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Integrated Physicochemical, ATR–FTIR, and HPLC Characterization of Blossom Honey from Northern Iraq: Sugar Composition and Quality Assessment

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ABSTRACT: Honey quality is influenced by its physicochemical characteristics, carbohydrate composition, and processing and storage conditions. This study aimed to evaluate the physicochemical properties, Fourier-transform infrared (FTIR) spectral characteristics, sugar profiles, and 5-hydroxymethylfurfural (HMF) concentrations of five blossom honey samples collected from Akre, Brifka, Bjil, Charbot, and Khnera in Northern Iraq. Physicochemical analyses included pH, electrical conductivity, moisture content, and total soluble solids (TSS). Attenuated total reflectance Fourier-transform infrared (ATR–FTIR) spectroscopy was employed to characterize functional groups, while high-performance liquid chromatography (HPLC) was used to quantify fructose, glucose, sucrose, maltose, and HMF. The samples exhibited pH values of 3.60–3.84, electrical conductivity of 0.274–0.521 mS/cm, moisture contents of 12.37–16.43%, and TSS values of 82.47–87.13 °Brix. ATR–FTIR spectra revealed characteristic absorption bands associated with O–H, C–H, and C–O vibrations, consistent with the carbohydrate-rich nature of honey. Fructose and glucose were the predominant sugars, with combined concentrations of 67.511–73.407 g/100 g, whereas sucrose concentrations ranged from 0.728 to 2.374 g/100 g. HMF concentrations were relatively low (1.432–4.831 mg/kg). All samples complied with the general Codex quality criteria for blossom honey regarding moisture, fructose-plus-glucose, sucrose, and HMF concentrations. Overall, the findings demonstrate favorable quality characteristics of the investigated honey samples and highlight the complementary value of physicochemical, spectroscopic, and chromatographic analyses for honey characterization in Northern Iraq.

1. INTRODUCTION

Honey is a natural, complex food product produced by honeybees from floral nectar or secretions derived from living plant parts and plant-sucking insects. During honey production, bees transform the collected materials through enzymatic activity, dehydration, and maturation within the honeycomb [1]. The chemical composition and physicochemical characteristics of honey are influenced by several factors, including botanical and geographical origin, climatic conditions, seasonal variations, harvesting practices, and storage conditions [2, 3, 4]. These factors contribute to variations in honey composition and quality, highlighting the importance of systematic physicochemical and analytical characterization.

Honey consists predominantly of carbohydrates, particularly the monosaccharides fructose and glucose, which account for most of its soluble solids [5]. Smaller quantities of disaccharides and oligosaccharides, including sucrose and maltose, are also present, together with organic acids, amino acids, proteins, enzymes, minerals, and phenolic compounds [6-9]. The relative proportions of these constituents influence important properties of honey, including sweetness, viscosity, crystallization behavior, and storage stability. In particular, the fructose-to-glucose ratio is associated with the tendency of honey to crystallize, while moisture content plays an important role in determining its susceptibility to fermentation during storage [9-13].

Physicochemical parameters such as pH, electrical conductivity, moisture content, and total soluble solids (°Brix) are widely employed as indicators of honey quality. The naturally acidic character of honey is associated with its organic acid composition, whereas electrical conductivity is influenced by the concentration of dissolved ions, minerals, and organic acids. Moisture content is particularly important for assessing honey maturation and storage stability, while total soluble solids provide information about the concentration of dissolved constituents, predominantly sugars [8,14,15]. International quality specifications, including the Codex Alimentarius Standard for Honey (CXS 12-1981), establish compositional criteria for moisture content and major sugars, providing a framework for evaluating honey quality [2].

In addition to conventional physicochemical measurements, instrumental analytical techniques provide valuable information about the molecular composition of honey. Attenuated total reflectance Fourier-transform infrared (ATR–FTIR) spectroscopy is a rapid analytical technique that enables the characterization of major functional groups with minimal sample preparation. The infrared spectrum of honey is dominated by absorption bands associated with O–H, C–H, C–O, and C–O–C vibrations, primarily arising from carbohydrates and other naturally occurring constituents. Previous studies have demonstrated the potential of ATR–FTIR spectroscopy for honey characterization, sugar analysis, and the investigation of compositional differences among honey samples [16,17]. Nevertheless, the overlapping nature of infrared absorption bands requires cautious interpretation, particularly when assigning signals to individual minor constituents.

High-performance liquid chromatography (HPLC) is an established analytical technique for determining the concentrations of individual sugars in honey. Quantification of fructose, glucose, sucrose, and maltose provides important information about carbohydrate composition and enables comparison with established quality specifications. Furthermore, hydroxymethylfurfural (HMF), a compound formed primarily through sugar degradation under acidic conditions, is widely used as an indicator of heat exposure and storage-related chemical changes in honey. Its formation is influenced by several factors, including temperature, storage duration, acidity, and sugar composition. Therefore, HMF determination, together with sugar profiling and physicochemical measurements, contributes to a more comprehensive assessment of honey quality [14,18,19].

The Kurdistan Region of Iraq includes geographically diverse environments that may contribute to variation in the composition of locally produced honey. Although physicochemical and instrumental analyses have been widely applied to honey from different geographical origins, region-specific analytical data remain important for documenting local products and evaluating their characteristics against internationally recognized quality criteria. In particular, the combined assessment of conventional physicochemical parameters, ATR–FTIR spectral characteristics, individual sugar concentrations, and HMF content can provide complementary information about honey composition and quality. However, these measurements alone cannot establish botanical origin or confirm honey authenticity without additional supporting analyses.

Accordingly, the present study aimed to characterize five composite honey samples obtained from multiple beehives in five locations within Duhok Governorate, Kurdistan Region of Iraq: Akre, Brifka, Bjil, Charbot, and Khnera. The investigation included the determination of pH, electrical conductivity, moisture content, and total soluble solids, together with ATR–FTIR spectral characterization and HPLC quantification of fructose, glucose, sucrose, maltose, and HMF. The measured parameters were compared with relevant international quality criteria to provide baseline analytical information on honey produced in the investigated locations.

2. MATERIALS AND METHODS

2.1. Honey Sample Collection and Storage

Five composite honey samples were obtained directly from local beekeepers in five locations within Duhok Governorate, Kurdistan Region of Iraq: Akre (A1), Brifka (A2), Bjil (A3), Charbot (A4), and Khnera (A5). Each composite sample

consisted of honey originating from multiple beehives within the corresponding sampling location. The samples were collected between July and September 2025 and transferred into clean, airtight glass or plastic containers. All samples were stored under ambient laboratory conditions, protected from direct sunlight, until analysis. Physicochemical and chemical analyses were completed within six months of sample collection. Each composite sample was analyzed in triplicate (n = 3), and the results were expressed as mean ± standard deviation (SD), where applicable. The geographical origins and identification codes of the investigated honey samples are presented in Table 1.

Table 1. Geographical origin and identification of honey samples collected from Duhok Governorate, Iraq.

Sample code	Sampling location	Sample type
A1	Akre	Composite honey
A2	Brifka	Composite honey
A3	Bjil	Composite honey
A4	Charbot	Composite honey
A5	Khnera	Composite honey

2.2. Physicochemical Analysis

The physicochemical characteristics of the honey samples were evaluated by determining pH, electrical conductivity (EC), moisture content, and total soluble solids (TSS). All measurements were performed in triplicate for each composite sample, and the results were expressed as mean ± standard deviation (SD).

2.2.1. Determination of pH

The pH of the honey samples was measured using a digital multiparameter meter (AZ pH/mV/Cond/TDS/Temp). Prior to measurement, the instrument was calibrated using standard buffer solutions at pH 4.0 and 7.0. For sample preparation, 10.0 g of honey was weighed into a 250 mL beaker and dissolved in 75 mL of distilled water. The pH electrode was immersed in the prepared solution, and the pH was recorded. Measurements were conducted at approximately 25 °C, following the procedure described in the original methodology [20].

2.2.2. Determination of Electrical Conductivity

Electrical conductivity (EC) was determined using a digital conductivity meter (AZ pH/mV/Cond/TDS/Temp). Approximately 10.0 g of honey was dissolved in 75 mL of distilled water in a 200 mL beaker. The mixture was stirred for approximately 30 min to obtain a homogeneous solution. The instrument was calibrated using a potassium chloride (KCl) reference solution before measurement. Electrical conductivity was expressed in millisiemens per centimeter (mS/cm) [14].

2.2.3. Determination of Total Soluble Solids and Moisture Content

Moisture content and total soluble solids (TSS) were determined using two digital refractometers manufactured by ATAGO Co., Ltd. (Japan). Honey moisture content was determined using a precision digital refractometer (RX-5000α) equipped with a temperature-controlled measurement system maintained at 20 °C. A representative portion of each honey sample was placed on the measuring prism, and the refractive index was recorded. The moisture content was calculated using a honey-specific refractive index–moisture conversion relationship and expressed as a percentage (%).

Total soluble solids were measured separately using a handheld digital refractometer (PAL-1, ATAGO Co., Ltd., Japan). Before each analytical session, the instrument was calibrated using distilled water. A representative portion of honey was placed directly on the measuring prism, and the total soluble solids were recorded in degrees Brix (°Brix).

All measurements were performed in triplicate for each composite honey sample (n = 3), and the results were expressed as mean ± standard deviation (SD).

2.3. ATR–FTIR SPECTROSCOPIC ANALYSIS

The infrared spectral characteristics of the honey samples were investigated using attenuated total reflectance Fourier-transform infrared (ATR–FTIR) spectroscopy. (FTIR) analysis was performed using a PerkinElmer Spectrum Two FTIR spectrometer (PerkinElmer, USA), equipped with a deuterated triglycine sulfate (DTGS) detector and a universal attenuated total reflectance (UATR) single-bounce diamond accessory. A small aliquot of each honey sample was placed directly onto the ATR crystal to ensure adequate contact with the crystal surface. Infrared spectra were recorded over the wavenumber range of 4000–500 cm^{-1} at a spectral resolution of 4 cm^{-1}, with 32 scans accumulated for each measurement. A background spectrum was acquired before each measurement to account for atmospheric and instrumental contributions. Between successive measurements, the ATR crystal surface was cleaned with ethanol to minimize sample carryover and cross-contamination. Each composite honey sample was analyzed in triplicate (n = 3). The acquired spectra were processed and examined using Shimadzu LabSolutions IR software to characterize the principal absorption bands and their associated vibrational functional groups, particularly those related to the carbohydrate-rich composition of honey. Spectral band assignments were interpreted with reference to published infrared spectroscopic data [16,17].

2.4. HPLC Determination of Hydroxymethylfurfural (HMF)

The concentration of 5-hydroxymethylfurfural (HMF) in honey samples was determined using high-performance liquid chromatography (HPLC) coupled with photodiode array (PDA) detection. Chromatographic analysis was conducted at the University of Zakho, Kurdistan Region of Iraq, using a PerkinElmer Flexar HPLC system equipped with an autosampler, a binary pump, and a PDA detector. Chromatographic data acquisition and processing were performed using Chromera software (version 3.4.0.5712).

Chromatographic separation was achieved using an Inertsil ODS-3 reversed-phase C18 column (250 × 4.6 mm, 5 μm particle size). The mobile phase consisted of deionized water and methanol (90:10, v/v), delivered at a flow rate of 1.0 mL/min. The detection wavelength was set at 284 nm, and the injection volume was 20 μL.

For sample preparation, 10.0 g of honey was accurately weighed and dissolved in deionized water. The resulting solution was quantitatively transferred into a 50 mL volumetric flask and diluted to volume with deionized water. The prepared solution was filtered through a syringe filter and transferred into an HPLC vial before analysis.

Quantitative determination of HMF was performed using an external calibration curve prepared from an HMF reference standard. HMF concentrations in the honey samples were calculated from the calibration relationship and expressed as milligrams per kilogram of honey (mg/kg).

3. RESULTS AND DISCUSSION

3.1. Physicochemical Characteristics of Honey Samples

The physicochemical characteristics of the five honey samples collected from different locations in Duhok Governorate are presented in Table 2. The investigated parameters included pH, electrical conductivity (EC), moisture content, and total soluble solids (TSS). All measurements were performed in triplicate, and the results are expressed as mean ± standard deviation (SD).

The pH values ranged from 3.60 ± 0.01 in Bjil honey (A3) to 3.84 ± 0.02 in Brifka honey (A2), indicating the acidic nature of all investigated samples. This acidity is consistent with the characteristic composition of honey, in which organic acids, particularly gluconic acid, contribute to the overall pH. The relatively narrow pH range suggests limited variation in acidity among the analyzed samples, although pH measurements alone cannot establish differences in organic acid composition.

Electrical conductivity varied from 0.274 ± 0.004 mS/cm in Charbot honey (A4) to 0.5213 ± 0.004 mS/cm in Akre honey (A1). Electrical conductivity is influenced by the concentration of dissolved ions, including mineral constituents and organic acids. The higher conductivity observed in A1 may reflect a greater contribution of ionizable constituents, whereas the lower value recorded for A4 suggests comparatively lower ionic conductivity. However, mineral composition was not directly determined in this study; therefore, these interpretations remain tentative. All five samples exhibited electrical conductivity values below 0.8 mS/cm, the commonly applied Codex limit for many blossom honeys, subject to honey-type-specific exceptions.

Total soluble solids ranged from 82.47 ± 0.15 °Brix in Charbot honey (A4) to 87.13 ± 0.19 °Brix in Akre honey (A1). The high °Brix values are consistent with the carbohydrate-rich nature of honey, in which sugars constitute the predominant fraction of soluble solids. Variations in TSS may reflect differences in water content and dissolved constituents among the samples.

Moisture content ranged from 12.37 ± 0.40% in Bjil honey (A3) to 16.43 ± 0.42% in Khnera honey (A5). All samples were below the general maximum moisture limit of 20% specified by the Codex Standard for Honey. The relatively low moisture contents are favorable for honey storage stability because water availability is an important factor influencing susceptibility to osmophilic yeast fermentation. Nevertheless, moisture content alone cannot establish microbial stability or exclude fermentation without additional microbiological assessment.

Overall, the investigated honey samples exhibited acidic pH values, relatively low electrical conductivity, high soluble solids, and moisture contents within the general international quality limit. The observed differences describe variability among the five composite samples but should not be interpreted as statistically established geographical effects because only one composite sample was analyzed per location.

Table 2. Physicochemical characteristics of honey samples collected from Duhok Governorate, Kurdistan Region of Iraq

Sample	pH	EC (mS/cm)	Moisture (%)	TSS (°Brix)
A1	3.64 ± 0.01	0.5213 ± 0.004	12.63 ± 0.25	87.13 ± 0.19
A2	3.84 ± 0.02	0.452 ± 0.004	14.50 ± 0.20	85.13 ± 0.12
A3	3.60 ± 0.01	0.344 ± 0.004	12.37 ± 0.40	86.57 ± 0.35
A4	3.63 ± 0.01	0.274 ± 0.004	15.63 ± 0.25	82.47 ± 0.15
A5	3.70 ± 0.05	0.427 ± 0.003	16.43 ± 0.42	84.50 ± 0.40

Values are mean ± SD of three analytical measurements (n = 3) per composite sample. EC = electrical conductivity; TSS = total soluble solids.

3.2. ATR–FTIR Spectral Characterization

ATR–FTIR spectroscopy was used to characterize the principal vibrational features of five honey samples collected from Akre (A1), Brifka (A2), Bjil (A3), Charbot (A4), and Khnera (A5). The spectra exhibited broadly similar absorption patterns, with minor variations in peak positions and transmittance values, indicating comparable major functional group characteristics across the investigated samples.

A broad absorption band was observed between 3285.12 and 3289.23 cm^{-1}, corresponding primarily to O–H stretching vibrations associated with water and hydroxyl-containing carbohydrates. Bands between 2930.14 and 2931.97 cm^{-1} were attributed to aliphatic C–H stretching vibrations. An additional absorption feature occurred between 1641.59 and 1643.67 cm^{-1}, consistent predominantly with H–O–H bending vibrations of water, although overlapping contributions from other constituents cannot be excluded.

The spectra also exhibited bands near 1413 and 1344 cm^{-1}, associated with carbohydrate-related deformation vibrations, together with absorption features around 1252–1254 cm^{-1}. The most prominent fingerprint-region absorption minimum occurred between 1024.34 and 1025.51 cm^{-1}, consistent with overlapping C–O and C–O–C vibrational modes characteristic of carbohydrates. Additional bands were recorded near 918, 865, 817, and 776 cm^{-1}, reflecting further fingerprint-region vibrations as shown in figure 2 and table 3.

The close correspondence of the principal absorption bands among the five samples suggests substantial similarity in their major infrared-active constituents. This observation is consistent with the carbohydrate-rich composition of honey, as supported by the HPLC identification and quantification of fructose, glucose, sucrose, and maltose. However, the relatively

small differences in band positions and transmittance should not be interpreted as direct evidence of specific botanical origins, bee-feeding practices, or adulteration.

Overall, the ATR–FTIR results provided complementary molecular-level information on the honey samples and demonstrated a broadly conserved carbohydrate-associated spectral profile across the investigated locations.

Table 3. Major ATR–FTIR absorption bands (cm^{-1}) of honey samples collected from different locations in Northern Iraq and their tentative vibrational assignments.

A1	A2	A3	A4	A5	Tentative vibrational assignment
3289.23	3285.12	3288.85	3287.70	3288.25	O–H stretching (water and carbohydrates)
2931.13	2930.63	2930.14	2931.39	2931.97	Aliphatic C–H stretching
1643.67	1642.99	1643.02	1641.59	1643.52	H–O–H bending (water); possible overlapping vibrations
1413.19	1413.52	1413.17	1413.26	1413.15	C–H deformation and carbohydrate-associated vibrations
1343.61	1343.96	1343.71	1343.79	1343.32	C–H and O–H deformation vibrations
1253.97	1253.83	1254.32	1253.31	1251.56	C–O stretching and coupled vibrations
1024.90	1024.34	1024.61	1025.51	1025.48	C–O and C–O–C stretching (carbohydrate fingerprint region)
918.71	918.33	919.18	918.00	917.70	Carbohydrate fingerprint vibrations
864.96	864.90	865.04	864.99	865.12	Carbohydrate ring-associated vibrations
817.18	817.18	817.25	817.09	817.05	Fingerprint-region vibrations
776.38	776.02	776.44	776.07	776.28	Fingerprint-region vibrations
514.66	516.90	514.77	514.65	514.63	Low-frequency fingerprint vibrations

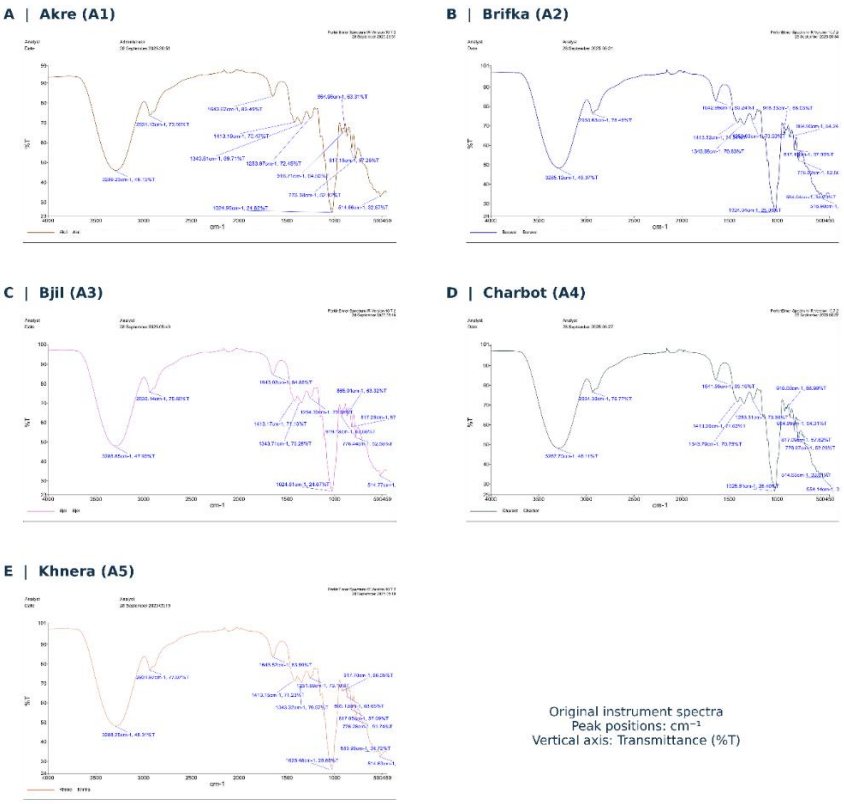

Figure 2. ATR–FTIR spectra of honey samples collected from five geographical locations in Northern Iraq.

3.3. HPLC Sugar Composition

The sugar composition of the five honey samples was determined by high-performance liquid chromatography with refractive index detection (HPLC–RID). Fructose, glucose, sucrose, and maltose were quantified, and their concentrations are presented in Table 4.

Fructose concentrations ranged from 33.913 g/100 g in Brifka honey (A2) to 38.294 g/100 g in Khnera honey (A5), whereas glucose concentrations varied from 33.373 g/100 g in Bjil honey (A3) to 37.526 g/100 g in Akre honey (A1). Fructose and glucose were the predominant sugars in all investigated samples, collectively accounting for 67.511–73.407 g/100 g of honey. This predominance is consistent with the characteristic carbohydrate composition of honey, in which monosaccharides represent the major sugar fraction.

Sucrose concentrations ranged from 0.728 g/100 g in A5 to 2.374 g/100 g in A3. All samples exhibited sucrose concentrations below the general maximum limit of 5 g/100 g established by the Codex Standard for Honey, although specific honey varieties may be subject to different limits. The relatively low sucrose concentrations are consistent with the expected composition of mature honey; however, sucrose content alone cannot establish authenticity or exclude adulteration.

Maltose concentrations ranged from 1.376 g/100 g in A2 to 2.406 g/100 g in A3. These comparatively low concentrations indicate that maltose constituted a minor proportion of the four quantified sugars. The sum of the measured sugars varied from 72.291 g/100 g in A3 to 76.762 g/100 g in A1. These totals represent only the four quantified sugars and should not be interpreted as the complete carbohydrate content of the samples.

The fructose-to-glucose (F/G) ratio ranged from 0.913 in A2 to 1.123 in A5. Fructose exceeded glucose in A3 and A5, whereas glucose was more abundant in A1, A2, and A4. Differences in the F/G ratio may influence the tendency of honey to crystallize, although crystallization also depends on moisture content, other dissolved constituents, and storage conditions. Consequently, the observed ratios alone are insufficient to predict the crystallization behavior of individual samples.

Overall, HPLC–RID analysis demonstrated that fructose and glucose dominated the measured sugar profiles of all five honey samples, while sucrose and maltose occurred at lower concentrations. The measured fructose-plus-glucose concentrations exceeded the general minimum requirement of 60 g/100 g applicable to blossom honey under the Codex Standard for Honey. Nevertheless, the botanical classification of the samples and their authenticity cannot be established from sugar composition alone.

Table 4. HPLC–RID sugar composition of honey samples collected from Northern Iraq (g/100 g).

Sample	Fructose	Glucose	Sucrose	Maltose	Total measured sugars	F/G ratio
A1	35.881	37.526	1.511	1.844	76.762	0.956
A2	33.913	37.141	1.747	1.376	74.177	0.913
A3	34.138	33.373	2.374	2.406	72.291	1.023
A4	34.189	35.957	2.189	1.947	74.282	0.951
A5	38.294	34.091	0.728	2.114	75.227	1.123

F/G = fructose-to-glucose ratio, calculated from the reported concentrations. Total measured sugars = fructose + glucose + sucrose + maltose. Concentrations are reported as g/100 g honey.

3.4. Hydroxymethylfurfural (HMF) Content and Quality Assessment

The concentrations of 5-hydroxymethylfurfural (HMF) in the five honey samples were determined using high-performance liquid chromatography with photodiode array detection (HPLC–PDA). The results are presented in Table 5.

HMF concentrations ranged from 1.432 mg/kg in Brifka honey (A2) to 4.831 mg/kg in Akre honey (A1). The remaining samples exhibited HMF concentrations of 2.902 mg/kg in Bjil honey (A3), 1.970 mg/kg in Charbot honey (A4), and 1.749 mg/kg in Khnera honey (A5).

All investigated samples exhibited HMF concentrations substantially below the general maximum limit of 40 mg/kg established by the Codex Standard for Honey. HMF is formed primarily through sugar degradation reactions, and its accumulation may be influenced by heating, storage duration, temperature, acidity, and honey composition. Therefore, HMF concentration is widely used as an indicator of honey quality and possible thermal or storage-related deterioration. The relatively low HMF concentrations observed in the present study are consistent with limited HMF accumulation in the analyzed samples. However, these findings do not independently establish the absence of previous heating or determine the precise storage history of the honey.

Table 5. Hydroxymethylfurfural (HMF) concentrations in honey samples collected from Northern Iraq.

Honey sample	HMF (mg/kg)
A1	4.831
A2	1.432
A3	2.902
A4	1.970
A5	1.749

HMF = 5-hydroxymethylfurfural. Values represent the reported concentrations for the five composite honey samples.

Although Akre honey (A1) exhibited the highest HMF concentration, its measured value remained well below the general international limit. Differences among the five samples may reflect variation in their composition, processing, or storage histories; however, the available data do not permit identification of the factors responsible for these differences.

Overall, the HPLC–PDA results demonstrated that all five honey samples complied with the general Codex HMF criterion, supporting their favorable quality status with respect to this parameter.

4. CONCLUSION

This study provided an integrated assessment of the physicochemical properties, ATR–FTIR spectral characteristics, sugar composition, and hydroxymethylfurfural (HMF) content of five honey samples collected from different geographical locations in Northern Iraq. The findings demonstrated variations in the measured quality parameters while revealing broadly similar chemical characteristics among the investigated samples.

The physicochemical analysis showed that all honey samples were acidic, with pH values ranging from 3.60 to 3.84, electrical conductivity values from 0.274 to 0.521 mS/cm, moisture contents from 12.37% to 16.43%, and total soluble solids from 82.47 to 87.13 °Brix. All samples exhibited moisture contents below the general maximum limit of 20%, indicating compliance with this important honey quality criterion.

ATR–FTIR analysis revealed characteristic absorption bands associated with O–H, C–H, and C–O vibrations, consistent with the carbohydrate-rich composition of honey. The spectra exhibited similar overall patterns, with minor differences in band positions and intensities among the samples.

HPLC analysis confirmed that fructose and glucose were the predominant sugars, with combined concentrations ranging from 67.511 to 73.407 g/100 g. Sucrose and maltose were present at comparatively lower concentrations. All samples satisfied the general Codex criteria for fructose-plus-glucose and sucrose concentrations applicable to blossom honey. Furthermore, HMF concentrations ranged from 1.432 to 4.831 mg/kg, remaining substantially below the general maximum limit of 40 mg/kg.

Overall, the findings indicate that the investigated honey samples exhibited favorable quality characteristics with respect to the measured physicochemical parameters, sugar composition, and HMF content. The combined application of physicochemical analysis, ATR–FTIR spectroscopy, and HPLC provides a useful analytical approach for characterizing honey from Northern Iraq. Further investigations incorporating pollen analysis, mineral profiling, and validated authenticity markers are recommended to establish botanical origin and evaluate potential adulteration more comprehensively.

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