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Original research article

Mineral Profiling of Honey Samples from Uzbekistan and Russia through Chemometric Analysis

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Abstract Mineral profiles of honey reflect the floral and environmental factors of nectar plants and play a role in determining its authenticity. However, systematic studies applying chemometric approaches to characterize these profiles are still in the early stages. This study evaluated five macroelements (Ca, K, Mg, Na, and P) and four microelements (Cu, Fe, Mn, and Zn) in 31 samples (29 honeys and 2 syrups) from Uzbekistan and Russia, using ICP-OES and ICP-MS. K and Ca were found most abundant in the honey samples, ranging from 97.3–977.3 mg/kg and 80.9–414.1 mg/kg. The concentrations of individual elements and the total mineral content differed significantly among floral origins, with the lowest levels observed in the syrup samples. Chemometric analyses, including Pearson's correlation analysis, revealed positive correlations between honey color and each of Ca, Cu, Mg, and P. Principal Component analysis clearly discriminated authentic honeys from syrup. Clustering Uzbek and Russian honeys together indicated that floral source exerts a stronger influence than geographical origin. This study provides the first comprehensive assessment of honey minerals in Uzbekistan and establishes a reference framework for developing a mineral-based database to support authenticity verification of honeys distributed in Uzbekistan.

Keywords Macroelements, Microelements, Authenticity, Syrup, ICP, Color

INTRODUCTION

Honey (blossom honey) is a widely consumed natural sweetener produced by honey bees from floral nectar (Codex Alimentarius, 2001). It is a highly complex substance, comprising nearly 200 compounds, including sugars, water, proteins, organic acids, vitamins, and minerals (Alvarez-Suarez *et al*., 2013; da Silva *et al*., 2016). The characteristics of honey are influenced by bee species, seasonality, environmental parameters, beekeeping practices, storage conditions, and most notably, its geographical location and botanical source (Leite *et al*., 2000; Bogdanov *et al*., 2008; Kaškonienė *et al*., 2010; da Silva *et al*., 2016).

In our previous studies, the botanical origins of honey samples collected from the Tashkent region in Uzbekistan were first identified through melissopalynological analysis, followed by a comprehensive investigation into their physicochemical properties. These studies highlighted the significant contribution of floral origin to honey composition and confirmed the overall high quality of Uzbek honey, thereby prompting further investigation into its mineral content (Jang *et al*., 2025a; Sun *et al*., 2025).

Minerals in honey primarily originate from the soil type and nectar-secreting plants (Bogdanov *et al*., 2007; Schmidlová *et al*., 2024). Solayman *et al*. (2016) identified 54 mineral elements previously reported in honey, comprising seven macroelements and 47 microelements. The total mineral content of honey has been reported to

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range from 126 to 4060 mg/kg, depending on the type of honey (Vanhanen *et al*., 2011). Several studies have shown that mineral levels and compositions differ significantly according to botanical and regional origins (Nalda *et al*., 2005; Ajtony *et al*., 2007; Bogdanov *et al*., 2007; Czipa *et al*., 2018; Bodó *et al*., 2020; Vukašinovič-Pešić *et al*., 2020). Dark-colored honey, whose color is largely determined by its floral origin, contains higher mineral content than light-colored ones (Alqarni *et al*., 2014; Bodó *et al*., 2021; Pavlin *et al*., 2023). Moreover, Liu *et al*. (2021) reported that honey exhibited higher levels of elements than syrup, and that syrup adulteration could be distinguished from authentic honey through chemometric analysis. Taken together, these findings underscore the significance of mineral profiling not only for evaluating the botanical origin and quality of honey but also for identifying potential adulteration.

The Republic of Uzbekistan is a Central Asian country bordered by Kazakhstan to the north, Kyrgyzstan and Tajikistan to the east and southeast, Turkmenistan to the west, and Afghanistan to the south. It has a predominantly continental and arid climate, which varies across regions (Belolipov *et al*., 2013). Beekeeping in the country is essential for supporting local economic growth through pollination services and honey production (Farmanov, 2025). Uzbek people have been consuming honey and honey-based products as a food resource for a long time (Abdiniyazova *et al*., 2016). However, despite its importance, comprehensive studies on the chemical characteristics of honey, particularly its mineral content, remain limited.

This study aims to expand the understanding of the mineral composition of honey collected from Tashkent, Uzbekistan. Specifically, this study focuses on determining the levels of macro- and microelements in honey samples and employs chemometric analyses to investigate the relationships among mineral composition, color, floral source and geographical origin, as well as to verify honey authenticity. We hypothesized that the floral origin of honey would have a stronger influence on its mineral composition than its geographical source. Through this approach, the study not only establishes baseline data for assessing the quality and authenticity of Uzbek honey but also offers valuable insights into the distinctive mineral signatures that characterize honey produced in Central Asia.

MATERIALS AND METHODS

1. Honey samples

A total of 31 samples, including 30 honeys from *Apis mellifera* collected in Tashkent, Uzbekistan, in 2022, were analyzed. Among the collected samples, 27 were produced in Tashkent, while 4 were produced in Russia. Among the Uzbek honeys, 7 were *Alhagi*, 4 *Helianthus*, 4 *Medicago*, 1 *Salvia*, 1 *Ferula*, 1 *Onobrychis*, and 1 *Tilia*. 6 samples were classified as multifloral honey, comprising 2 dominated by *Helianthus* and 1 each dominated by *Alhagi*, *Calligonum*, *Ferula*, and *Onobrychis*. 2 samples were classified as artificial syrup prepared from fructose, glucose, and sucrose. From Russia, 3 samples were *Helianthus* and 1 was *Medicago*. Although the number of samples was relatively small due to the limited market availability, all honey products available in Tashkent during the sampling period were collected, ensuring that the dataset represents the overall honey market in Tashkent. Detailed information on the botanical origins of these honey samples is available in previous studies (Jang *et al*., 2025a; Sun *et al*., 2025), and a summary is presented in Table 1.

2. Determination of honey color

The Pfund scale, which is the most commonly used method, is widely applied to determine honey color based on color intensity (Bogdanov *et al*., 2004). A portable honey color photometer (HI96785, Hanna Instruments, Seoul, South Korea), calibrated using a glycerol standard, was used for color measurement. After calibration, approximately 4 mL of honey was transferred into a cuvette, and the color was measured carefully to avoid air bubbles. The values were classified according to the USDA honey color standards (1985) as follows: 0–8 mm—water white, 8–17 mm—extra white, 17–34 mm—white, 34–50 mm—extra light amber, 50–85 mm—light amber, 85–114 mm—amber, and >114–140 mm—dark amber. The results are summarized in Table 1.

3. Mineral analysis

Sample preparation for mineral quantification was performed according to the method previously described by Jang *et al*. (2025b). A 0.5 g portion of homogenized honey was treated with 5 mL of concentrated nitric acid

Table 1. Floral sources, sample size, pollen frequency determined by melissopalynological analysis, and Pfund scale–based color classification of honey and syrup samples collected in Tashkent, Uzbekistan, in 2022

Country	Floral source		N	Dominant pollen frequency (%)	Pfund scale (mm)	Color description
	Family	Genus				
Uzbekistan	Fabaceae	*Alhagi*	7	77.7 ± 11.5	79.4 ± 35.7	Light amber
	Asteraceae	*Helianthus*	4	63.8 ± 16.5	70.3 ± 10.1	Light amber
	Fabaceae	*Medicago*	4	45.4 ± 7.1	91.0 ± 27.8	Amber
	Apiaceae	*Ferula*	1	53.3 ± 5.3	69.7 ± 1.5	Light amber
	Fabaceae	*Onobrychis*	1	69.6 ± 4.1	81.7 ± 0.6	Light amber
	Lamiaceae	*Salvia*	1	69.7 ± 2.5	84.0 ± 0.0	Light amber
	Malvaceae	*Tilia*	1	95.6 ± 13.3	68.0 ± 1.0	Light amber
	Multifloral	*Helianthus* + *Alhagi*	2	37.9 ± 6.6, 11.6 ± 14.6	80.0 ± 15.4	Light amber
		Alhagi + *Helianthus*	1	26.2 ± 2.8, 25.0 ± 5.2	78.3 ± 0.6	Light amber
		Calligonum + *Salvia*	1	37.5 ± 0.8, 10.7 ± 1.3	105.0 ± 0.0	Amber
		Ferula + *Alhagi*	1	38.8 ± 3.7, 16.0 ± 1.3	125.7 ± 1.2	Dark amber
		Onobrychis + *Medicago*	1	39.4 ± 1.6, 33.1 ± 1.3	83.0 ± 1.0	Light amber
	–	Syrup	2	–	25.0 ± 1.1	White
Russia	Asteraceae	*Helianthus*	3	85.3 ± 9.4	62.0 ± 4.4	Light amber
	Fabaceae	*Medicago*	1	41.6 ± 6.1	111.7 ± 0.6	Amber

(HNO_3) and digested in a high-pressure microwave digestion system equipped with a single reaction chamber (UltraWAVE, Milestone, Sorisole, Italy) at 180°C for 30 min. After digestion, the solution was allowed to cool to room temperature and then diluted with distilled water to a final volume of 50 mL. Ca, Fe, K, Mg, Na, and P in the honey samples were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES; Agilent 5110, Agilent Technologies, Santa Clara, CA, USA), whereas Cu, Mn, and Zn were determined by inductively coupled plasma mass spectrometry (ICP-MS; Agilent 7800, Agilent Technologies, Santa Clara, CA, USA). For ICP-OES, standard instrumental conditions were applied as described by Gąsecka *et al.* (2021), while the ICP-MS parameter settings were adopted from Alhagri and Albeshry (2023). Contents of both macroelements (Ca, K, Mg, Na, and P) and microelements (Cu, Fe, Mn, and Zn) in the samples were expressed in mg/kg. All measurements were performed in triplicate to ensure reproducibility and accuracy.

4. Statistical analysis

All statistical and chemometric analyses were performed using R software (version 4.4.1; R Core Team, Vienna, Austria). Normality and homogeneity of variances were assessed using the Shapiro-Wilk and Levene's tests, respectively. Since the data met the assumption of normality but violated the assumption of homogeneity of variances ($p < 0.05$), differences among floral origins for macroelements, microelements, and total mineral content were analyzed using Welch's ANOVA, followed by the Games-Howell post hoc test. Principal component analysis (PCA) was applied to explore the relationships between the honey samples and their mineral compositions. PCA score and loading plots were generated to visualize the clustering patterns of the samples and the contribution of variables, respectively. Pairwise correlations among mineral elements and between the mineral content and color intensity of the honey samples were evaluated using Pearson's correlation analysis. The significance level was set at $\alpha = 0.05$, and all results are presented as mean ± standard deviation (SD).

RESULTS AND DISCUSSION

1. Elemental composition of honey samples

The concentrations of 5 macroelements (Ca, K, Mg, Na, and P) and 4 microelements (Cu, Fe, Mn, and Zn) were analyzed in a total of 31 samples, including 25 Uzbek honeys of distinct floral origins (*Alhagi*, *Helianthus*, *Medicago*, *Ferula*, *Onobrychis*, *Salvia*, *Tilia*, and multifloral types), 4 Russian honeys, and 2 artificial syrup samples. These data are summarized in Tables 2 and 3, and the variations in total mineral content, which was calculated as the sum of the 9 measured elements, are depicted in Fig. 1. All elements, as well as the total mineral content, showed statistically significant differences among the samples ($p < 0.001$). Similarly, previous studies have also reported significant differences in mineral composition depending on geographical and botanical origins (Bogdanov *et al*., 2007; Valverde *et al*., 2022; Pavlin *et al*., 2023; Mongi, 2024). These differences are thought to be influenced by agricultural practices and the mineral composition of soils, as plants absorb and transfer these elements into nectar and subsequently into honey (Hemalatha and Satyanarayana, 2015; Lanjwani and

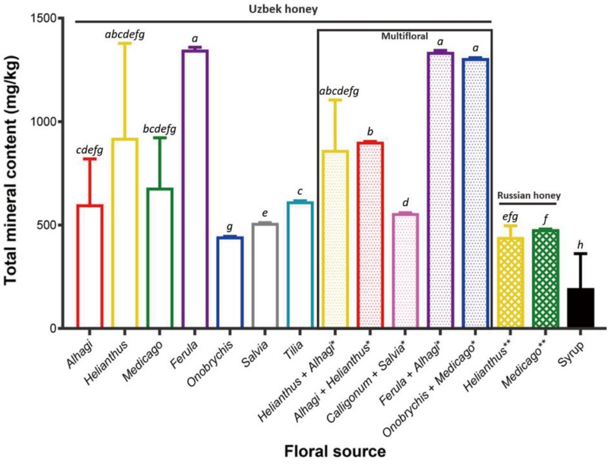


Fig. 1. Total mineral contents (mg/kg) in honey and syrup samples from different floral origins collected in Tashkent, Uzbekistan, in 2022. Values are presented as mean ± standard deviation. Different superscript letters indicate significant differences among floral groups (Welch's ANOVA followed by the Games-Howell post hoc test for multiple comparisons, $p < 0.05$). Asterisks (*) indicate multifloral honeys, and double asterisks (**) denote honeys produced in Russia.

Table 2. Contents of macroelements (mg/kg) in honey and syrup samples from different floral origins collected in Tashkent, Uzbekistan, in 2022

Floral source	Macroelement content (mg/kg)				
	Ca	K	Mg	Na	P
Alhagi	145.6 ± 43.2 c	248.8 ± 153.6 d	36.5 ± 9.8 c	90.3 ± 20.6 a	76.5 ± 26.4 ab
Helianthus	228.5 ± 113.5 abcd	487.2 ± 324.7 abcde	53.6 ± 16.6 abc	86.0 ± 18.6 a	62.8 ± 6.3 b
Medicago	160.9 ± 40.7 bc	317.2 ± 172.0 bcd	34.0 ± 14.4 bcde	83.1 ± 15.2 a	83.0 ± 13.0 a
Ferula	321.6 ± 2.4 a	771.3 ± 7.5 a	76.1 ± 0.5 a	103.8 ± 0.9 a	71.0 ± 0.4 ab
Onobrychis	105.7 ± 0 .4 c	177.5 ± 0.6 d	22.2 ± 0.1 e	70.0 ± 0.2 a	66.3 ± 0.4 ab
Salvia	128.2 ± 0.1 c	187.6 ± 1.0 d	35.8 ± 0.1 c	83.1 ± 0.1 a	72.4 ± 0.4 a
Tilia	81.2 ± 0.3 d	425.8 ± 1.5 c	22.7 ± 0.2 e	59.0 ± 0.6 a	23.8 ± 0.7 c
*Helianthus + Alhagi**	193.1 ± 99.4 abcde	504.0 ± 102.4 abcd	37.1 ± 21.4 abcdef	74.2 ± 9.9 a	51.7 ± 6.3 b
*Alhagi + Helianthus**	218.6 ± 0.3 b	483.8 ± 0.8 b	48.1 ± 0.1 b	87.1 ± 0.4 a	61.6 ± 0.2 b
*Calligonum + Salvia**	145.3 ± 0.3 c	233.2 ± 1.1 d	26.4 ± 0.1 d	73.9 ± 0.62 a	75.1 ± 0.7 a
*Ferula + Alhagi**	320.8 ± 1.9 a	763.1 ± 3.4 a	75.6 ± 0.4 a	104.8 ± 0.6 a	69.1 ± 0.9 ab
*Onobrychis + Medicago**	310.6 ± 1.0 a	749.5 ± 0.9 a	73.4 ± 0.2 a	101.8 ± 0.4 a	67.7 ± 0.2 ab
*Helianthus***	139.2 ± 4.8 c	143.0 ± 36.1 d	33.3 ± 2.2 c	62.5 ± 3.6 a	61.5 ± 13.6 ab
*Medicago***	130.7 ± 0.5 c	196.2 ± 0.5 d	30.0 ± 0.1 c	59.9 ± 0.1 a	60.3 ± 0.3 b
Syrup	11.0 ± 10.7 e	29.6 ± 27.3 e	5.0 ± 1.9 f	146.9 ± 124.5 a	0.057 ± 0.053 d
df_2 ($df_1 = 14$)	16.56	17.11	17.13	16.99	15.13
F	22645	61298	23307	3772	51713
p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Values are presented as mean ± standard deviation.

Different superscript letters within each column indicate significant differences among floral groups (Welch's ANOVA followed by the Games-Howell post hoc test for multiple comparisons, $p < 0.05$).

*Multifloral honeys

**Honeys produced in Russia

Table 3. Contents of microelements (mg/kg) in honey and syrup samples from different floral origins collected in Tashkent, Uzbekistan, in 2022

Floral source	Microelement content (mg/kg)			
	Cu	Fe	Mn	Zn
Alhagi	0.281 ± 0.166 bcde	2.81 ± 1.27 abcd	0.029 ± 0.006 ab	0.160 ± 0.053 a
Helianthus	0.293 ± 0.142 bcde	3.60 ± 1.13 abc	0.037 ± 0.007 a	0.158 ± 0.052 a
Medicago	0.294 ± 0.064 cd	3.00 ± 0.54 abc	0.052 ± 0.022 ab	0.166 ± 0.056 a
Ferula	0.374 ± 0.014 bc	3.63 ± 0.00 abc	0.037 ± 0.002 a	0.163 ± 0.005 a
Onobrychis	0.223 ± 0.008 d	2.51 ± 0.05 c	0.055 ± 0.002 a	0.151 ± 0.005 a
Salvia	0.309 ± 0.012 bcd	3.48 ± 0.05 ab	0.043 ± 0.001 a	0.192 ± 0.002 a
Tilia	0.547 ± 0.011 a	1.77 ± 0.09 d	0.049 ± 0.001 a	0.111 ± 0.004 a
*Helianthus + Alhagi**	0.287 ± 0.101 abcde	3.24 ± 1.31 abcd	0.034 ± 0.004 a	0.125 ± 0.003 a
*Alhagi + Helianthus**	0.347 ± 0.012 bc	2.83 ± 0.06 c	0.031 ± 0.002 ab	0.150 ± 0.004 a
*Calligonum + Salvia**	0.328 ± 0.020 bcd	3.71 ± 0.01 a	0.035 ± 0.001 ab	0.159 ± 0.004 a
*Ferula + Alhagi**	0.371 ± 0.003 c	3.31 ± 0.03 b	0.032 ± 0.003 ab	0.148 ± 0.005 a
*Onobrychis + Medicago**	0.379 ± 0.007 bc	3.22 ± 0.01 bc	0.019 ± 0.002 b	0.152 ± 0.006 a
*Helianthus***	0.163 ± 0.073 de	2.73 ± 1.67 abcd	0.040 ± 0.018 ab	0.143 ± 0.009 a
*Medicago***	0.422 ± 0.004 b	1.69 ± 0.05 d	0.029 ± 0.006 ab	0.165 ± 0.005 a
Syrup	0.111 ± 0.034 e	1.53 ± 1.09 abcd	0.075 ± 0.015 a	1.510 ± 0.983 a
df_2 ($df_1 = 14$)	16.74	16.46	16.86	16.69
F	129.53	459.28	38.86	88.38
p	<0.001	<0.001	<0.001	<0.001

Values are presented as mean ± standard deviation.
Different superscript letters within each column indicate significant differences among floral groups (Welch's ANOVA followed by the Games-Howell post hoc test for multiple comparisons, $p < 0.05$).
*Multifloral honeys
**Honeys produced in Russia

Channa, 2019; Mongi, 2024). Furthermore, Table 4 provides reference data on the macroelement and microelement contents of honeys with different floral origins from various countries, including Poland and Italy (Grembecka and Szefer, 2013), Serbia (Jovetić *et al*., 2017), China (Zhou *et al*., 2013), Spain (González-Miret *et al*., 2005), and India (Nayik and Nanda, 2016), for comparison with the present results. The mineral concentrations observed in the present study were generally comparable to those reported in honeys from other parts of the world (González-Miret *et al*., 2005; Grembecka and Szefer, 2013; Zhou *et al*., 2013; Jovetić *et al*., 2017).

K was the most abundant element across all honey samples, with the exception of the syrup samples (Table 2). Comparable findings have been documented for honeys from Serbia (Sakač *et al*., 2019), New Zealand (Vanhanen *et al*., 2011), Malaysia (Moniruzzaman *et al*., 2014), Slovenia (Pavlin *et al*., 2023), Tanzania (Mongi, 2024), Romania (Pop *et al*., 2022), Ethiopia (Gebeyehu and Jalata, 2023), and Italy (Pisani *et al*., 2008), although the levels of K differed considerably among countries and also varied with the botanical origins of the honeys produced in each country.

In the Uzbek honey samples, the concentrations of macroelements varied within the following ranges (mg/kg): Ca, 80.93–414.06; K, 97.33–977.29; Mg, 17.49–78.65; Na, 58.67–130.84; and P, 23.10–120.19 (Table 2). The Russian honeys contained Ca, 130.08–145.35; K, 108.12–196.57; Mg, 29.99–35.40; Na, 57.63–65.60; and P, 45.70–77.75 mg/kg. Overall, the macroelement contents of these honeys were within the wide ranges documented in other countries. For instance, Romanian honeys contained Ca, 15.7–429.8; K, 46–1507; Mg, 10.8–339.0; Na, 28.4–292.6; and P, 21.8–145.1 mg/kg (Pop *et al*., 2023). Similarly, Argentine honeys showed Ca, 33–83; K, 126–1490; Mg, 8–44; Na, 22–62; and P, 33–150 mg/kg (Cabrera and Santander, 2022), while Hungarian honeys exhibited Ca, 9.12–124; K, 102–2212;

Table 4. Comparative summary of macroelement and microelement contents (mg/kg) in monofloral honey samples of various floral origins from different countries, as reported in previous studies

Country	Floral source	N	Content (mg/kg)									Source*
			Macroelement					Microelement				
			Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn	
Poland	Lime	7	40±8.4	393±126	16±6.3	19±14	130±75	0.3±0.1	2.5±1.8	1.1±0.7	8.4±5.4	1
	Buckwheat	6	34±12	322±96	17±3.8	9.8±2.1	696±182	0.7±0.2	6.7±10	4.7±1.5	3.8±2.4	
	Acacia	5	49±17	166±29	10±4.1	13±17	140±99	0.1±0.0	1.2±1.1	0.5±0.3	4.1±3.9	
	Rape	5	51±17	190±172	19±8.3	11±8.3	75±57	0.1±0.0	3.0±3.1	0.6±0.5	2.1±1.7	
	Heather	2	73±19	532±83	17±1.4	56±51	577±92	0.3±0.0	1.4±0.1	8.0±3.8	8.1±1.2	
	Dandelion	1	61±2.9	511±16	9.0±0.0	74±2.3	72±0.1	0.3±0.0	0.8±0.0	0.9±0.1	6.5±0.4	
Italy	Apple	1	57±4.3	736±5.8	145±6.1	24±0.1	488±21	2.2±0.1	5.7±0.2	1.2±0.1	1.1±0.1	
	Chestnut	1	55±1.3	709±4.6	49±0.5	7.8±0.4	143±0.1	0.6±0.0	1.4±0.0	0.8±0.0	0.7±0.0	
	Eucalyptus	1	53±5.0	453±13	18±2.1	56±0.7	571±36	0.2±0.0	1.1±0.0	1.0±0.1	0.8±0.1	
	Orange	1	28±0.7	167±8.5	5.5±0.7	9.5±0.1	512±56	0.1±0.0	0.8±0.1	0.1±0.0	0.5±0.0	
Serbia	Acacia	162	27±10	200±64	6.4±2.3	15±8.1	N/A**	0.2±0.1	1.6±1.6	1.6±6.0	2.8±11	2
	Sunflower	23	87±30	398±119	22±7.2	21±13	N/A	0.3±0.1	1.8±0.9	0.8±1.2	3.2±7.3	
	Linden	11	84±21	1543±189	20±3.5	13±6.4	N/A	0.3±0.1	1.4±1.0	1.6±0.9	1.4±1.0	
	Rape	7	49±18	372±177	14±5.5	19±12	N/A	0.2±0.1	2.4±2.2	0.6±0.6	1.1±0.3	
	Basil	3	47±2.6	270±76	13±2.8	14±8.3	N/A	0.3±0.1	1.2±0.4	0.7±0.7	2.0±1.4	
China	Jujube	23	132±11	1869±35	19±0.9	46±5.6	N/A	0.6±0.0	3.4±0.3	0.5±0.0	2.2±0.1	3
Spain	Rosemary	11	47±27	275±141	14±17	81±17	6±24	0.4±0.3	2.4±0.7	1.5±1.1	4.9±2.2	4
	Citrus	10	51±21	237±51	11±3.6	84±24	49±12	0.5±0.2	2.8±1.1	1.2±0.4	4.9±2.3	
	Heather	5	51±25	870±250	58±21	77±9.1	154±107	0.8±0.3	4.5±4.6	6.1±4.7	4.8±2.2	
	Chestnut	4	103±33	1090±467	76±33	94±17	104±36	0.7±0.1	4.7±2.3	8.5±3.8	6.1±3.5	
	Eucalyptus	4	90±43	477±194	29±6.0	144±117	74±35	0.6±0.3	1.8±1.3	3.6±1.5	3.9±2.5	
	Lavender	4	50±27	326±92	24±14	81±7.4	75.8±22.1	0.4±0.1	2.8±0.5	1.6±0.5	4.3±1.9	
	Thymus	4	69±14	485±179	27±13	176±86	108±44	0.8±0.5	3.0±3.9	1.5±0.6	4.2±0.7	
	Avocado	2	69±24	1130±778	92±73	128±38	259±132	1.6±0.7	5.6±3.6	3.0±2.1	8.8±3.8	
India	Apple	11	210±4.1	1137±4.6	N/A	122±5.0	74±3.4	0.3±0.1	1.6±0.2	1.2±0.1	1.0±0.2	5
	Wild bush	10	136±4.0	638±6.2	N/A	36±4.3	32±3.3	0.2±0.0	2.7±0.2	1.3±0.1	0.2±0.1	
	Cherry	8	172±4.9	862±4.5	N/A	73±2.8	42±3.6	0.1±0.1	1.0±0.1	1.2±0.1	0.6±0.1	
	Saffron	8	117±3.4	426±4.8	N/A	17±3.3	19±2.2	0.1±0.1	1.2±0.1	1.1±0.1	0.2±0.1	

Data are presented as mean±standard deviation.
*Sources (1–5): Grembecka and Szefer (2013); Jovetić *et al.* (2017); Zhou *et al.* (2013); González-Miret *et al.* (2005); Nayik and Nanda (2016).
**N/A: not available

Mg, 3.83–60.2; Na, 3.02–17.9; and P, 32.0–138 mg/kg (Czipa *et al.*, 2018).

Across all honey samples from Uzbekistan and Russia, the concentrations of trace elements ranged as follows (mg/kg): Cu, 0.098–0.558; Fe, 1.05–6.70; Mn, 0.016–0.194; and Zn, 0.100–1.140 (Table 2). Similar concentration ranges have been reported in honeys from other regions, as observed for the macroelements, including Argentina (Cu, <0.1–0.27; Fe, 0.38–4.21; Mn, 0.12–1.62; Zn, 0.45–4.82 mg/kg; Cabrera and Santander, 2022), Switzerland (Cu, 0.051–1.966; Fe, 0.136–9.852; Mn, 0.125–12.354; Zn, 0.016–4.133 mg/kg; Bogdanov *et al.*, 2007), Slovenia (Cu, 0.015–0.626; Fe, 0.00–134.59; Mn, 0.17–15.77; Zn, 0.01–4.53 mg/kg; Pavlin *et* *al*., 2023), and Italy (Cu, 0.172−5.9; Fe, 0.97−13.7; Mn, 0.13−16.9; Zn, 0.72−3.66 mg/kg; Pisani *et al*., 2008).

2. Differences between countries and among floral origins

Fig. 1 demonstrate significant differences ($p < 0.001$) in total mineral content among honeys of different origins, ranging from 386.02 to 1630.01 mg/kg in Uzbek honeys, and 401.18 to 516.08 mg/kg in Russian honeys. Pavlin *et al*. (2023) reported total mineral contents of honeys with various botanical and geographical origins ranging from 267.80 to 4423.37 mg/kg, produced from different floral sources in Slovenia, Bulgaria, Turkey, Morocco, and Croatia.

However, comparing the present findings with previously published data remains challenging. Variations in sample decomposition approaches (such as microwave, wet, or dry ashing) and analytical methodologies could account for inconsistencies among studies (Pisani *et al*., 2008). Therefore, establishing standardized procedures for these methods is essential to ensure consistency across future investigations.

Meanwhile, the syrup samples exhibited significantly lower concentrations of most elements than the authentic honeys, and their total mineral content was the lowest among all samples (Tables 2 and 3; Fig. 1). This finding is consistent with the results reported by Liu *et al*. (2021), who observed that syrup samples showed significantly lower mineral concentrations than honeys, except for Ba. In their study, Ca, Na, P, Ba, and Mg were identified as the most abundant elements in syrups, whereas in our results, Na, K, Ca, Mg, and Fe predominated. This discrepancy is likely attributed to the fact that syrups are mainly produced from sugar beet or sugarcane, whose intrinsic chemical composition markedly affects the elemental profile of the final product (Pohl and Stecka, 2011).

Ferula, multifloral (*Ferula*), and *Onobrychis*+*Medicago* honey samples exhibited high values in most analyzed elements as well as in total mineral content (Tables 2 and 3; Fig. 1). The genus *Ferula*, which includes around 180−185 species globally (Kadereit and Bittrich, 2018), is found throughout the Mediterranean, Siberia, Central Asia, and northern Africa (Pimenov and Leonov, 1993; Wu *et al*., 2003; Ajani and Ajani, 2008; Qin *et al*., 2023). Numerous *Ferula* species possess medicinal properties and are widely utilized in both folk and traditional pharmacy practices (Qin *et al*., 2023). Furthermore, *Ferula* species exhibited the highest concentrations of macroelements (P, K, Ca, Mg, and S) and microelements (Cu and Zn) among 21 plant species from different genera, as reported by Ghafoor *et al*. (2019). This may explain, at least partially, the elevated mineral levels observed in the honey derived from regions containing *Ferula* species.

In contrast to *Helianthus* and *Helianthus*+*Alhagi* or *Ferula* and *Ferula*+*Alhagi* honeys, significant differences in total mineral content were observed between *Alhagi* and *Alhagi*+*Helianthus* honeys, as well as between *Onobrychis* and *Onobrychis*+*Medicago* honeys (Fig. 1). In *Helianthus*+*Alhagi* honey, *Helianthus* pollen accounted for 37.9% and *Alhagi* 11.6% (Table 1), while the total mineral contents of the respective monofloral honeys were 922.2 and 601.0 mg/kg, correspondingly (Fig. 1). Therefore, the slightly lower, but not statistically different, total mineral content of the multifloral sample (863.7 mg/kg; Fig. 1) is likely due to the minor contribution of *Alhagi* with a lower mineral content. A similar trend was also observed for *Ferula*+*Alhagi* honey. Additionally, *Alhagi*+*Helianthus* honey contained 26.2% *Alhagi* and 25.0% *Helianthus* pollen, showing nearly equal proportions of the two major floral sources (Table 1). Since the total mineral contents of *Alhagi* and *Helianthus* monofloral honeys did not differ significantly, the *Alhagi*+*Helianthus* honey also exhibited no significant difference in mineral composition compared with the corresponding monofloral honeys (Fig. 1). In the case of *Onobrychis*+*Medicago* honey, the two dominant pollen types, *Onobrychis* and *Medicago*, accounted for 39.4% and 33.1%, respectively (Table 1). However, this sample differed statistically from both corresponding monofloral honeys (Fig. 1), which is likely attributable to the contribution of minor floral sources with relatively higher mineral contents.

Helianthus and *Medicago* honeys were present in both Uzbekistan and Russia, showing no statistical differences in the concentrations of most individual elements and the total mineral content between the two countries (Tables 2 and 3; Fig. 1). A previous study also reported no significant difference in total mineral content between acacia honeys produced in Slovenia and those from Bulgaria (Pavlin *et al*., 2023). Furthermore, Bogdanov *et al*. (2007) highlighted that the trace element profile of honeys is primarily determined by their botanical origin rather than by geographical or environmental factors.

3. Chemometric and correlation analysis

Fig. 2 shows the PCA biplot illustrating the relationships among honey samples and the contribution of each element to the total variance based on the loadings of the variables. The first and second principal components explained 48.3% and 19.4% of the total variance, respectively, accounting for 67.7% in total. PC1 showed positive correlations with Na, Zn, and Mn, whereas PC2 was negatively correlated only with P. The PCA plot revealed a clear separation between the syrup and honey samples, with the syrups located distinctly on the positive side of PC1, mainly influenced by high Na and Zn contents. A similar pattern was observed by Liu *et al*. (2021), who also found distinct clustering between authentic honeys and syrup samples in PCA based on their mineral compositions. In contrast, most honey samples clustered toward the negative side of PC1, characterized by higher levels of Ca, K, Mg, Cu, and P. Uzbek and Russian honeys showed no distinct separation from each other, suggesting that the element compositions from the two regions are similar. These PCA results are consistent with the statistical comparisons in Tables 2 and 3 and Fig. 1, further supporting that mineral patterns are primarily influenced by botanical rather than geographical origin. This finding is also in agreement with the results reported by Bogdanov *et al*. (2007), as discussed earlier.

The Pearson correlation coefficients among the elemental concentrations and color in the honey samples are presented in Fig. 3. Strong positive correlations were observed among the major elements, particularly between Ca and Mg ($r=0.95$, $p<0.001$), Ca and K ($r=0.88$, $p<0.001$), and K and Mg ($r=0.83$, $p<0.001$). Similarly, notable correlations were also found between Cu and K ($r=0.71$, $p<0.001$) and between Na and Zn ($r=0.69$, $p<0.001$). Moderate but significant correlations were detected between Ca and Cu ($r=0.59$, $p<0.001$), Cu and Mg ($r=0.58$, $p<0.001$), Fe and P ($r=0.53$, $p<0.01$), Mg and P ($r=0.49$, $p<0.01$), Mn and Zn ($r=0.47$, $p<0.01$), and Ca and P ($r=0.44$, $p<0.05$). In contrast, moderate negative correlations were observed between P and Zn ($r=-0.54$, $p<0.01$), Ca and Zn ($r=-0.41$, $p<0.01$), and Mg and Zn ($r=-0.41$, $p<0.01$). Kędzierska-Matysek *et al*. (2018) found a strong positive correlation between K and Mg, and a moderate correlation between Ca and Mg in Polish honey samples. In another study,

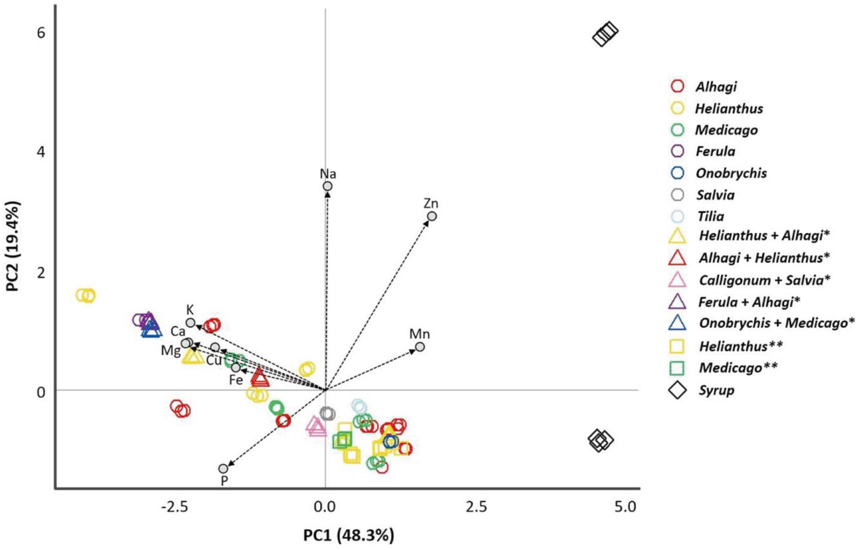
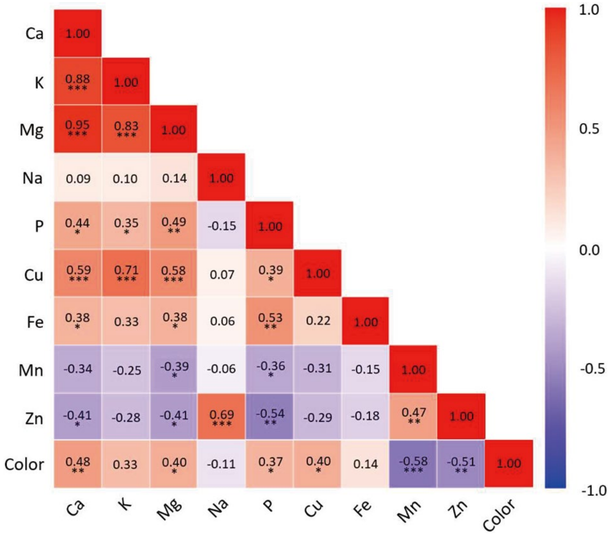


Fig. 2. Principal component analysis (PCA) biplot based on the concentrations of macro- and microelements in honey and syrup samples from different floral origins collected in Tashkent, Uzbekistan, in 2022. Arrows represent mineral loading vectors, and symbols indicate individual samples grouped by floral origin. Asterisks (*) indicate multifloral honeys, and double asterisks (**) denote honeys produced in Russia.



	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn	Color
Ca	1.00									
K	0.88***	1.00								
Mg	0.95***	0.83***	1.00							
Na	0.09	0.10	0.14	1.00						
P	0.44*	0.35*	0.49**	-0.15	1.00					
Cu	0.59***	0.71***	0.58***	0.07	0.39*	1.00				
Fe	0.38*	0.33	0.38*	0.06	0.53**	0.22	1.00			
Mn	-0.34	-0.25	-0.39*	-0.06	-0.36*	-0.31	-0.15	1.00		
Zn	-0.41*	-0.28	-0.41*	0.69***	-0.54**	-0.29	-0.18	0.47**	1.00	
Color	0.48**	0.33	0.40*	-0.11	0.37*	0.40*	0.14	-0.58***	-0.51**	1.00

Fig. 3. Pearson correlation matrix among the mineral elements and color in honey and syrup samples from different floral origins collected in Tashkent, Uzbekistan, in 2022. The numbers indicate Pearson correlation coefficients, and asterisks denote significance levels: $p<0.05$ (*), $p<0.01$ (**), and $p<0.001$ (***).

Slovakian honeys exhibited a strong positive correlation between Cu and Mg, as well as a moderate positive correlation between Ca and Mg (Kacaniová *et al.*, 2009). A strong positive correlation between Mn and Zn was found in Swiss honeys (Bogdanov *et al.*, 2007). These correlations collectively suggest that the mineral balance of honey is a complex outcome of floral origin, soil composition, and surrounding environmental factors. In particular, cations such as K^+, Ca^{2+} and Mg^{2+} are often taken up concurrently due to overlapping transport mechanisms in plant roots (Marschner, 2012). This may partially explain the strong positive correlations observed among these elements in the honey samples. Additionally, the color of the honey samples showed significant positive correlations with Ca ($r=0.48$, $p<0.01$), Cu ($r=0.40$, $p<0.05$), Mg ($r=0.40$, $p<0.05$), and P ($r=0.37$, $p<0.05$), while exhibiting negative correlations with Mn ($r=-0.58$, $p<0.001$) and Zn ($r=-0.51$, $p<0.01$). Several studies have reported that darker-colored honeys generally contain higher levels of specific minerals and total mineral content compared to lighter-colored honeys (Terrab *et al.*, 2003; González-Miret *et al.*, 2005; Nalda *et al.*, 2005; Osman *et al.*, 2007; Pisani *et al.*, 2008; Alqarni *et al.*, 2014; Solayman *et al.*, 2016; Bodó *et al.*, 2021; Pavlin *et al.*, 2023).

CONCLUSION

This study represents the first comprehensive assessment of mineral composition of honeys from Tashkent, Uzbekistan, using chemometric techniques. The integration of multivariate statistical analysis with mineral quantification provided clear discrimination between authentic honeys and syrup samples, underscoring the robustness of this approach for authenticity evaluation. Furthermore, the consistent clustering of Uzbek and Russian honeys indicates that floral source exerts a stronger influence than geographical origin. Due to limited sample availability in the local market of Tashkent, particularly for Russian honeys, the generalizability of geographic trends remains restricted. Future studies should expand sample collection beyond Tashkent to other regions of Uzbekistan to overcome this limitation. Nevertheless, this study establishes a reference framework for developing a mineral-based database to support authenticity verification of honey distributed in Tashkent, Uzbekistan.

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