Research Insight Open Access

Factors Influencing Honey Quality in Different Production Environments

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Bioscience Methods, 2026, Vol.17, No.2 doi: 10.5376/bm.2026.17.0008
Received: 29 Jan., 2026
Accepted: 07 Mar., 2026
Published: 20 Mar., 2026

Preferred citation for this article:
Chen H.J., 2026, Factors influencing honey quality in ddifferent production environments, Bioscience Methods, 17(2): 82-94 (doi: 10.5376/bm.2026.17.0008)

Abstract As a natural and nutritious food product, the quality of honey is subject to the combined influence of various environmental factors. Based on a comprehensive system of quality evaluation indicators, this paper systematically analyzes the mechanisms by which different environmental conditions impact honey quality, examining aspects such as physicochemical properties, nutritional composition, and functional activity. The study focuses specifically on exploring the pathways through which climatic factors (temperature, humidity, and precipitation), geographical environments (altitude, soil type, and vegetation), and ecological settings (pollution levels and biodiversity) influence honey quality. Furthermore, by integrating an analysis of nectar source plant structure, bee population characteristics, and foraging behaviors, the paper elucidates the underlying causes behind variations in honey composition. Additionally, the study examines the impact of processing and storage conditions on the stability of honey quality, and validates the pivotal role of environmental factors in shaping honey quality through comparative case studies of representative regions. The findings indicate that environmental conditions ultimately determine the nutritional value and sensory attributes of honey by influencing the composition of nectar source plants and the foraging behaviors of bees. This paper provides a theoretical foundation and practical reference for optimizing honey production environments and enhancing product quality.

Keywords Honey quality; Environmental factors; Nectar source plants; Climatic conditions; Quality evaluation

1 Introduction

Honey is a natural sweetener valued for its nutritional, sensory and medicinal properties, and its quality strongly shapes consumer trust, market price and regulatory control (Awulachew, 2025). Quality is defined by a combination of sensory, physicochemical, microbiological and bioactive parameters, which in turn depend on botanical and geographical origin, bee species, and production and storage conditions. The rapid growth of international trade, coupled with rising demand for “natural” and premium honeys, has intensified concerns around quality deterioration and fraud, making rigorous characterization of honey quality an important scientific and economic issue (Ntakoulas et al., 2024).

From a regulatory and technical perspective, honey quality is typically evaluated through moisture content, sugar profile (fructose, glucose, sucrose, reducing sugars), electrical conductivity, free acidity, diastase activity and hydroxymethylfurfural (HMF), alongside melissopalynological and sometimes sensory analyses. These parameters are codified in international and regional standards to ensure product stability, prevent fermentation, and detect overheating or poor handling (Vîjan et al., 2023). At the same time, honey contains minerals, organic acids, phenolics, flavonoids, enzymes and volatile compounds that both influence its health value and provide fingerprints of botanical and geographical origin (Geană et al., 2020). Consequently, research has increasingly examined how soil, climate, floral resources, beekeeping practices, processing and storage jointly shape these physicochemical and bioactive traits in diverse production environments.

Current research spans broad mapping of composition and stability, as well as specialized work on authenticity and origin. Large regional surveys have quantified how floral origin, harvest year, region and climate affect sugars, acidity, conductivity, HMF and enzyme activities, often revealing significant differences among honey types and areas, and identifying non-compliant or adulterated samples (Tsagkaris et al., 2021). Comparative studies of local versus imported honeys, or honeys from contrasting climates, show consistent impacts of geographical origin and production conditions on moisture, enzyme activity, acidity, color and mineral content, with implications for both quality grading and the suitability of current standards (Vîjan et al., 2023). Parallel research has developed and applied multivariate chemometric tools and advanced analytical platforms (chromatography, spectroscopy, NMR, isotope ratios, LC-MS/MS) to classify honeys by botanical and geographical origin and to detect adulteration, complementing routine physicochemical tests (Gela et al., 2023; Ntakoulas et al., 2024; Tasić et al., 2024).

Despite this progress, several gaps remain regarding how specific production environments-defined by combinations of climate, floral landscape, management practices and post-harvest handling-jointly influence honey quality. Many studies focus on one country or region, one dimension of environment (e.g., floral or geographical origin alone), or on authenticity rather than integrated quality profiles across environments (Yayinie et al., 2021; ALaerjani and Mohammed, 2024). The present study addresses these gaps by systematically examining factors influencing honey quality in different production environments, relating standard physicochemical indicators and selected bioactive or compositional markers to environmental and management variables across multiple contexts (Tsagkaris et al., 2021; Awulachew, 2025). By integrating quality assessment with detailed information on floral sources, climatic conditions and beekeeping and processing practices, and by applying multivariate analysis to resolve patterns, this work aims to clarify how environment-specific factor combinations shape honey properties and compliance with standards (Puścion-Jakubik et al., 2020; Raweh et al., 2023; Insha et al., 2024). The study's novelty lies in its comparative, environment-oriented design and its focus on linking practical production conditions to measurable quality outcomes, thereby informing region-adapted quality control, supporting fair trade and guiding producers toward practices that maintain or enhance honey quality in diverse production systems (Vîjan et al., 2023).

2 Honey Quality Evaluation Indicator System

2.1 Physicochemical parameters

Physicochemical parameters form the backbone of legal standards for honey identity and quality. Key indices include moisture, sugar profile (fructose, glucose, sucrose), pH, free acidity, electrical conductivity, color, hydroxymethylfurfural (HMF) and diastase activity (Kivima et al., 2021). These parameters indicate freshness, proper ripening, resistance to fermentation, and heat or storage damage, and they underpin Codex and regional limits used worldwide (Pătruică et al., 2022). Large surveys show that most commercial honeys fall within these limits, but out-of-range moisture and HMF values are common signals of poor processing or storage (Ayton et al., 2025).

Physicochemical profiles are also powerful tools for authentication and differentiation of botanical and geographical origin. Studies in Romania, Portugal, Chile and elsewhere demonstrate that electrical conductivity, acidity, color, enzyme activity and basic sugars can discriminate monofloral types and confirm label claims when combined with melissopalynology and chemometric analysis (Khan et al., 2024). Stable carbon isotope ratios and protein-sugar δ13C differences further support the detection of C4 plant syrup adulteration while still relying on the same core physicochemical dataset (Suárez-Ramos et al., 2023). Thus, physicochemical parameters simultaneously support compliance, traceability and fraud detection.

2.2 Nutritional components

Honey's nutritional value is largely determined by its carbohydrate fraction, supplemented by small but important amounts of proteins, amino acids, minerals, vitamins, organic acids and a wide range of phenolic compounds (Valverde et al., 2022). Fructose and glucose dominate energy supply, while oligosaccharides, amino acids (especially proline), minerals and organic acids contribute to metabolic and technological properties. Detailed analyses from different regions show substantial variation in mineral levels and organic acids with botanical origin, highlighting the need to consider production environment when assessing nutritional quality (Becerril-Sánchez et al., 2021; Suárez-Ramos et al., 2023).

Beyond basic nutrients, phenolic compounds and flavonoids are central to honey's functional nutrition. Numerous studies link higher total phenolics and flavonoids to stronger antioxidant capacity and often to darker color, making these components key indicators of nutritional "added value" (Sharma et al., 2023). Recent reviews 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 among regions in soil composition and climate generate distinctive mineral fingerprints and variations in sugars, conductivity, acidity and HMF, allowing discrimination of honeys from contrasting landscapes within the same country. In multi-regional datasets, altitude and regional climate interact with floral composition to produce significant variability in fructose, glucose, sucrose, electrical conductivity and acidity, while some parameters such as moisture remain relatively stable across sites (Shakoori et al., 2023; González et al., 2024). Altitudinal gradients also influence phenolic content and antioxidant capacity, with honeys from higher elevations frequently showing increased phenolic levels compared with lowland counterparts of similar botanical origin (Mărgăoan et al., 2024; Ayton et al., 2025).

Vegetation distribution driven by geography determines the mix of nectar and honeydew sources, which has strong effects on phenolic profiles, antioxidant activity and color. Comparative studies across bioclimatic zones show that Mediterranean and forest-type vegetation, or honeydew-rich environments, yield darker honeys with higher phenolics, flavonoids and antioxidant capacity than honeys from more open or agricultural areas (Mračević et al., 2020; ALaerjani and Mohammed, 2024). Spatial contrasts between arid, sub-humid and humid regions are reflected in clear groupings of samples by physicochemical and antioxidant traits, underlining the joint influence of regional flora and environmental conditions. Thus, geographic environment acts primarily through its control of soil-climate-vegetation mosaics, shaping both the inorganic and organic fraction of honey and providing geographical signatures that can be exploited for authentication and quality differentiation (González et al., 2024; Inaudi et al., 2025).

3.3 Ecological Environment

The broader ecological environment—including contamination resulting from heavy metals, pesticides, and industrial activities—alters the composition of honey and may compromise its safety, while simultaneously enabling it to serve as a bioindicator (Inaudi et al., 2025). Even when basic physicochemical parameters remain within acceptable limits, honey sourced from areas impacted by mining or intensive agriculture typically exhibits higher concentrations of metals—such as lead, cadmium, iron, copper, and zinc—compared to honey from protected areas (Vîjan et al., 2023). In these contaminated environments, elevated metal levels coincide with reduced concentrations of phenolic and flavonoid compounds, as well as diminished antimicrobial activity, indicating that pollution is accompanied by a decline in functional quality attributes. Consequently, chemical fingerprinting based on inorganic elements can aid in assessing the bioactivity of honey. This approach plays a pivotal role in tracing geographical origins while simultaneously reflecting the status of environmental pollution, thereby closely linking honey quality control with ecosystem monitoring (Inaudi et al., 2025).

Biodiversity and landscape quality also shape the characteristics of honey by enriching the sources of pollen and nectar and by buffering the effects of environmental stressors (Petrova et al., 2024). Regions characterized by rich and heterogeneous vegetation provide a wide array of pollen types and diverse nectar chemistries; this manifests in the honey as a complex profile of phenolic compounds, alongside robust antioxidant and antimicrobial activities (ALaerjani and Mohammed, 2024). Conversely, simplified or degraded ecosystems—including highly urbanized areas or regions under intensive cultivation—may limit plant diversity and expose honeybees to higher pollutant loads, thereby narrowing the spectrum of phytochemicals found in the honey and potentially increasing the risk of residue levels exceeding regulatory limits (Raweh et al., 2023). By integrating botanical data, physicochemical properties, and pollutant data, a series of recent studies has highlighted the dual role played by honey: it serves both as a product whose quality is contingent upon ecological integrity, and as a sensitive indicator for monitoring environmental health across diverse production settings (Inaudi et al., 2025).

4 Influence of Botanical Origin and Nectar Source Structure

4.1 Differences between monofloral and multifloral honey sources

Monofloral honeys are characterized by the predominance of pollen and nectar from a single plant, confirmed by melissopalynology and supported by distinctive physicochemical and volatile profiles. Reviews of monofloral honeys (e.g., acacia, chestnut, lavender, thyme, sunflower) show that each type tends to present specific patterns of volatile organic compounds that generate characteristic aroma fingerprints, even when produced in different countries (Machado et al., 2020; Hussein and Seid, 2024). Studies on Portuguese and Italian monofloral honeys further demonstrate that parameters such as electrical conductivity, color, sugar spectrum, diastase activity, and specific VOCs allow discrimination among floral types, underscoring the tight link between single dominant nectar sources and honey composition (Ballarin et al., 2022).

Multifloral honeys, in contrast, result from bees collecting nectar from many species simultaneously, reflecting high floral richness and flexible foraging strategies. Pollen analyses in Ethiopia and other regions reveal that a substantial proportion of harvested honeys are multifloral or bifloral, often containing dozens of pollen types and integrating contributions from herbs, shrubs, and trees across habitats (Tesfu and Habte, 2021; Bratosin et al., 2025). Diet studies using pollen traps and landscape analysis show that, even where mass-flowering crops dominate nectar intake, a wide diversity of wild and weed species contributes to pollen and, to a lesser extent, nectar, particularly between major crop flowering peaks (Inaudi et al., 2025). Consequently, multifloral honeys often show more complex but less predictable profiles, and their quality depends strongly on the composition and continuity of surrounding floral communities (Machado et al., 2022).

4.2 Impact of plant species on honey composition

Individual plant species imprint specific chemical signatures on honey through their nectar and secondary metabolites. Comparative analyses of honeys from sunflower, linden, rapeseed, acacia, and other floral types show that botanical origin significantly affects moisture, sugars, electrical conductivity, free acidity, phenolics, flavonoids, and antioxidant activity. For example, sunflower honey has been reported with particularly high conductivity and phenolic and flavonoid contents, while multifloral honeys in the same region exhibit higher total sugars, illustrating how plant traits translate into distinct nutritional and technological properties (Machado et al., 2022). Similarly, monofloral honeys from thyme, linden, and buckwheat often contain markedly higher total phenolics and antioxidant capacities than acacia honeys, reflecting species-specific phenolic profiles (Jaśkiewicz et al., 2025).

Beyond bulk parameters, plant species influence detailed phenolic and volatile fingerprints that support authentication and origin differentiation. Studies on varietal honeys show that particular phenolic acids and flavonoids (e.g., caffeic, p-coumaric acids, quercetin, hesperetin, chrysin) reach characteristic levels in honeys from thyme, coriander, jujube or other specific plants, enabling chemometric models to classify monofloral types with high accuracy (Akbari et al., 2020). Reviews of honey volatiles identify dominant aroma compounds associated with citrus, chestnut, eucalyptus, lavender, rosemary, and other sources, while also highlighting that interactions with geography and processing can complicate marker selection (Machado et al., 2020; Hussein and Seid, 2024). Overall, the plant species providing nectar act as primary drivers of compositional diversity, setting the baseline upon which environmental and management factors further operate.

4.3 Analysis of flowering cycles and nectar source stability

Flowering phenology and seasonal continuity of nectar sources critically influence both the botanical origin of honeys and the stability of their quality. Whole-farm and landscape-scale studies reveal strong seasonal fluctuations in nectar production, with clear peaks and “gaps” when floral resources are scarce relative to pollinator demand (Vîjan et al., 2023). In temperate farmlands, two main nectar peaks often occur around mass-flowering crops, separated by a late-spring dearth (“June gap”), and further periods of low availability in early spring and late summer-autumn (Figure 1) (Inaudi et al., 2025). These temporal mismatches affect which plant species dominate nectar flows at different times, creating seasons where monofloral honeys (e.g., rapeseed, sunflower) are likely, and intervening periods when bees rely more on diverse weeds, hedgerows, and semi-natural habitats, favoring multifloral profiles (Inaudi et al., 2025).

At regional scales, characterization of honeybee floras and flowering seasons shows that specific months can be classified as major nectar flow and honey flow periods linked to key plant species, while other months act as dearth or minor harvest seasons with different dominant flora (Silva et al., 2025). For instance, highland and lowland areas may produce monofloral honeys from distinct species in separate peak seasons, with additional minor harvests from other taxa in between (Tesfu and Habte, 2021). Longitudinal studies of pollen diversity also indicate that bees collect pollen from relatively few species in early spring and late summer, but from many more taxa in mid-season, and that semi-natural habitats become especially important for maintaining pollen diversity at the end of the flowering season (Vîjan et al., 2023). Consequently, the timing and stability of nectar sources-defined by flowering cycles, habitat composition, and landscape management-play a central role in determining whether honeys are monofloral or multifloral and how consistent their botanical and quality attributes are across years and production environments.

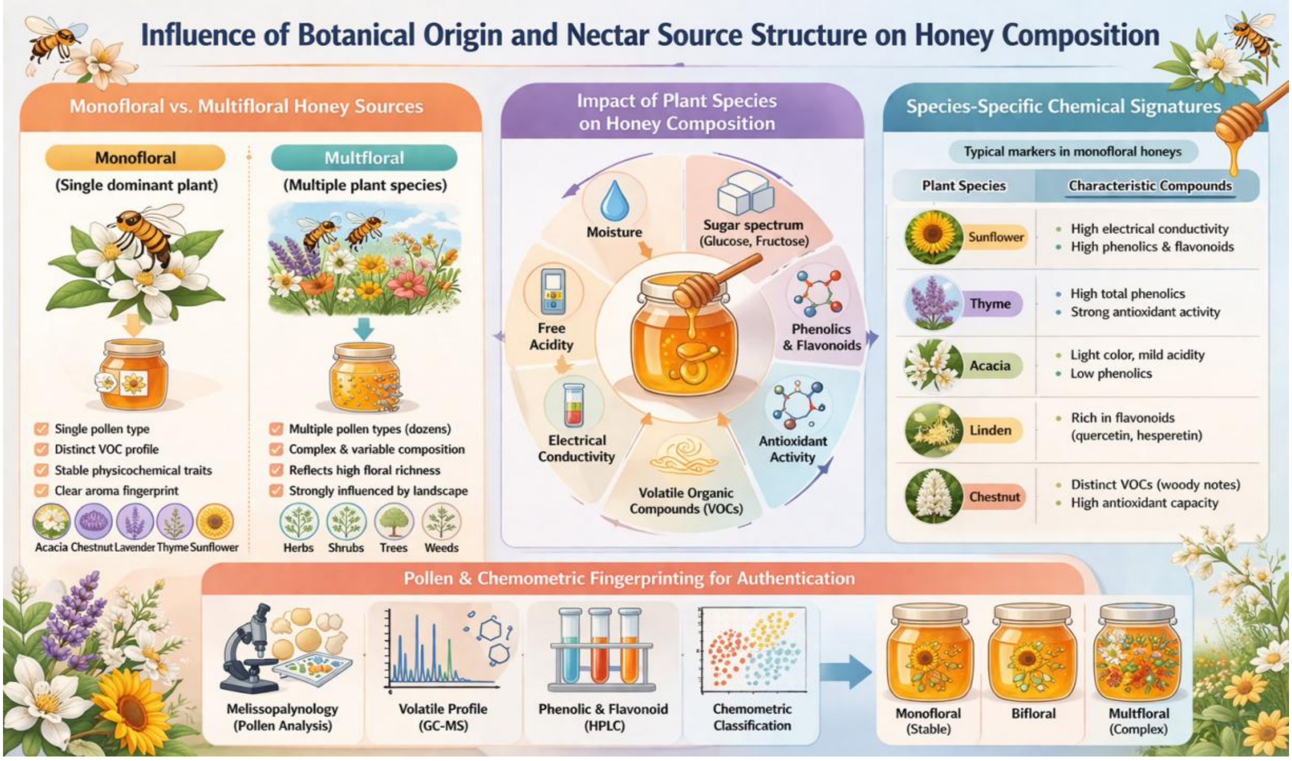

Figure 1 Influence of botanical origin and nectar source structure on honey composition and quality

5 Factors Related to Bee Populations and Foraging Behavior

5.1 Impact of bee breed differences on honey quality

Differences among bee species and breeds can modify the physicochemical and bioactive characteristics of honey by shaping which flowers are visited, how nectar is processed, and how honey is stored. Comparative work on Apis mellifera and stingless bees shows that bee type significantly affects moisture, free acidity, HMF, phenolic content, and antioxidant capacity of honey, with stingless bee honeys generally having higher moisture, higher acidity, and different phenolic profiles than A. mellifera honeys (Dupont et al., 2025). These interspecific differences are linked not only to floral choices but also to morphological and behavioral traits, such as body size, flight range, and preferred plant strata, which together define access to nectar sources and conditions of in-hive ripening (Dwarka et al., 2025).

A systematic meta-analysis further indicates that bee type (A. mellifera vs. various stingless genera) is a significant covariate explaining variability in phenolics, flavonoids, and several physicochemical parameters across countries and floral sources (Dwarka et al., 2025). Stingless bees often forage on smaller flowers and perform shorter flights than A. mellifera, and they store honey in cerumen pots rather than wax combs, introducing additional material and microenvironmental effects that can alter the final honey composition. These findings imply that breed or species composition of bee populations is a primary biological factor underlying regional patterns in honey quality, even under comparable environmental conditions (Dupont et al., 2025).

5.2 Foraging behavior and nectar collection efficiency

Foraging behavior determines which nectar and pollen resources are incorporated into honey, thereby influencing sugar profiles, micronutrients, and specialized metabolites. DNA metabarcoding and palynological studies show that honey bees use only a fraction of available flowering plants and display marked selectivity for both nectar and pollen, with plant choices shifting strongly over time and among colonies in the same landscape (Zaldívar-Ortega et al., 2024). Colonies typically exploit a high number of potential floral resources, yet at any moment most of the collected nectar or pollen is dominated by a few taxa, indicating dynamic but non-random preferences that structure honey's botanical fingerprint and metabolite composition (Zaldívar-Ortega et al., 2024).

At the colony level, resource allocation between nectar and pollen foraging is plastic and responds to internal nutritional status and external resource profitability. Experimental manipulations demonstrate that the profitability of nectar sources (sugar concentration or flow rate) alters the probability that bees switch between nectar and pollen collection and changes the colony-level ratio of pollen to non-pollen foragers. Other behavioral studies reveal that only a minority of highly active foragers perform a disproportionate share of trips, and that foraging performance improves with experience, indicating that colony nectar intake and honey yield are strongly dependent on the activity and learning of this subset of workers (McMinn-Sauder et al., 2022). These behavioral mechanisms link environmental floral heterogeneity and colony state to the efficiency and selectivity of nectar collection, shaping both honey quantity and quality.

5.3 Hive health status and microbial influences

Hive health status influences honey quality through both nutritional dynamics and microbiological processes within the colony. Comparative analysis of healthy and stressed hives shows that honey from healthy colonies has significantly higher phenolic content, antioxidant capacity, and antimicrobial activity than honey from stressed hives, despite similar floral resources. Stressed colonies, characterized by poor brood patterns, low bee populations, or disease signs, produce honey with reduced "activity," suggesting that suboptimal colony condition can depress the enrichment of phenolics and other bioactive constituents during nectar processing and storage (Layek et al., 2020).

Microbial communities in and around the hive also modulate nectar transformation and honey properties. Work on nectar-associated yeasts demonstrates that colonization by Metschnikowia reukaufii alters nectar amino acid levels, sugar composition, and volatile emissions, but honey bees avoid yeast-inoculated nectar even when pollen is present, indicating that microbial metabolites can deter foraging and thereby indirectly influence which nectars enter the hive (Yokota et al., 2024). Parallel profiling of gut, hive, and honey microbiomes in healthy versus stressed colonies reveals significant differences in core and opportunistic taxa, with stressed hives showing higher microbial diversity that may reduce the capacity to exclude pathogens and potentially affect honey stability and antimicrobial characteristics (Layek et al., 2020). Together, these results highlight that hive health and associated microbial communities constitute an important internal environmental layer governing honey quality in addition to external floral and climatic factors.

6 Impact of Processing and Storage Conditions

6.1 Honey harvesting and initial processing methods

Harvesting and early handling steps such as extraction, filtration, and moisture reduction shape the initial "starting point" for subsequent quality evolution. Studies on acacia and rape honeys show that centrifugation and filtration generally reduce concentrations of enzymes, phenolics, minerals, and other constituents (due to removal or dilution of pollen and suspended solids), while moisture reduction at elevated temperatures increases HMF and can lower diastase activity (Mohammad et al., 2023; Gruznov et al., 2024). Even relatively mild preheating (45 °C-55 °C) and vacuum drying steps significantly decreased diastase and phenolic contents in rape honey, indicating that functional components are sensitive to routine industrial treatments (Scepankova et al., 2024).

At the same time, some processing innovations seek to minimize quality loss compared with conventional pasteurization. High-pressure processing (HPP) has been evaluated as an alternative that improves microbial safety with less impact on HMF, diastase, and antioxidant activity during storage than standard heat pasteurization (Kamboj et al., 2024). In a comparative study, pasteurization at 78 °C/6 min immediately eliminated microorganisms but led to HMF and diastase values outside legal limits after 12-24 months, whereas HPP-treated and raw honeys stored for 24 months remained within standards and retained higher antioxidant capacity. These findings highlight the need to balance microbiological safety with the preservation of freshness markers and bioactive compounds when selecting initial processing methods.

6.2 Heat treatment and changes in enzyme activity

Heat treatment is widely used to reduce viscosity, dissolve crystals, and lower moisture content, but it directly drives HMF formation and enzyme inactivation. Kinetic studies demonstrate that temperatures above about 60 °C cause a sharp increase in HMF and a concomitant decline in diastase, with both effects accelerating as time and temperature rise. Heating at 40 °C for long periods had little effect on HMF or diastase, whereas exposure at 60 °C-100 °C caused regular HMF increases and diastase decreases, implying relatively narrow thermal windows for safe processing. Similar patterns were observed in Apis florea honey, where treatments at 55 °C-65 °C for several hours raised HMF by up to ~45% and reduced diastase and invertase activities by ~60%-72%, clearly demonstrating enzyme deactivation at higher temperatures and longer durations (Wu et al., 2022).

Thermal processing also affects antioxidant-related compounds and activities. Experiments at 63 °C for up to 30 min on different floral honeys showed increases in HMF and reductions in total phenolic content, accompanied by declines in DPPH radical-scavenging and FRAP values in some honeys (Jaya et al., 2022). A broader review concludes that thermal treatment significantly influences honey color, moisture, HMF, diastase, microbial load, and antioxidant parameters, and that time-temperature combinations must be carefully managed to moderate these negative effects (Bhure et al., 2025). Overall, evidence indicates that maintaining temperatures at or below about 40 °C-45 °C during routine handling, and limiting exposure at 60 °C-65 °C to very short times, is critical to preserve enzyme activity and bioactive components while achieving technological goals (Al-Rubaie, 2022).

6.3 Impact of storage environment (temperature, light, duration) on quality

Storage temperature and duration are major drivers of long-term changes in freshness markers and sensory/nutritional quality. Multiple studies show that room-temperature or warm storage increases HMF and reduces diastase, whereas cool storage markedly slows these reactions (Ramly et al., 2021). For example, sunflower honey stored 18 months at ~22 °C in the dark exhibited a 17-fold increase in HMF and a two-fold decrease in diastase, though moisture and free acidity remained relatively stable. Two-year storage of varietal honeys at room temperature caused about a 79% rise in HMF and ~67% reduction in diastase, whereas storage at 4 °C or below limited HMF increases to ~25%-33% and produced smaller enzyme losses, also reducing color changes (Kędzierska-Matysek et al., 2025).

A systematic review of 43 studies confirms that prolonged storage can deteriorate sensory, nutritional, and antioxidant properties and promote fermentation, granulation, and quality indicators such as increased HMF and decreased diastase and invertase (Manickavasagam et al., 2024). Work on stingless bee and other honeys further indicates that storage at 40 °C accelerates HMF formation and loss of phenolics and antioxidants, while storage at 4 °C-5 °C preserves bioactive compounds and antimicrobial activity much better (Rababah et al., 2024).

7 Case Study: Comparative Analysis of Honey Quality Under Different Regional Environmental Conditions

7.1 Selection of study areas and sample collection methods

Comparative evaluation of regional environmental effects on honey quality requires sampling areas that differ clearly in climate, land use, pollution history, and topography. Recent work has contrasted honeys from multiple Romanian regions with distinct geological and anthropogenic backgrounds, using 61 samples from eight areas to capture gradients in soil composition, industrial activity, and atmospheric inputs (Shakoori et al., 2023). Other studies designed regional comparisons by selecting contrasting agroecological zones or climatic regions (e.g., cold vs. hot climates, or temperate vs. tropical zones), ensuring that differences in humidity, temperature, vegetation and land use were adequately represented for subsequent chemometric analysis (Rosiak et al., 2021).

Sampling strategies typically combine spatial replication with careful control of production variables to isolate environmental effects. Multifloral honeys are often collected directly from beekeepers or apiaries to avoid market adulteration and to link samples reliably to specific landscapes and pollution sources (Rosiak et al., 2021).

In-depth regional surveys record for each sample the geographic coordinates, altitude, surrounding land use, and potential anthropogenic influences (industrial plants, waste sites, intensive agriculture), together with harvest year and extraction methods, creating metadata needed to interpret elemental and quality differences (Bora et al., 2024). Such designs allow later use of multivariate statistics to relate honey quality patterns to mapped environmental drivers.

7.2 Comparison of honey quality indicators under different environmental conditions

Regional comparisons usually start from a core set of physicochemical indicators (moisture, pH, sugars, electrical conductivity) and extend to mineral profiles, potentially toxic elements and antioxidant traits. Multi-regional studies in Romania and Serbia have shown that contents of K, Mg, Na and microelements (Al, Cu, Fe, Mn, Ni, Zn, Se) vary significantly with both geographical and botanical origin, while toxic metals such as Pb and Cd may exceed safety limits in some polluted areas (Bora et al., 2024). Parallel assessment of pH, moisture, color and antioxidant activity across agroecological zones or climatic regions reveals systematic regional differences, with some zones producing darker honeys with higher phenolic and flavonoid contents and stronger antioxidant capacity (Smith et al., 2021).

In landscapes with known industrial or agro-industrial pollution, honey quality comparisons focus more explicitly on food safety and bioindicator functions. Surveys in historically contaminated Romanian regions found Pb and Cd concentrations consistently above international safety thresholds, with spatial analysis showing higher contamination at sites closer to former industrial facilities and along suspected atmospheric transport pathways (Shakoori et al., 2023). Other long-term or broad-scale datasets using honey as a recorder of environmental lead demonstrate that metal concentrations and Pb isotopic compositions differ between urban, rural, and agricultural settings, reflecting both local emissions and larger-scale legacy pollution (Awolu et al., 2025). Together, these comparative indicators reveal how divergent environmental conditions translate into distinct nutritional profiles, contaminant burdens and functional qualities of honey (Figure 2).

Figure 2 Comparative analysis of honey quality under different regional environmental conditions

Hangzhou Linan Hongjian Bee Breeding Family Farm utilizes the superior natural environment and high-quality honey crops in the area to produce high-quality honey with a good taste, which is highly welcomed by consumers (Figure 3).

Figure 3 Natural Environment and Honey Source Crops of the Base of Hangzhou Linan Hongjian Bee Breeding Family Farm (Left: Environment; Middle: Honey Harvesting; Right: Honey Source Crop Loquat) (Photo by Hongjian Chen)

7.3 Analysis of results and identification of key environmental influencing factors

Multivariate statistics are central to disentangling which environmental factors most strongly shape regional honey quality. Principal component analysis and clustering applied to large elemental datasets have successfully discriminated honeys by geographical origin, with the first two principal components often explaining most of the variance and separating samples into groups that correspond to specific regions or pollution histories (Bora et al., 2024). In such analyses, high loadings for elements like K, Mg, Mn, Cu or Pb highlight combined influences of soil geochemistry, agricultural practices and industrial emissions, while dendrograms based on metal profiles frequently align with known regional boundaries or land-use types (Shakoori et al., 2023).

Case studies from polluted agro-industrial landscapes further illustrate how altitude, distance to emission sources and land-use pattern emerge as key predictors of contaminant levels in honey. Spatial analyses linking Pb, Cd, Cu and Zn concentrations to former industrial facilities show clear gradients, with higher burdens near emission hotspots and evidence for atmospheric transport effects at elevated sites (Shakoori et al., 2023). Comparative work across urban centers and agricultural islands using Pb isotopes indicates that sampling resolution (city vs. regional vs. global) determines whether local infrastructure, agricultural operations or the legacy of leaded gasoline dominates the signal recorded in honey (Awolu et al., 2025). By integrating these chemometric and spatial findings, regional case studies identify a small set of critical environmental drivers-geology and soil, industrial and traffic emissions, climate and altitude-that must be considered when interpreting honey quality differences and designing targeted monitoring and regulatory measures.

8 Conclusion and Outlook

Current research converges on the view that honey quality emerges from the interaction of environment, colony management, and processing, rather than any single factor. Reviews emphasize that climate, floral and geographical origin, pollution, hive health, and processing/storage jointly determine physicochemical traits, contaminant loads, and functional properties such as antioxidant and antimicrobial activity. Environmental degradation, intensive agriculture, and improper storage or adulteration add new pressures, but the same studies show that honey and other bee products are sensitive bioindicators, linking product quality directly to ecosystem status and human practices.

Management and technology are equally central. Syntheses of best beekeeping practices demonstrate that hive management, Varroa control strategies, and biosecurity programs are key drivers of colony survival, productivity, and the production of residue-safe, high-quality honey. Parallel reviews of analytical methods highlight rapid advances in authenticity and quality assessment, including NIR spectroscopy, chemometrics, and metabolomics, which can classify floral and geographical origin and detect adulteration or contamination with increasing precision. Together, these findings show that both good environmental stewardship and evidence-based technical tools are needed to secure honey purity and excellence.

Improving honey quality requires systematic reduction of environmental stressors around apiaries. Reviews on pollution and contaminants recommend limiting pesticide and antibiotic use, enforcing maximum residue limits, and monitoring heavy metals, PAHs, and other xenobiotics that can accumulate in honey and compromise safety. Because bees and honey effectively mirror local contamination, integrating honey-based biomonitoring into regional environmental surveillance can both protect pollinators and provide early warning of risks to food quality.

At landscape scale, strengthening floral resources and habitat quality is crucial. Reviews of beekeeping constraints and “good apiculture practices” emphasize preventing deforestation of nectar plants, diversifying forage, and aligning farming systems with ecologically sound practices to sustain strong colonies and high-value honeys. Urban and anthropized-area studies further suggest that thoughtful urban greening, reduced air pollution, and control of microplastics and other emerging contaminants will be increasingly important where urban honey production grows. Coordinated policies that couple habitat conservation with pollutant reduction therefore represent a primary environmental lever for improving honey quality.

Several research frontiers are emerging around measurement, contamination, and management optimization. Methodological reviews point to rapid development of NIR spectroscopy, electronic tongues/noses, metabolomics, and DNA-based tools as fast, non-destructive approaches for quality grading, authenticity, and origin tracing, with likely expansion into portable, in-field devices. Parallel work on authenticity stresses the need for integrated workflows that combine advanced extraction, hyphenated chromatography-mass spectrometry, and chemometric models to detect increasingly sophisticated adulteration and to support robust regulatory supervision.

On the stressor side, new syntheses underline rising concerns about contaminant “cocktails” and novel pollutants such as microplastics, calling for multi-residue analytical methods and updated legislation that reflect real exposure patterns in honey and bees. Beekeeping-management research is moving toward quantitative indices and scenario-based frameworks that link specific practice packages to colony health and product quality at regional scales, supporting evidence-based extension and policy. Future work integrating environmental monitoring, advanced analytics, and standardized management metrics will be essential to protect pollinators while ensuring high-quality, traceable honey in increasingly complex production environments.

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