conclude that phenolic acids and flavonoids, rather than vitamins, account for most of the in-vitro antioxidant activity, and they are increasingly used as markers of both botanical origin and health potential (Sharma et al., 2023). Newer work extends this to enriched products, showing that additions such as bee pollen or plant ingredients can modify phenolic profiles and thus enhance or modulate nutritional and functional attributes (Habryka et al., 2021).

2.3 Sensory quality and functional activity

Sensory quality-color, aroma, flavor, mouthfeel and overall acceptability-is a decisive factor for consumer choice and price. Descriptive sensory studies from Estonia, Italy and Malaysia show that floral, fruity, berry-like, sour and sweet attributes, together with color intensity, vary systematically with botanical origin, bee species and climatic conditions (Qi et al., 2025). Standardized sensory panels and flavor wheels enable objective profiling, while chemometric integration with physicochemical data reveals strong correlations between sensory traits and parameters such as color, acidity, conductivity and moisture (Ayton et al., 2025). These tools allow sensory quality to be treated as a measurable indicator, not only a subjective impression.

Functional activities-especially antioxidant and antimicrobial effects-are now widely included in honey quality evaluation systems. Studies across many floral types report that honeys richer in phenolics and flavonoids exhibit stronger radical-scavenging and reducing power, as well as higher in-vitro antimicrobial activity against foodborne and clinical pathogens (Becerril-Sánchez et al., 2021). Reviews consolidating recent work confirm robust positive relationships between phenolic/flavonoid content and antioxidant assays, while emphasizing that botanical origin and production environment modulate these links (Molina et al., 2020; Sharma et al., 2023). Advanced assessments combining artificial “electronic senses” with bioactivity tests further demonstrate that sensory fingerprints, composition and antimicrobial performance are tightly interconnected, reinforcing the view that functional activity indicators are integral to modern honey quality assessment (Machado et al., 2022; Qi et al., 2025).

3 Mechanisms of Environmental Impact on Honey Quality

3.1 Climatic factor

Climatic conditions during nectar flow and harvest determine key physicochemical parameters such as moisture, acidity, enzyme activity and HMF, thereby influencing stability and compliance with standards (Pham et al., 2022). Higher ambient humidity and rainfall around the apiary, or harvesting during rainy periods, increase moisture content and water activity, favoring fermentation and shortening shelf life (Mărgăoan et al., 2024). Seasonal patterns of temperature and precipitation modify flowering phenology and nectar concentration, which in turn alter sugar profiles and antioxidant capacity across seasons, even when bee species and management remain constant (Şireli and Saylak, 2025). At the same time, hot climates accelerate non-enzymatic browning and degradation of thermosensitive compounds in stored honey, raising HMF and sometimes lowering diastase, so that honeys from hot or desert regions may exceed conventional HMF limits despite correct beekeeping practices (Homrani et al., 2020; Shakoori et al., 2023).

Post-harvest exposure to elevated temperature and ambient humidity continues these climatic effects through storage and processing (Glevitzky et al., 2025). Studies in different climatic zones show that honeys stored or produced under hot tropical or desert conditions tend to accumulate more HMF and may show reduced enzyme activities compared with those from cooler or temperate areas, even when initial composition is comparable (Shakoori et al., 2023). Regression analyses further demonstrate that honey moisture is significantly driven by environmental relative humidity, confirming that macro- and micro-climatic water balance directly constrains safe moisture ranges (Pham et al., 2022; Mărgăoan et al., 2024). Consequently, climatic factors operate through both field-level (nectar concentration, flowering, bee foraging) and post-harvest (heating, storage) pathways to shape honey quality trajectories over time (Homrani et al., 2020; Harbane et al., 2024).

3.2 Geographic environment

Geographic setting controls altitude, soil characteristics and vegetation patterns, which together define the floral resources available to bees and thus the baseline chemical profile of honey (Petrova et al., 2024). Differences