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Research Article

Regional Influence on Physicochemical Properties of Honeys from Elazığ: A Quality and Authenticity Assessment

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Abstract **–** This research investigated the physicochemical characteristics of honey samples from Ağın, Kovancılar, and Arıcak in Elazığ, Turkey. The research aims to elucidate how local flora, climate, and soil composition influence the physicochemical properties and chemical composition, which is critical for quality control and authenticity verification. Using advanced and classical techniques, including Fourier transform infrared (FTIR), microscopy, refractometer, viscometer, and electrical conductivity measurements, quality parameters such as density, viscosity, pH, electrical conductivity, brix value, and moisture content were analyzed. Significant variability was found in properties like density, viscosity, pH, electrical conductivity, brix value, and moisture content. For instance, Ağın samples showed the highest electrical conductivity (0.775 mS/cm) and Kovancılar the lowest (0.406 mS/cm). All samples met Codex Alimentarius and Turkish Food Codex standards, with pH between 4.23-4.50, moisture below 20%, and acceptable electrical conductivity. FTIR spectroscopy provided detailed molecular fingerprints, confirming the presence of key compounds. The findings underscore the importance of regional studies for combating honey adulteration and validating medicinal applications. This research contributes to honey authentication, offering valuable insights for local beekeepers and supporting market integrity by aligning properties with national and international standards.

Keywords – Honey Sample, Density, Viscosity, pH, Electrical Conductivity, Brix Value, Moisture Content, FTIR.

I. INTRODUCTION

Honey, a natural product synthesized by honeybees through the enzymatic processing of floral nectar, has been revered for millennia as both a nutritional staple and a therapeutic agent. Its complex chemical composition-comprising carbohydrates, proteins, amino acids, vitamins, minerals, and bioactive compounds such as polyphenols and flavonoids-confers diverse health benefits, including antioxidant, antimicrobial, anti-inflammatory, and wound-healing properties [1, 2].

Honey has occupied a central role in human civilization, serving as a food source, sweetener, and medicinal remedy across diverse cultures. Ancient Egyptian, Greek, and Ayurvedic texts document its use in treating wounds, gastrointestinal disorders, and respiratory ailments, a tradition sustained in modern complementary medicine [1,2]. The resurgence of interest in natural products has propelled honey into the spotlight of scientific research, particularly for its antioxidant capacity, which mitigates oxidative stress linked to chronic diseases such as diabetes, cardiovascular disorders, and cancer [3]. The nutritional profile of honey further underscores its value. As a source of prebiotic oligosaccharides and micronutrients such as zinc, selenium, and vitamin C, honey supports gut microbiota diversity and immune function [4, 5]. Recent trends in functional food development have integrated honey into products like lactic acid beverages fortified with blueberries, enhancing their antioxidant capacity and consumer appeal [4]. However, the therapeutic and nutritional efficacy of honey is contingent on its purity and compositional integrity, which are increasingly compromised by adulteration practices such as syrup dilution or mislabeling of botanical origins [6, 7]. For example, adulterated honey samples exhibit altered sugar ratios (e.g., elevated sucrose) and diminished enzyme activity, undermining both health benefits and market trust [6-9]. The physicochemical properties of honey vary significantly depending on the region and floral sources. Differences in altitude, climate, and vegetation influence the nectar composition collected by bees, resulting in distinct honey profiles. Studies have demonstrated that honey from different geographical locations exhibits variation in water content, pH, electrical conductivity, density, viscosity sugar composition, and enzymatic activity, which can be used to differentiate honey types and verify their origin [10-12].

Thus, rigorous physicochemical characterization is essential to verify authenticity and ensure compliance with international standards set by the Codex Alimentarius and International Honey Commission [13,14]. However, the physicochemical and biological characteristics of honey are profoundly influenced by its botanical and geographical origins, which determine the nectar composition, environmental conditions, and beekeeping practices [15-17]. The therapeutic efficacy of honey is intrinsically tied to its physicochemical properties. Moisture content, for example, influences shelf life and microbial stability, with values below 20% generally considered optimal [15, 16] Electrical conductivity, a proxy for mineral content, varies with floral origin; sunflower honey from Southern Romania registered 483.92 µS/cm, reflecting its high mineral density [15]. Free acidity, indicative of fermentation risk, must remain below 50 mEq/kg under international standards-a criterion met by all samples in a Turkish study of Bayburt honey [16]. Furthermore, hydroxyl methyl furfural (HMF) levels, which increase during improper storage or heating, serve as a marker of freshness. Linden honey from Romania contained 33.94 mg/kg HMF, well within the Codex Alimentarius limit of 40 mg/kg [15]. These parameters not only ensure safety and quality but also authenticate honey’s botanical and geographical origins, a critical consideration in global trade [17,18]. The physicochemical and bioactive properties of honey are profoundly shaped by its geographical and botanical origins. Floral diversity, soil composition, climate, and beekeeping practices collectively determine the nectar profile, which in turn modulates parameters such as pH, water content, electrical conductivity, and antioxidant activity [15-17]. Geographical authentication has gained urgency amid rising concerns over honey fraud. The European Union’s Honey Directive mandates labeling of floral and regional origins, yet enforcement remains challenging due to sophisticated adulteration techniques [17, 18].

In this study, the physicochemical properties of honey samples from three different regions of Elazığ were analyzed using a combination of advanced and classical techniques. Honey is naturally acidic, with pH values typically ranging from 3.2 to 4.5. pH affects honey's stability and antimicrobial properties [10, 11, 19]. EC is related to mineral content and ash, serving as an indicator of honey type (e.g., nectar vs. honeydew honey). The standard EC range for floral honeys is usually between 0.2 and 0.8 mS/cm [20].

Density depends on moisture and sugar content, with typical values around 1.32 to 1.49 g/cm^3. It is important for quality control and standardization [10, 21]. Used to measure moisture content, refractometer is critical since moisture affects honey's shelf life and susceptibility to fermentation. The acceptable moisture content in honey is generally below 20% according to international standards [22].

Viscosity is a measure of resistance to flow, is influenced by temperature, moisture, and sugar profile. Karaman et al. (2008) conducted seminal work on Turkish honey rheology, reporting viscosities ranging from 2.8 to 101 Pa·s at 10–40 °C. Citrus honey exhibited the lowest viscosity (2.8 Pa·s at 40 °C), while darker varieties like chestnut honey reached 101 Pa·s at 10 °C [23].

Fourier transform infrared (FTIR) is a rapid, non-destructive method used to identify functional groups and molecular composition in honey. It provides fingerprint spectra that can be correlated with honey quality and adulteration [24-26]. This technique allows the examination of pollen grains and other particulate matter, aiding in melissopalynological analysis to determine botanical origin and authenticity [27].

This variability underscores the importance of regional studies to authenticate honey quality, combat adulteration, and validate its medicinal applications. In this context, the present study investigates the physicochemical properties of honey sourced from three distinct regions of Elazığ (Türkiye), to elucidate how local flora, climate, and soil composition impact honey composition. The physicochemical properties of honey samples were analyzed using various techniques, including FTIR spectroscopy, refractometer, viscometer, microscopic imaging, density, pH, and electrical conductivity measurements. This research aims to contribute to the growing body of literature on honey authentication while providing actionable insights for local beekeepers and policymakers. and comparing results against international (Codex Alimentarius) and national (Turkish Food Codex) honey standards. and Developing a chemometric model to differentiate honeys based on regional origin using physicochemical data.

Furthermore, this research contributes to the global discourse on honey authentication. With adulteration rates estimated at 20–30% worldwide, robust regional databases are essential for developing origin-specific biomarkers. The chemometric approach proposed here-combining traditional assays with advanced statistics-offers a scalable model for other regions. Lastly, as climate change alters floral landscapes, baseline data from this study will inform future monitoring of ecological impacts on honey quality.

II. MATERIAL AND METHOD

Collection of samples honey

Honey Samples were collected from Three different areas of Elazığ, including (Ağın, Kovancılar, and Arıcak). honey samples were collected and stored in the laboratory at room temperature until processing for quality parameters. For physicochemical property analysis. honey samples were prepared and analyzed following the harmonized method of the International Honey Commission [28].

Physicochemical properties of honey

The physicochemical properties of honey samples were analyzed using various techniques, including, refractometer, viscometer, microscopic imaging, density, pH, and electrical conductivity measurements. And using FTIR spectroscopy to identify functional groups and molecular composition in honey. It provides fingerprint spectra that can be correlated with honey quality and adulteration

pH measurement

75 mL of deionized water enriched with 10 g of honey was blended. The honey solution was poured into a beaker, and a pH-meter (Hanna® pH PPM Meter HI-9813-6N, Nusfalau, Romania) was inserted into the solution. Steady-state pH readings were then obtained from the pH meter [29, 30].

Electrical Conductivity (EC)

The EC was determined with an EC-meter (Hanna® pH PPM Meter HI-9813-6N, Nusfalau, Romania). It was initially standardized with deionized water and the conductance cell was immersed in 10% honey solution. EC reading was taken after the instrument had settled down[29, 30].

Moisture content and Brix value

The moisture content—that is, water content—and Brix value—that is, sugar concentration—were determined from honey's refractive index. An Erma hand refractometer (Tokyo) was used for regular calibration with distilled water, thermally stabilized at 25 °C. This method provides a rapid and nondestructive assessment of honey quality, as the refractive index is directly correlated with the total Soluble solids content [31].[31].

Determination of Viscosity

The viscosity of the honey samples was determined using the rotary viscometer. The viscosity was recorded in centipoises [32]. The instrument was calibrated before each measurement using a standard viscosity reference fluid. Viscosity readings were recorded in centipoise (cP), and each measurement was performed in triplicate to ensure accuracy and reproducibility. The viscometer, viscosity is the measured resistance to flow encountered by a spring when a spindle rotates in liquid. The most common application of this type of measurement is the quantification of a fluid's viscosity when compared to either a target performance or when compared against another fluid.

Density

Pycnometric method was used for the determination density of honey as (Abu Jdayil et al., 2002) by using dry and pure pycnometer at the first empty pycnometer was weighted then filled with the honey then adjust temperature of honey by warm water to 26 ºC and weighted. Calculate the density by Eq. 1:

$$\text{Density} = \frac{(W_2 - W_1)}{V} \qquad (1)$$

When W_1 is the pycnometer's weight, W_2 is the pycnometer's weight plus honey, and V is the pycnometer's volume [33].

Microscopic images

Microscopic images were conducted to identify pollen grains, crystals, and other particulate matter in honey samples. A small amount of honey was diluted with distilled water, and a drop of the mixture was placed on a glass slide. Images of honey samples were examined with a Dcorn HDMI LCD Digital Microscope (7 Inc IPS Screen – 16 MP). The morphology of pollen grains was analyzed to determine the botanical origin of the honey, while the presence of foreign particles indicated potential adulteration [34].

FTIR spectra analysis

Fourier transform infrared spectroscopy (FTIR) was performed using Shimadzu IR Spirit QATR-S instrument to analyze the molecular composition of honey samples. A small aliquot of honey was placed directly onto the Attenuated Total Reflectance (ATR) crystal, and spectra were recorded in the 4000–400 cm^{-1} range with a resolution of 4 cm^{-1}, and 16 scans were averaged per sample to ensure accurate results. The instrument was calibrated using a background scan before each measurement to eliminate interference from the atmosphere. Each analysis was conducted in triplicate for reproducibility. The spectra were analyzed using Shimadzu Lab Solutions IR software to identify functional groups and detect potential adulterants. This method is highly effective in characterizing honey's sugars, organic acids, and phenolic compounds [35].

III. RESULTS AND DISCUSSIONS

Some physical and chemical properties of the honey samples in the study and the results obtained are expressed in this section.

pH

The pH of three honey samples was measured, and the results, which are listed in Table 1 and Figure 1, fell within the range of pH 4. 23 to 4. 50, which is within the acceptable range of pH 3. 40 to 6. 10 [36] for preserving the freshness of honey samples. Kovancılar honey was the most acidic of all honey varieties (pH 4. 23), followed by Ağın (4. 41). Arıcak honey had the lowest acidity at 4. 50. Kovancılar honey sample had a greater acidity than Ağın and Arıcak honey. Three tested varieties of honey samples had pH values that were comparable to those earlier recorded for Indian, Algerian, Brazilian, Spanish, and Turkish honeys (between pH 3. 49 and 4. 70) [37]. Honey's high acidity is related to the fermentation of its sugars into organic acid, which is accountable for two key properties of honey: flavor and resistance to microbial deterioration [38]. Additionally, it may also suggest that the honey samples have a high mineral concentration [39, 40].

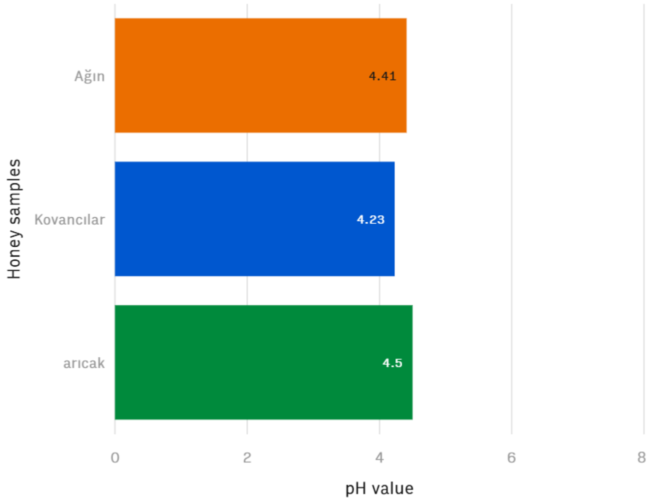

Figure 1. The graph for pH results of the honey samples.

Table 1 Physical properties of honey samples

S/N	Physicochemical Properties	Ağın	Kovancılar	Arıcak
1	pH	4.41	4.23	4.5
2	Conductivity (mS/cm)	0.775	0.406	0.65
3	Moisture Content (%)	14.5	17.5	13.5
4	Brix value (%)	84	81	85
5	Density (g/mL)	1.5	1.474	1.492
6	Viscosity (Pa·s)	23.375	19.583	38.208

Electrical Conductivity

Another investigated quality parameter is the electrical conductivity of honey. The experimental results of this parameter are presented comparatively in Table 1 and Figure 2. The electrical conductivity results of the investigated honey samples were between 0.404 mS/cm to 0.775 mS/cm The average electrical conductivity of the investigated honey samples was determined as 0.610 mS/cm. Among the honey samples, it was determined that the Ağın sample had the highest electrical conductivity with the value of 0.775 mS/cm and the Kovancılar sample had the lowest electrical conductivity with the value of 0.406 mS/cm. Since the electrical conductivity of blossom honey is reported to be maximum 0.8 mS/cm according to the Turkish Food Codex Honey Communiqué, it has been observed that all the studied honey samples are in compliance with this Communiqué.

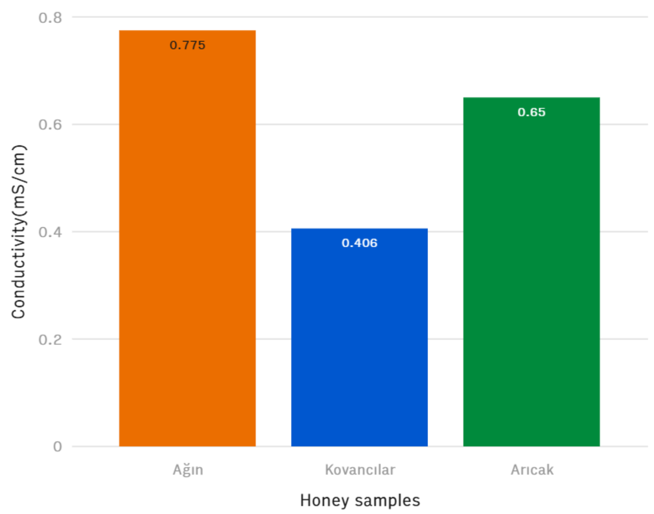

Figure 2. The graph for electrical conductivity results of the honey samples.

Moisture Content and Brix value

The moisture content in honey is the most reliable predictor of its maturity and shelf life. The moisture content of honey is contingent upon environmental factors and handling throughout the harvesting process. It may also fluctuate with the season and year. A high moisture content in honey indicates that it was collected before to maturity [41, 42]. The moisture content of honeys from various origins typically ranges from 13% to 29%. The moisture content of the Turkish honey samples aligned with that of Indian honey, ranging from 18.7% to 21.8%, and Moroccan honey, ranging from 16.8% to 20.3%. Conversely, Saudi honeys had a lower moisture level, ranging from 14.0% to 16.9%, whereas Chinese honeys showed a greater moisture content, between 19.8% and 29.0%. The Turkish food codex stipulates a maximum moisture percentage of 20% for honey, and all analyzed honey samples had moisture levels below this threshold [23]. The moisture content of the Elazig honey samples was in the range of 13.5–17.5% in Table 1 and Figure 3. The highest value of moisture content among the analyzed samples was observed for the Kovancılar honey sample, followed by the Ağın honey sample, while the Arıcak honey sample had the lowest value.

The Brix scale, expressed in degrees (°Bx), quantifies the concentration of soluble solids-primarily sugars-in a liquid. In honey, this metric reflects the proportion of fructose, glucose, and minor carbohydrates dissolved in the matrix. Measured via refractometer, Brix values (sugar content) correlate inversely with moisture content, making them a critical determinant of honey's stability against fermentation and microbial growth [43, 44]. For instance, a Brix value of 80° corresponds to approximately 20% moisture, a threshold pivotal for preserving honey's shelf life [45, 46]. The Codex Alimentarius Commission, jointly overseen by the FAO and WHO, establishes the international benchmark for honey quality. According to Codex Stan, honey must exhibit a minimum Brix value of 80°, equating to ≤20% moisture content [47-49]. The brix value of the Elazig honey samples was in the range of 81–85% in Table 1 and Figure 3. The highest value of brix among the analyzed samples was observed for the Arıcak honey sample, followed by the Ağın honey sample, while the Kovancılar honey sample had the lowest value. So all samples in the standard range.

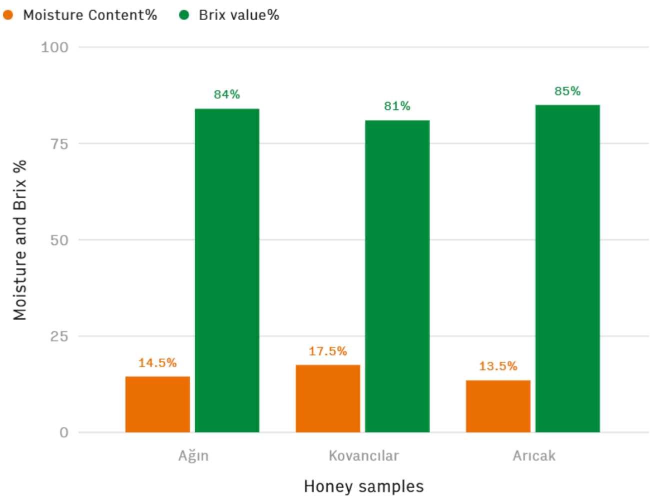

Figure 3. The results for Moisture Content and Brix value of the honey samples.

Viscosity

Viscosity is a measure of resistance to flow, is influenced by temperature, moisture, and sugar profile. Karaman et al. (2008) conducted seminal work on Turkish honey rheology, reporting viscosities ranging from 2.8 to 101 Pa·s at 10–40 °C. Citrus honey exhibited the lowest viscosity (2.8 Pa·s at 40 °C), while darker varieties like chestnut honey reached 101 Pa·s at 10 °C [23]. The influence of botanical origin and storage on honey viscosity and crystallization, showing variability in viscosity linked to composition and storage conditions [50, 51]. The effect of temperature on honey viscosity, with examples of viscosity decreasing significantly from about 6.12 Pa·s at 30 °C to 0.145 Pa·s at 70 °C, demonstrating temperature dependence. Moisture content affecting viscosity, where lower moisture (e.g., 20%) leads to higher viscosity values (up to ~95.3 Pa·s), highlighting the role of water content in rheological behavior [52]. The wide range of viscosities observed in honeys from different floral origins and processing conditions, including commercial honeys mostly falling between 1 and 30 Pa·s at 20 °C [51, 52].

The results of the viscosity of Elazig's honey were in the range of 19.583–38.208 Pa·s at 20 °C and shear rate (12 rpm) in Table 1 and Figure 4. The highest value of viscosity among the analyzed samples was observed for the Arıcak honey sample, followed by the Ağın honey sample, while the Kovancılar honey sample had the lowest value. Viscosity measurements indicated that Arıcak honey had the highest viscosity 38.208 Pa·s, implying higher sugar density, lower water content and complex structural properties compared to Kovancılar honey.

If the viscosity of your honey is higher than the typical range, possible reasons include: Adulteration with high-fructose corn syrup (HFCS) or other sugar syrups can increase viscosity by raising total soluble solids and sugar content, as well as altering water activity and pH. Studies on Kelulut honey showed that increasing HFCS concentration significantly increased viscosity [53]. Reduced water content in honey leads to higher viscosity because water acts as a diluent. Drying or dehydration processes that lower moisture can substantially increase viscosity. and Prolonged storage or freezing can promote crystallization, increasing viscosity and changing texture [54]. Different floral sources produce honeys with varying sugar profiles and solids content, which affect viscosity. Some honeys naturally have higher viscosities due to their specific sugar ratios and solids [53].

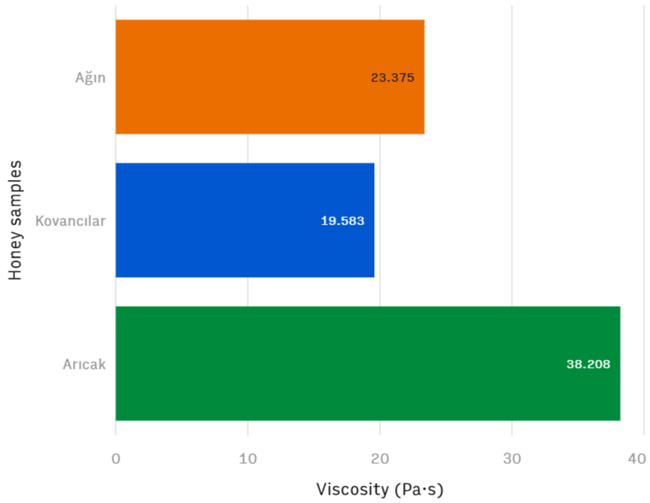

Figure 4. The results for moisture content and Brix value of the honey samples.

Density

The density of honey is a significant physical characteristic influencing its stratification. The density of honey is somewhat greater than that of water, contingent upon its moisture content [14]. Honey density spans 1.11–1.55 g/mL, primarily dictated by moisture, sugar composition, and processing. Mauritian honey samples exhibited densities spanning 1.11–1.55 g/mL, with variations linked to moisture content (17.63–24.87%) and floral origin, Lower moisture content in Mauritian honey correlated with higher density values (e.g., 1.55 g/mL at 17.63% moisture [55]. Algerian honey samples further corroborated this range, showing densities of 1.38–1.50 g/mL [56]. In this study, the range of density of 3 different honey samples was 1.47-1.500 g/mL in Table 1 and Figure 5. The densities of Ağın honey (1.50 g/mL), Kovancılar honey (1.474 g/mL), and Arıcak honey (1.492 g/mL) fall within the typical range reported for honey density, which generally spans approximately 1.11 to 1.55 g/mL depending on factors such as botanical origin, moisture content, and regional characteristics. These values suggest that all three honeys have relatively high density, likely indicating moderate to low moisture content and a substantial concentration of sugars and dissolved solids, consistent with quality honey samples from different Turkish regions. Such differences are consistent with findings that mineral profiling combined with chemometric approaches can differentiate honey origins within Turkey and other regions. Overall, the density values support the authenticity and good quality of these honeys, aligning with typical physicochemical profiles of Turkish honeys characterized by regional specificity.

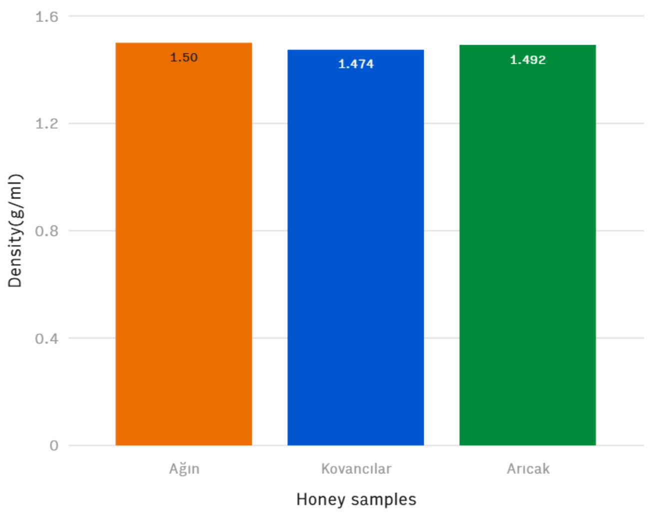

Figure 5. The graph for density results of the honey samples.

Microscope

Figure 6, Figure 7, and Figure 8 show microscope images of different honey samples. Microscopic examination revealed differences in pollen grains and crystal structures. Kovancılar honey exhibited diverse pollen types, while Arıcak honey contained fewer pollen particles.

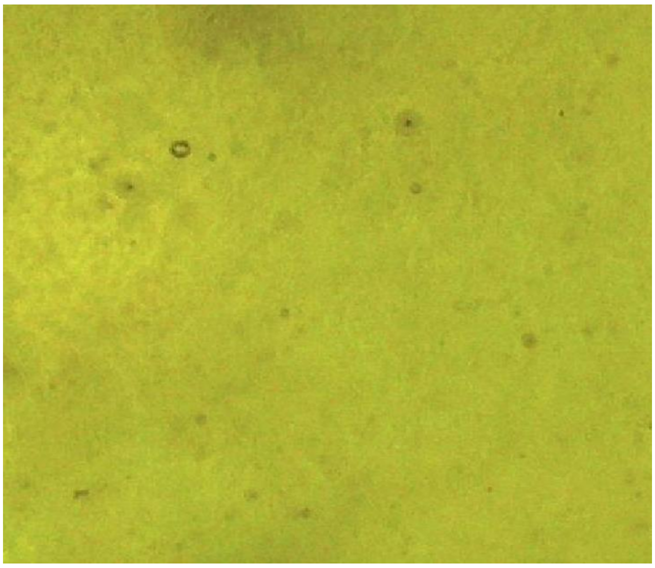

Figure 6. Ağın honey under microscope images

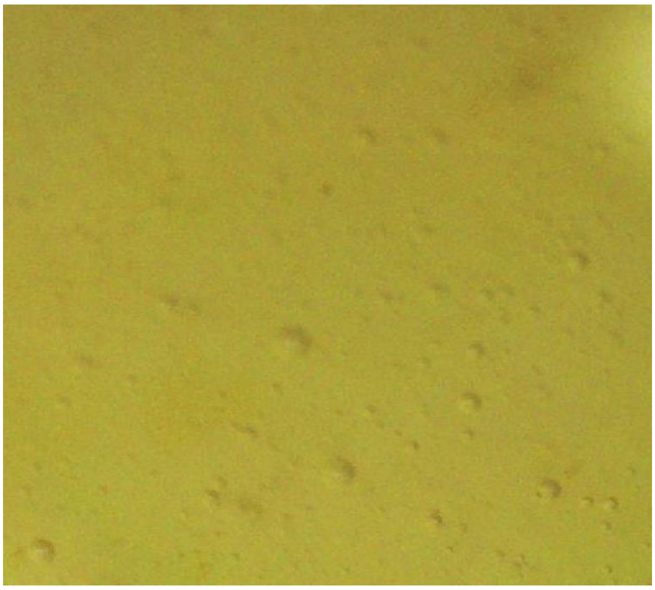

Figure 6. Kovancılar honey under microscope images

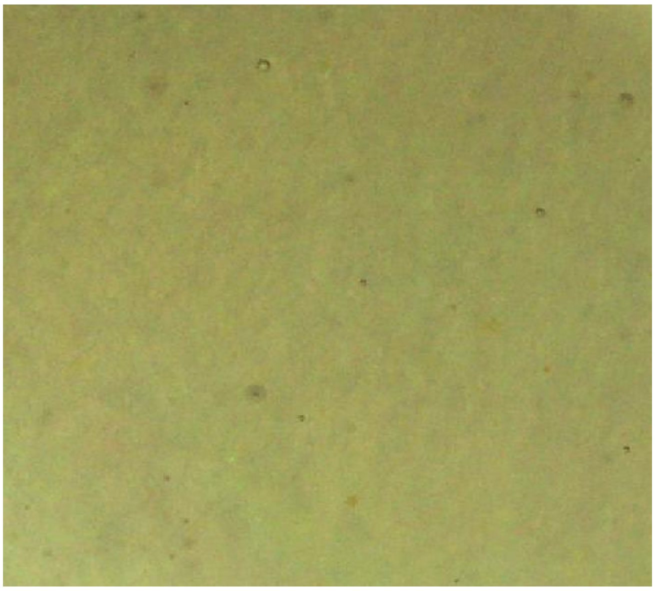

Figure 6. Arıcak honey under microscope images

FTIR spectra analysis

FTIR spectroscopy operates on the principle of measuring the absorption of infrared radiation by molecular bonds, generating a spectrum that reflects the vibrational energy transitions of functional groups. In honey, which comprises carbohydrates (fructose, glucose), organic acids, amino acids, enzymes, and phenolic compounds, distinct absorption bands arise from characteristic molecular vibrations [57, 58]. The mid-infrared region (4000–400 cm^{-1}) is particularly informative, as it captures fundamental vibrations of O-H, C-H, C-O, and C=O bonds, which dominate honey's spectral profile [59, 60]. Attenuated Total Reflection (ATR)-FTIR, a sampling technique that minimizes preparation requirements, has become the standard for honey analysis. By pressing a honey sample against a high-refractive-index crystal (e.g., diamond), the evanescent wave penetrates the sample, yielding reproducible spectra even for viscous or crystallized honeys [58, 59]. evidenced by its ability to differentiate liquid and crystallized states of honey, as glucose monohydrate crystallization alters the O-H stretching region (3550–3250 cm^{-1}) and the C-O-C pyranose ring vibrations (1200–900 cm^{-1}) [59, 60]. The C-O stretching vibrations of fructose and glucose generate intense bands in the 1200–900 cm^{-1} range, often referred to as the "fingerprint region" for sugars. Glucose-rich honeys exhibit a prominent doublet at 1077 and 1025 cm^{-1}, attributed to C-O-C asymmetric stretching in α-glucopyranose, while fructose dominance shifts absorption toward 1055 cm^{-1} due to β-fructofuranose configurations [59, 60].

The ratio of band intensities at 1025 cm^{-1} (glucose) to 1055 cm^{-1} (fructose) has been proposed as a rapid indicator of monosaccharide composition, enabling classification into glucose-dominant (e.g., rapeseed honey), fructose-dominant (e.g., acacia honey), or balanced varieties [59, 61]. HMF, a Maillard reaction product formed during honey storage or heating, exhibits distinct carbonyl (C=O) stretching vibrations at 1680 cm^{-1} and aromatic C=C bending at 1580 cm^{-1} [60, 62].

FTIR's sensitivity to HMF is enhanced by coupling with UV spectroscopy, as HMF's conjugated double bonds absorb strongly at 284 nm, allowing quantification even at low concentrations (≤40 mg/kg) [60, 63]. Elevated HMF levels correlate with reduced antioxidant capacity, evidenced by diminished absorbance in the 3300–3500 cm^{-1} region (O-H stretching of phenolic acids)[60, 64]. Proline, the predominant amino acid in honey, contributes to bands at 1540 cm^{-1} (N-H bending) and 1450 cm^{-1} (C-N stretching), while organic acids like gluconic acid absorb near 1400 cm^{-1} (COO^- symmetric stretching) [61, 65]. These regions are critical for assessing enzymatic activity (e.g., diastase) and floral origin, as amino acid profiles vary with pollen source [61, 66].

FTIR spectra of different honey types are shown in Figure 7, Figure 8, and Figure 9. Based on the FTIR spectra for the three honey samples (Ağın, Arıcak, and Kovancılar), we can analyze and compare their main features to assess their quality and composition. All three spectra display the typical characteristics of natural honey, but there are subtle differences that may relate to their botanical origin, processing, or storage.

The spectrums show a broad and strong absorption
band around 3300 cm^{-1}, which is attributed to O–H stretching vibrations from water and hydroxyl groups in sugars. This is a hallmark of honey's high moisture and sugar content. The intensity and width of this band are quite similar in all samples, indicating comparable moisture levels and a natural honey matrix.
In the region around 2900 cm^{-1}, corresponding to C–H stretching vibrations of carbohydrates, Arıcak and Kovancılar samples exhibit very deep and sharp peaks, almost reaching the baseline. This suggests a higher concentration or a slightly different composition of sugars, particularly glucose and fructose, compared to Ağın sample, where the peak is less pronounced. This difference might be due to variations in floral source or the degree of crystallization.
The fingerprint region (1200–900 cm^{-1}), which is dominated by C–O and C–C stretching vibrations from various sugars, is highly structured and intense in all three spectra. This region is crucial for distinguishing between different honey types. The Arıcak and Kovancılar samples are nearly identical in this area, with well-defined peaks, suggesting a similar sugar profile and possibly a shared botanical origin. The Ağın sample, while still showing the characteristic intense bands, has slightly different peak shapes, which could indicate a unique floral source or minor differences in composition.
In the 1700–1500 cm^{-1} region, associated with C=O stretching (from carbonyl compounds like HMF and organic acids), all samples show only weak absorptions. This is a positive indicator, as it suggests low levels of HMF, meaning the honeys are fresh and have not been exposed to excessive heat or prolonged storage.
No unusual peaks or features are present in any of the spectra that would indicate adulteration with foreign sugars or syrups. The overall spectral patterns confirm that all three samples are authentic, high-quality honeys. The subtle differences between the Ağın sample and the other two may reflect natural variability due to floral origin or local environmental factors.
In summary, the FTIR analysis of these honey samples confirms their authenticity and good quality, with Arıcak and Kovancılar appearing very similar and possibly sharing a botanical source, while Ağın shows minor differences that may be linked to its unique origin. None of the samples show signs of spoilage or adulteration.

Table 2. summary of results FTIR for honey samples

Wave- number (cm^{-1})	Main Assignments	Ağın	Arıcak	Kovancılar
3200–3400	O–H stretch (water/sugar)	Broad, moderate	Broad, strong	Broad, strong
2800–3000	C–H stretch (sugars)	Moderate	Sharp, strong	Sharp, strong
1600–1700	C=O/Amide (HMF/acids)	Weak	Weak	Weak
1000–1200	C–O/C–C (sugars)	Intense, structured	Intense, structured	Intense, structured
<1000	Complex (minor sugars)	Multiple peaks	Multiple peaks	Multiple peaks

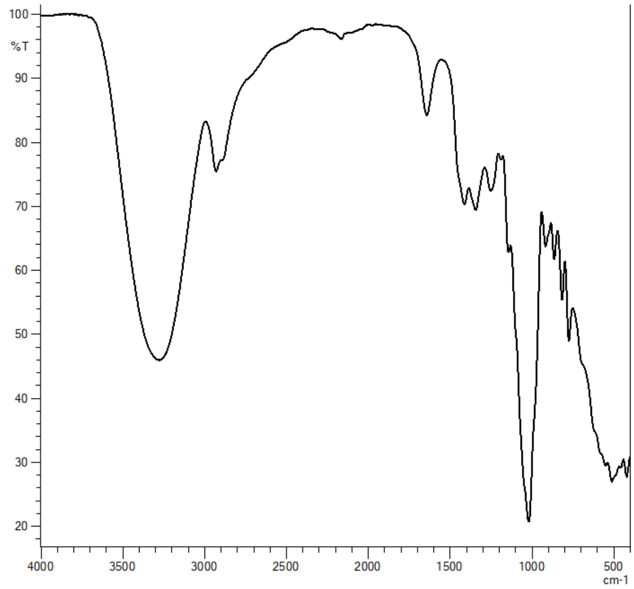

Figure 7. FTIR spectra of Ağın sample

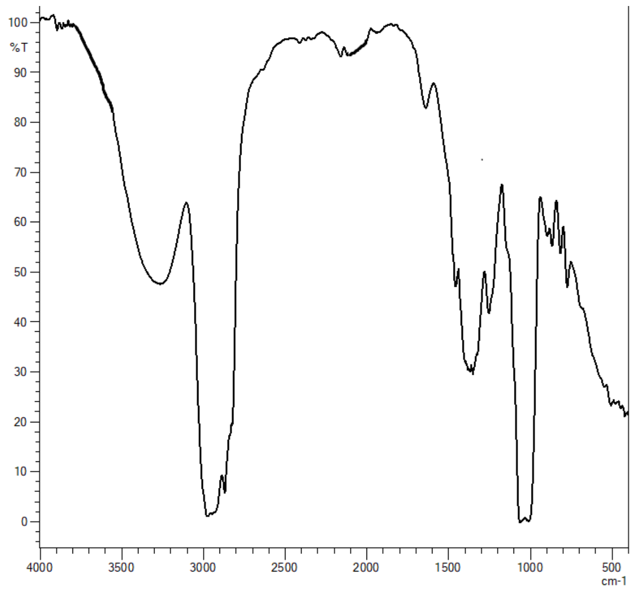

Figure 8. FTIR spectra of Kovancılar sample

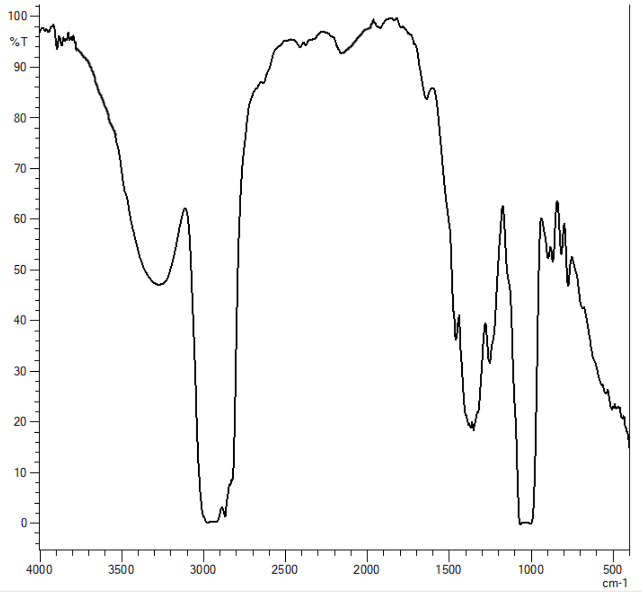

Figure 8. FTIR spectra of Arıcak sample

IV. CONCLUSIONS

The comprehensive analysis of honey samples from Ağın, Kovancılar, and Arıcak regions of Elazığ (Türkiye), through advanced physicochemical characterization and FTIR spectroscopy, underscores the critical interplay between geographical origin and honey quality. All tested samples adhered to international standards set by the Codex Alimentarius and Turkish Food Codex, with pH values (4.23–4.50), moisture content (<20%), and electrical conductivity (specific to floral origins) aligning with established thresholds for authenticity and safety. The observed variations in acidity, mineral content, and viscosity among the three regions highlight the influence of local flora, soil composition, and microclimatic conditions on honey composition. For instance, Kovancılar honey's elevated acidity (pH 4.23) may reflect its unique floral sources, while Arıcak honey's lower viscosity correlates with its distinct sugar profile and moisture dynamics.

FTIR spectroscopy emerged as a robust tool for molecular fingerprinting, successfully identifying characteristic functional groups (e.g., O–H, C=O, and C–O bonds) associated with carbohydrates, organic acids, and phenolic compounds. The spectral profiles not only confirmed the absence of adulterants such as corn syrup or beet sugar but also provided region-specific markers that could aid in geographical authentication. These findings align with global efforts to combat honey fraud, which affects 20–30% of commercially available products, by establishing chemometric models for origin verification.

The study's methodological rigor-combining classical assays (refractometer, viscometer) with modern spectroscopic techniques-offers a replicable framework for regional honey characterization. Such an approach is vital for Türkiye, a leading honey producer, to enhance market trust and comply with the European Union's Honey Directive, which mandates precise origin labeling. Furthermore, the documented physicochemical properties, including density (1.32–1.49 g/mL) and Brix values (>80%), provide local beekeepers with actionable data to optimize harvesting and storage practices, thereby minimizing fermentation risks and preserving bioactive compounds.

Future research should expand the geographical scope to include additional regions of Anatolia, and explore the bioactivity of region-specific phenolic compounds. Longitudinal studies tracking seasonal variations in honey composition could further refine quality benchmarks, while stakeholder education programs are essential to translate scientific findings into sustainable beekeeping practices. By bridging traditional apiculture with advanced analytical science, this study contributes to the global pursuit of honey authenticity, consumer safety, and the preservation of apicultural heritage.

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