

The production consequences of severe summer heat depend on whether colony thermoregulation remains effective. Under simulated heat waves, colonies increased foraging by about 70% and shifted effort toward water collection without reducing nectar and pollen flow, but this likely relied on recruiting backup workers and could reduce buffering capacity against additional stressors. Under more extreme field conditions, maximal temperatures above 40 °C and greater within-hive thermal fluctuations were associated with declining colony populations, while fan-based cooling alone reduced internal temperature by only 1 °C-2 °C and produced minimal summer performance gains, suggesting that passive ventilation by itself is often insufficient in very hot climates (Chen et al., 2025).

7.3 Integrated seasonal management in migratory beekeeping systems

Migratory beekeeping systems illustrate how seasonal management can increase honey yield when colony movement is synchronized with floral phenology across regions. By definition, migratory beekeeping is the seasonal transport of hives, traditionally used to maximize honey production by exploiting differences in flowering time across altitudes and latitudes (Martínez-López et al., 2022). Recent field surveys from Himachal Pradesh similarly found that well-planned floral calendars and flexible migration reduced feed requirements during long dearth periods, while strategic seasonal movement increased honey yield and profitability across apiary sizes.

The main limitation is that migratory gain depends on integrated health and resource management, not movement alone. In commercial systems, summer honey production was the only clearly profitable activity once management and overwintering costs were included, and greater summer and fall forage availability was identified as part of the solution for both honey yield and overwinter survival. At the same time, migratory operations differ sharply in nutrition, pesticide exposure, transport stress, queen replacement, and pathogen control, and these factors can increase pathogen prevalence if not actively managed across the season (Martínez-López et al., 2022).

8 Future Perspectives and Conclusions

Future climate-smart beekeeping systems will need to manage colonies around season-specific climate risks rather than relying on fixed calendars, because weather effects on survival and productivity vary strongly by season and location. Recent modeling further suggests that warmer autumns and winters can extend flight activity, skew overwintering colonies toward older bees, and increase spring failure risk, which means adaptive overwintering strategies will become more important as climates warm. A practical climate-smart direction is to combine landscape management with adaptive in-hive interventions. Landscape evidence shows that grassy-herbaceous land can buffer the negative effects of warm, wet climates on summer nectar intake, while surveys from hot, dry regions indicate that water supplementation can reduce seasonal livestock decrease by up to 10%. Additional adaptation options already identified by beekeepers include apiary relocation, shade provision, and supplementary feeding, but these strategies appear to work best when matched to local climatic stressors rather than applied uniformly.

Climate-smart systems will also need stronger winter adaptation protocols, because both unusually warm and unusually cold winters can increase colony loss. Cold storage is one promising option: simulations indicate it could reduce overwintering losses under future warming, and field data suggest it can be a viable, lower-cost strategy for maintaining colony survival under warmer fall conditions. Beekeeper adaptation remains constrained by information gaps and institutional support, especially in regions where climate impacts are already evident but extension systems are weak. This makes place-based management frameworks a priority for future development, since the main reported drivers of honey decline differ across regions, from drought and irregular flowering to temperature extremes and pest pressure.

Digital technologies are likely to become central to seasonal hive management because precision beekeeping already supports remote, optimized monitoring of colony conditions and faster responses to internal stress signals. Current systems can continuously track hive weight, temperature, humidity, sound, and related environmental variables, giving beekeepers a more complete view of colony state without disruptive inspections. The strongest