory registration is added. At the hive entrance, this is done via radiofrequency tags: the bee carries a lightweight transponder, and antennas at the entrance automatically register departures and arrivals, allowing large datasets to be collected at the individual and colony levels without requiring observers at each hive. The practical side of such systems is described in detail in a 2021 methodological paper, which shows how a multi-antenna setup can simultaneously monitor dozens of colonies and record their behavior, including queen and drone flights (Alburaki et al., 2021). For actual routes in the air, harmonic radar is used, providing continuous flight traces in the landscape and allowing observation of switching between straight and looping movement segments. In honeybees, this approach was employed in 2021 to map drone search flights and stable spatial nodes, demonstrating the method's resolving power for real flights rather than laboratory surrogates (Woodgate et al., 2021). Attempts to apply satellite coordinate loggers to insects exist, but for honey bees, a key limitation remains the device mass and the aerodynamic cost of the payload; therefore, in practice, entrance tags are often combined with radar and video observation (Alburaki et al., 2021).

Laboratory paradigms are necessary when the field has too many degrees of freedom: the animal can be set, visual flow can be controlled, and polarization cues can be independently switched on and off, allowing the vulnerability of particular navigation channels to be tested. In flight simulators, turning responses and course choice under polarization rotation are measured, enabling a quantitative assessment of the sky-compass channel without the use of landscape landmarks. In tethered flying bees, it has been demonstrated that movements are aligned with the rotation of the polarization stimulus, indicating directed orientation by polarization (Kobayashi et al., 2020). In parallel, learning and memory tasks (e.g., associative conditioning) are used to separate changes in cognitive processing from purely motor effects: this is important because RF exposure may not jam sensors directly but may disrupt coordination among internal clocks, visual cues, and spatial memory retrieval, i.e., affecting system interfaces rather than its separate elements (Treder et al., 2023).

A critical part of any RF-field experiment is dosimetry: it is necessary not simply to specify frequency, but to measure field strength and power density at flight points and at the hive, account for geometry, distances, and emission mode, and then link the incident field to how much energy the bee body actually absorbs at different frequencies. This is why contemporary literature increasingly combines in situ measurements with computational insect models; for example, a 2020 study based on microtomographic bee models and hive measurements shows that even redistribution of a small fraction of power (10%) from below 3 GHz into higher frequencies can increase absorbed power by more than threefold, i.e., frequency structure may be more critical than mean background level (Thielens et al., 2020). Against this background, field-test results appear as follows: under realistic irradiation in Wi-Fi bands, prolonged exposure spanning development and early life in the hive reduced the proportion of successful returns (95.2% in control versus 78.6% in exposure; statistical significance p = 0.0064), whereas short exposure of about 40 minutes immediately before release did not yield an effect on the return proportion (on average 90.0% versus 86.6%; p = 0.4696) (Treder et al., 2023). Finally, there are indirect behavioral and physiological indicators that can accompany navigation shifts: in experiments with mobile phones, increase of alarm acoustic signals of worker bees was recorded, and in a one-year field exposure at 900 MHz changes in oxidative stress markers were reported that depended on developmental stage and field level, which more strongly indicates a stress component of the response than a single compass mechanism (Vilić et al., 2024). Table 1 illustrates Navigation & RF/EMF Effects in Honeybees.

Table 1. Navigation & RF/EMF Effects in Honeybees: Core Experimental Assays and Readouts

Approach	What you measure	Tool/setup	Why is it used
Field homing return test	% returned, return time	tag → displace a fixed distance → record returns	integrated navigation performance
RFID at hive entrance	departures/arrivals, delays	transponder + entrance antennas	high-throughput individual monitoring
Harmonic radar	flight path, straight vs looping segments, hotspots	radar tracking in a landscape	localize where the route breaks down
Lab flight simulators (polarization)	heading choice / turning response	tethered flight + controlled polarized light	isolate the sky-compass channel
Learning & memory assays	learning/memory scores	associative conditioning tasks	separate cognitive vs motor effects
Dosimetry + modeling	field/power density, absorbed energy	measurements + computational bee model	link exposure to actual absorbed dose
Indirect stress markers	alarm sounds, oxidative stress	acoustics/biomarkers	capture stress-related responses

If it is accepted that hive return relies on several interchangeable cues, the most natural hypothesis is not switching off navigation but disrupting coordination among channels. One candidate vulnerability is magnetic sensitivity, which is associated with either magnetite particles in tissues or photochemical processes in light-sensitive proteins. A radiofrequency field may interfere with these processes at the microscale: either by altering the mechanical state of magnetic inclusions or by affecting chemical pairs of intermediate radicals on which sensitivity to weak magnetic impact depends. However, even if such a channel exists, it likely functions as a reserve and is expressed more strongly under conditions of poor visual surroundings; therefore, the effect of the radiofrequency background may not always be noticeable, but mainly where visual and celestial cues are incomplete or contradictory.

Another group of hypotheses concern learning, memory, and signal integration. Navigation requires not only recognizing landmarks but also binding them to direction, time of day, and the current state of the organism; any slight shift in sensory processing can increase decision noise without causing gross behavioral breakdowns. RF exposure in this case is considered a factor that may alter the excitability of neural circuits, the balance of inhibition and excitation, or the speed of memory consolidation after orientation flights. The expected consequence, then, is not a loss of flight ability but an increased fraction of course-selection errors, more frequent search loops, and an increased return time, especially in young foragers whose spatial memory is still developing.

Finally, the stress-physiological and energetic component should be considered. Even if the field does not act directly on compass mechanisms, it can alter the overall stress level, affect redox balance, and thereby impact flight motivation, readiness for long trips, and resilience to additional loads, such as high temperatures, food deficits, or parasitic pressure. The thermal aspect here is not limited to perceptible heating: frequency-dependent energy absorption can lead to local tissue changes or increase thermoregulation demands, and under chronic exposure, this can accumulate as hidden costs. As a result, navigation errors may be secondary, as a manifestation that the organism more often chooses conservative strategies, depletes faster, or recovers worse after flights. Therefore, the same external stimulus yields different behavioral outcomes depending on exposure duration and the combination of accompanying factors.

In the face of uncertain factors, it is reasonable to proceed from the precautionary principle and select low-cost measures that reduce the probability of chronic exposure. Practically, this means not attempting to shield an apiary at any cost, but avoiding clearly excessive sources near hives. Hives are better placed at some distance from points of continuous data transmission and from places where communication equipment is concentrated. Within wintering rooms and pavilions, active transmitters should not be placed in immediate proximity to colonies. If cameras, sensors, or routers are used in the apiary, it is helpful to select modes with minimal power consumption and infrequent transmission.

Additionally, it is beneficial to separate electronics from hives by physical distance and to use simple screens made of construction materials, which simultaneously protect from wind and precipitation. Such a strategy does not require precise confidence in the exposure mechanism. It is consistent with the view that potential risk is more often associated with a long-term rather than short-term background.

To understand whether something substantial is occurring under particular conditions, observing colony behavior is more critical than disputing theories. The most informative simple indicators are the fraction of returning foragers after a working day, the rhythm of departures and arrivals during peak flow hours, the presence of prolonged search flights, as well as overall losses of flying bees manifested as weakening foraging activity under an unchanged forage base. It is helpful to track signs of orientation disruption, such as the aggregation of bees at others' entrances, prolonged circling before landing, and delays after release during displacement at a familiar distance. Ideally, observations are complemented by regular assessment of colony strength, brood, and stores, because changes in foraging and task allocation within the colony can mask navigation disturbances.

For correct inferences, the key is disciplined data recording. Otherwise, any effect will be indistinguishable from randomness and seasonal shifts. In a log, it is advisable to record hive location and orientation, distances to noticeable radiation sources and power lines, changes in communication infrastructure around the apiary, as well as weather conditions, nectar flow state, parasite treatments, and drug applications. It is also essential to record what is often forgotten: time of day and season, because the solar compass and polarization cues change, and with them, the load on landscape memory changes. If deterioration of return is suspected, comparability of conditions must be maintained by avoiding simultaneous changes to multiple factors. Otherwise, the cause becomes irreducibly confounded with management, forage situation, or diseases. Such ecological bookkeeping does not render conclusions final, but instead transforms observations into testable data, allowing for the distinction between a stable signal and noise. Beehive Protection Strategies are illustrated in Figure 2.

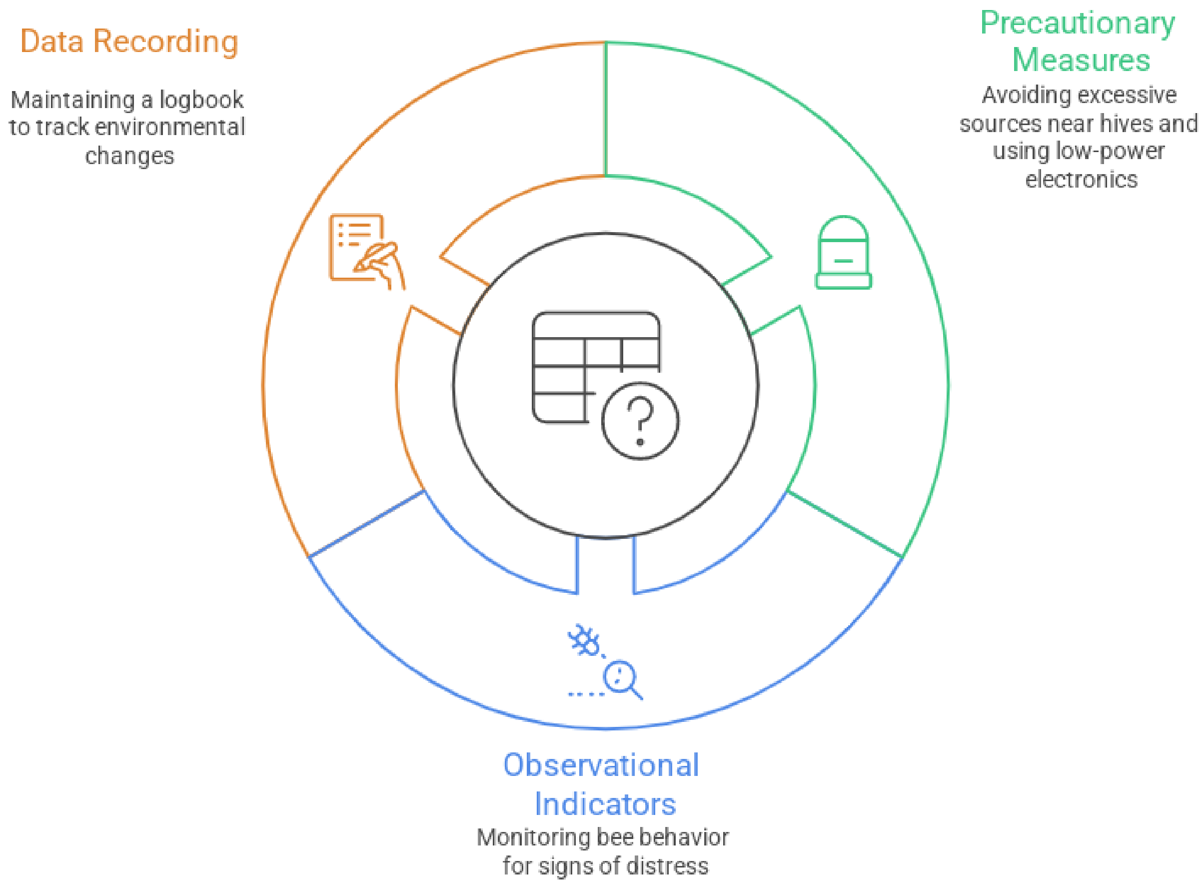

Fig. 2. Beehive Protection Strategies

Thus, the practical inference from the precautionary principle is to manage the background rather than fight it. By reducing unnecessary exposure through the reasonable placement of hives and household equipment, and simultaneously establishing a strict yet straightforward observation system, colonies can be protected. At the same time, data suitable for interpretation can be obtained. At the apiary level, this means that any assumptions about the influence of electromagnetic fields should rely not on single episodes but on repeatable behavioral signs and comparable records of environment, season, and colony condition; precisely this coupling of risk minimization and control of variables makes local decisions justified and allows separating a possible field effect from more likely factors, including forage situation, parasitic load, and weather fluctuations.

Conclusion

Taken together, the presented materials allow electromagnetic fields from wireless infrastructure to be regarded not as an exotic, local irritant, but as a stable component of the physical environment in which the honey bee performs its key tasks for ecosystems, including food search and return to the hive. Against the background of measurable exposure levels in real landscapes and under changing data-transmission scenarios, the question of biological significance shifts from the abstract can the field affect? to the more operational in which regimes and under which durations can exposure disrupt the integral behavioral outcome, i.e., homing success itself, through which navigation functionality as a system is expressed.

It is critically vital that bee navigation is described as a multichannel ensemble in which the solar compass with circadian compensation, polarization cues, and long-term landscape memory not only coexist but mutually calibrate one another; therefore, the most plausible framework for discussing anthropogenic radiofrequency background is not an orientation shutoff scenario but a scenario of gradual destabilization of cue coordination. In this logic, even small, not necessarily catastrophic shifts in one link, whether a vulnerable reserve magnetic input, fine tuning of sensory integration, or parameters of spatial memory consolidation, can manifest as increased error probability, extended searching, and reduced return proportion specifically where the environment imposes heightened demands on coherence among compass, time of day, and retrieval of landscape traces.

The empirical picture underlying the discussion highlights the fundamental distinction between short-term and chronic exposure: in a field homing test at Wi-Fi-typical frequencies, reduced return success was observed after prolonged exposure spanning early life in the hive, whereas a comparable effect did not accompany short exposure immediately before release on return proportion. This distinction is meaning-forming because it shifts focus from instantaneous interference to more inertial processes of behavioral tuning, learning, route formation, and calibration of navigation strategies, where a small addition of noise or a shift in signal balance can accumulate and manifest not as a single failure but as a statistically detectable loss of reliability.

A separate methodological line foregrounds dosimetry and environmental frequency structure: mere statements about field presence are insufficient if absorbed power depends not only on distance and mean power density, but also on frequency distribution, emission regime, and geometry. For this reason, coupling in situ measurements with absorption modeling and using integral field endpoints (return percentage, return time), supplemented by high-throughput entrance monitoring (RFID) and trajectory tracking (harmonic radar), appears not merely convenient but necessary: it allows discussing radiofrequency background influence in terms of comparable doses and reproducible behavioral outcomes rather than in terms of difficult-to-test assumptions about damage to particular sensors.

At the same time, a practical interpretation predictably converges on caution. Under mechanistic uncertainty and exposure heterogeneity, a reasonable conclusion reduces to managing the background rather than attempting to defeat it. Placing hives away from locations with constant, intensive data transmission, avoiding positioning active household transmitters directly adjacent to colonies, and selecting gentle operating modes for apiary electronics are logically consistent with the framework that associates risk primarily with prolonged exposure. Simultaneously, the strict recording of context, weather, season, forage situation, parasitoid load, and changes in surrounding communication infrastructure turns observations into interpretable data, allowing for the separation of a possible radiofrequency contribution from more likely and often stronger drivers of colony dynamics.

Thus, the present work embeds the problem of wireless electromagnetic fields into the contemporary understanding of bee navigation as an ensemble of interchangeable cues, emphasizing that biologically meaningful effects should be sought primarily in the plane of long-term behavioral tuning and stress-physiological costs, rather than only in the plane of instantaneous sensory interference. From this follows a scientific perspective: further studies should maintain simultaneously three optics, precise dosimetry accounting for frequencies and regimes, behavioral tests sensitive to cue-coordination errors among channels, and designs capable of distinguishing short-term robustness of an already tuned system from effects arising under chronic exposure during development, learning, and formation of navigation memory.

References

1. Alburaki, M., Madella, S., & Corona, M. (2021). RFID Technology Serving Honey Bee Research: A Comprehensive Description of a 32-Antenna System to Study Honey Bee and Queen Behavior. *Applied System Innovation*, *4*(4), 88. https://doi.org/10.3390/asi4040088
2. Bullinger, E., Greggers, U., & Menzel, R. (2023). Generalization of navigation memory in honeybees. *Frontiers in Behavioral Neuroscience*, *17*, 1070957. https://doi.org/10.3389/fnbeh.2023.1070957
3. Dandy, J., Alves, O. C., Abreu, F., & Acosta-Avalos, D. (2024). Magnetite in the abdomen and antennae of Apis mellifera honeybees. *Journal of Biological Physics*, *50*(2), 215–228. https://doi.org/10.1007/s10867-024-09656-4
4. Doussot, C., Purdy, J., & Lihoreau, M. (2023). Navigation: Cognition, learning, and memory. In *The Foraging Behavior of the Honey Bee (Apis mellifera, L.)* (pp. 85–104). Academic Press. https://doi.org/10.1016/B978-0-323-91793-3.00007-9
5. ETSI. (2025). *5G User Equipment radio transmission and reception*. ETSI. https://www.etsi.org/deliver/etsi_ts/138100_138199/13810101/17.18.00_60/ts_13810101v171800p.pdf

6. Feuerbacher, A. (2025). Pollinator declines, international trade and global food security: Reassessing the global economic and nutritional impacts. *Ecological Economics*, *232*, 108565. https://doi.org/10.1016/j.ecolecon.2025.108565
7. Gazzea, E., Batáry, P., & Marini, L. (2023). Global meta-analysis shows reduced quality of food crops under inadequate animal pollination. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-40231-y
8. ICNIRP. (2020). Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz). *Health Physics*, *118*(5), 483–524. https://doi.org/10.1097/hp.0000000000001210
9. IEEE Standards Association. (2023, May 16). *The Evolution of Wi-Fi Technology and Standards*. IEEE Standards Association. https://standards.ieee.org/beyond-standards/the-evolution-of-wi-fi-technology-and-standards/
10. Kobayashi, N., Okada, R., & Sakura, M. (2020). Orientation to polarized light in tethered flying honeybees. *Journal of Experimental Biology*, *223*(23), jeb228254. https://doi.org/10.1242/jeb.228254
11. Menzel, R. (2023). Navigation and dance communication in honeybees: a cognitive perspective. *Journal of Comparative Physiology A-Neuroethology Sensory Neural and Behavioral Physiology*, *209*(4), 515–527. https://doi.org/10.1007/s00359-023-01619-9
12. Porto, R. G., de Almeida, R. F., Cruz-Neto, O., Tabarelli, M., Viana, B. F., Peres, C. A., & Lopes, A. V. (2020). Pollination ecosystem services: A comprehensive review of economic values, research funding and policy actions. *Food Security*, *12*(6), 1425–1442. https://doi.org/10.1007/s12571-020-01043-w
13. Thielens, A., Greco, M. K., Verloock, L., Martens, L., & Joseph, W. (2020). Radio-Frequency Electromagnetic Field Exposure of Western Honey Bees. *Scientific Reports*, *10*(461). https://doi.org/10.1038/s41598-019-56948-0
14. Treder, M., Müller, M., Fellner, L., Traynor, K. S., & Rosenkranz, P. (2023). Defined exposure of honey bee colonies to simulated radiofrequency electromagnetic fields (RF-EMF): Negative effects on the homing ability, but not on brood development or longevity. *Science of the Total Environment*, *896*, 165211. https://doi.org/10.1016/j.scitotenv.2023.165211
15. Veludo, A. F., Stroobandt, B., Bladel, H. V., Sandoval-Diez, N., Deprez, K., Aerts, S., Chikha, W. B., Wiart, J., Vecsei, Z., Necz, P. P., Thuróczy, G., Benini, M., Bonato, M., Gallucci, S., Tognola, G., Parazzini, M., Beláčková, L., Vaupotič, N., Mamrot, P., & Marianska, M. (2025). Assessing radiofrequency electromagnetic field exposure in multiple microenvironments across ten European countries with a focus on 5G. *Environment International*, *200*, 109540. https://doi.org/10.1016/j.envint.2025.109540
16. Vilić, M., Žaja, I. Ž., Tkalec, M., Tucak, P., Malarić, K., Popara, N., Žura, N., Pašić, S., & Gajger, I. T. (2024). Oxidative Stress Response of Honey Bee Colonies (Apis mellifera L.) during Long-Term Exposure at a Frequency of 900 MHz under Field Conditions. *Insects*, *15*(5), 372. https://doi.org/10.3390/insects15050372
17. Woodgate, J. L., Makinson, J. C., Rossi, N., Lim, K. R., Reynolds, A. G., Rawlings, C. J., & Chittka, L. (2021). Harmonic radar tracking reveals that honeybee drones navigate between multiple aerial leks. *IScience*, *24*(6), 102499. https://doi.org/10.1016/j.isci.2021.102499