

Comprehensive analysis of the elemental composition and isotope ratios of honeys from US East Coast

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ABSTRACT

Honey is increasingly recognized not only as a valuable natural food product but also as a sensitive environmental indicator. In this study, we analyzed 121 honey samples from the eastern part of United States (2017–2019) using ICP-OES, ICP-MS, and MC-ICP-MS to evaluate their elemental composition along with strontium, and lead isotope ratios. Potassium dominated the mineral composition, while aluminium showed spatial trends linked to soil composition. Strontium isotope ratios reflected heterogeneous regional geology, and lead isotopes indicated predominantly anthropogenic sources, mainly legacy gasoline use. Multivariate analyses (CDA, PCA) revealed clear classifications by botanical and geographic origin, though isotope ratios alone were insufficient for precise provenance. This is the first study to combine comprehensive elemental analysis with Sr and Pb isotope ratios for U.S. honeys. Our findings confirm honey's utility as a geochemical archive and support its application in environmental monitoring, food safety, and traceability frameworks.

1. Introduction

Honey is a product of great commercial value, with numerous health benefits and medicinal importance due to the mineral, enzyme, protein and vitamin content (Machado De-Melo et al., 2017). In addition to the practical value of honey and its role in traditional medicine, honey is the product of bioaccumulation processes and its composition represents a useful biomarker for monitoring environmental conditions around the hive (Ćirić et al., 2021; Crane, 1984; Cunningham et al., 2022; Smith et al., 2019a; Tesauro et al., 2023). The composition and quality of honey depend greatly on the botanical and geographical origin, climatic conditions, as well as handling and storage circumstances (Sajtos et al., 2019; Varga et al., 2020). The foraging area of the European honey bee (*Apis mellifera* L.) is several km² and may incorporate to natural and

anthropogenic sources (Smith et al., 2019). Agricultural and industrial emissions can contaminate pollen grains and nectar and be propagated into honey. Thus, honeys can be considered as important biomarkers of specific environmental assessments.

The composition of honey is crucial not only for food safety but also for environmental monitoring, as it serves as an excellent indicator of the bees' habitat. Notably, Smith and Weis (2020) demonstrated the effectiveness of honey as a real-time bioindicator by analyzing samples from beehives across Paris following the catastrophic 2019 Notre-Dame Cathedral fire. The fire released substantial amounts of lead into the atmosphere, and the researchers found that honey from hives located downwind of the cathedral exhibited lead concentrations up to four times higher than those from other areas. Despite these elevated levels, all samples remained within the European Union's safety limits for

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consumption. This and a limited amount of other research underscore honey's potential in monitoring acute environmental pollution events and highlight the importance of further studies on lead isotopic compositions in honey for urban environmental assessments (Smith et al., 2021; Smith & Weis, 2022).

The metal composition of historical honey can also be used as a long-term environmental indicator - like a "time capsule", old samples preserve information regarding the state of their habitat (Sajtos et al., 2022; Varga et al., 2020). The metal composition of honeys does not undergo degradation during storage and preserves the qualitative and quantitative features of the environment at the time of collection. As such, the mineral content of honey can serve as a proxy for assessing and reconstructing the environmental conditions of the nectar-producing region and its surrounding areas.

Besides metal concentrations, studies in food research use different isotopes to authenticate products and materials. In addition to the light stable isotopes, such as carbon and hydrogen, isotopes of the heavier elements, such as the stable isotope ratio of strontium ($^{87}\text{Sr}/^{86}\text{Sr}$), can carry geographical information about the origin of the samples. Spatial variation in bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios is predominately driven by the underlying geology, namely bedrock type and age (Bataille et al., 2020). The local $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is transmitted predictably from soils to plants to animals and can thus be used as a geographic tracer. However, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in plants from a given location might differ due to distinct $^{87}\text{Sr}/^{86}\text{Sr}$ ratio with soil depth with different rooting zones creating challenges in provenance studies (Capo et al., 1998; Frei et al., 2020; Holt et al., 2021; Poszwa et al., 2004). Numerous studies have tried to use $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, to detect geographical differences in soil and food (Bataille et al., 2020; Frank et al., 2021; Ryan et al., 2018; Widga et al., 2017). The literature shows a focus on plants, animals, water and soil strontium isotopic composition, but there is a lack of information on specific data such as honey strontium isotope ratios.

Strontium isotope ratio analysis has proven to be a valuable tool in food authentication; when combined with elemental analysis, it can provide a fingerprint-like identification of the products (Aoyama et al., 2017; Hiraoka et al., 2016; Hong et al., 2022; Saar de Almeida et al., 2023). Since honey is a natural-origin foodstuff - similar in this respect to wine - authentication and the detection of adulteration are of great importance. Nevertheless, studies focusing on the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio in honey remain scarce. The available literature data show that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of global honey collection covers the 0.7065–0.7230 interval (Baroni et al., 2015; Voerkelius et al., 2010). Silva et al., 2021 analyzed the trace and rare earth element content of Brazilian honey samples alongside strontium isotope ratios, concluding that the geographic origin of honey can be authenticated using its $^{87}\text{Sr}/^{86}\text{Sr}$ ratio.

Legacy pollution can have a lasting impact on honey composition. By analyzing the same sample series as the present study, Kaste et al. (2021) demonstrated that ^{137}Cs , a long-lived fission product mimicking potassium uptake in plants, is still present in U.S. honey due to its absorption by vegetation and concentration by pollinators. They showed that soil potassium levels strongly control ^{137}Cs transfer to plants and honey, with the highest contamination in potassium-poor southeastern U.S. soils - which poses potential ecological risks to pollinators even decades after deposition (Kaste et al., 2021). Varga et al. (2024) analyzed carbon isotopes in the same samples to show that significant amounts of "old" carbon (carbon photosynthesized years earlier or respired from soils) are incorporated into plants and propagated into honey isotope composition. These studies highlight the promise of using isotopes in honey as bioindicators for tracing contaminants or carbon cycling dynamics. Honey metal and isotope analysis has only been conducted in a few studies in the United States (Schuette, 1932; Schuette & Huenink, 1937; Schuette & Remy, 1932; Schuette & Triller, 1938; Tong et al., 1975; United States Department of Agriculture, 1980; Weilert et al., 2022). Recently Godebo et al. (2025) conducted the first nationwide bio-monitoring study analyzing 260 honey samples from 48 U.S. states to

assess environmental contamination through the presence of toxic metals. The study detected arsenic, lead, cadmium, nickel, chromium, and cobalt in the samples, with concentrations generally below global averages and within safe consumption limits. However, regional variations were notable: elevated arsenic levels were found in the Pacific Northwest, higher cobalt in the Southeast, and increased lead in the Carolinas. These findings suggest that honey can serve as an effective bioindicator for tracking localized environmental pollution and guiding public health interventions.

In this gap-filling study, our aim is to analyze the elemental and isotope profiles of honeys from the East Coast of the United States to determine their mineral composition, identify botanical and geographical patterns, local pollutions and potential hot spots. This study also highlights the importance of conducting further research on the elemental content of honey from the United States.

2. Materials and methods

2.1. Sample collection

121 raw, pure and unfiltered honey samples were gathered from mostly small-scale beekeepers by researchers from William & Mary, Williamsburg, Virginia (U.S.). Approximately 10 g of honey was placed in plastic containers and shipped to Hungary in a box, where the samples were kept at room temperature. The samples were from the years mostly 2017–2019, covering the East Coast of the United States. The exact geographic coordinates of the honey collection sites are unknown; rather, sample origins are based on records of the county and state of collection (Fig. 1.) Based on the nectar-producing regions, from the 121 honeys we assigned 109 samples to 12 states ($N \geq 3$), and, using FIPS codes, 30 samples to 6 counties ($N \geq 3$). Given the high diversity of the

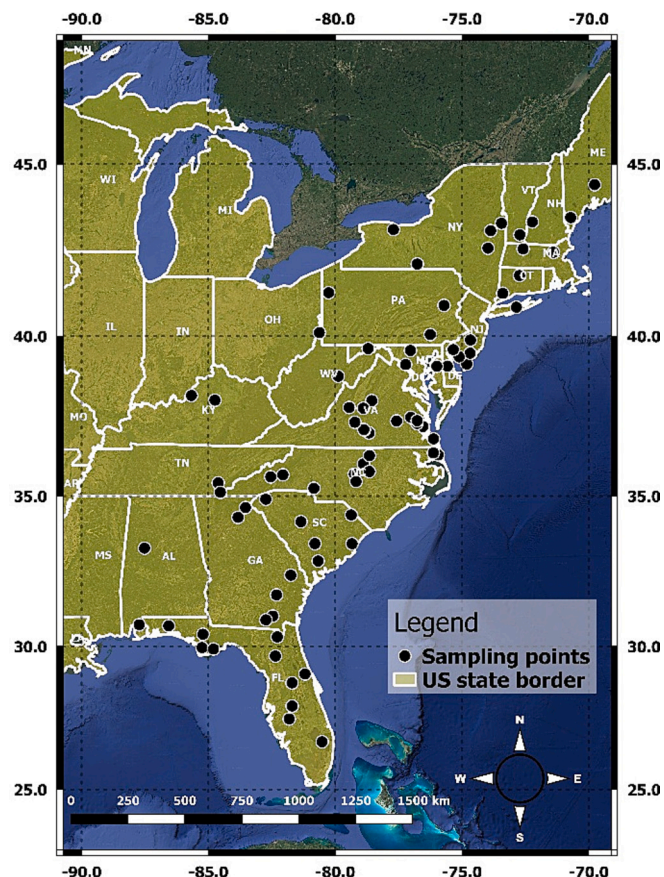


Fig. 1. Origin of the studied honey samples(Kaste et al., 2021).

sample set, only 69 samples could be grouped into seven declared botanical origin categories represented by at least three samples each ($N \geq 3$). Botanical origin information provided by beekeepers and market labels was treated as indicative background information rather than as formal botanical classification.

2.2. Sample preparation for elemental analysis, ICP-OES and ICP-MS measurements

Honey samples were pre-treated by our previously validated method (Sajtos et al., 2019, 2022; Varga et al., 2020). Samples of 0.5 g of homogenized honey were measured (Precisa 240 A) into 50.00 mL glass beakers and dried to constant weight in a drying cabinet (105 °C) for about 24 h. The dried samples were digested in the same beaker with a mixture of 4.0 mL of 65% (m/m) HNO_3 (Suprapure, Merck) and 1.0 mL H_2O_2 (Suprapure, Merck) based on Sajtos et al. (2019). Samples were heated 4 h at 100–120 °C until complete dissolution, then were diluted up to 12.00 mL and transferred to volume calibrated PP centrifuge tubes without loss with ultrapure water (Sinergy UV Millipore). The prepared samples were kept in the dark, at room temperature until the analysis. All glassware and laboratory equipment were preliminary immersed in a 1:5 diluted nitric acid for 24 h, then rinsed with distilled water (Sajtos et al., 2019). Although the applied sample preparation procedure is widely used, minor analyte loss (e.g., of volatile As and Sb species) cannot be excluded; however, overall trends are expected to remain preserved.

The concentration of 16 elements (Al, B, Ba, Bi, Ca, Cu, Fe, K, Li, Mg, Mn, Na, P, S, Sr, and Zn) from the honey samples were determined by inductively coupled plasma optical emission spectrometry (5110 ICP-OES Vertical Duo View, Agilent Technologies, Santa Clara, USA). An autosampler (Agilent SPS4), Meinhard® type nebulizer and double pass spray chamber were used. The ICP-OES operating conditions and measurement parameters are indicated in **Supplementary Table 1 and 2**, respectively. Standard solutions of Ca, K, Mg, Na, P and S were prepared from the mono element spectroscopic standard of 1000 mg L^{-1} (Scharlau), while Al, B, Ba, Bi, Cd, Co, Cu, Cr, Fe, Li, Mn, Ni, Pb, Sr, Zn from the multi element spectroscopic standard solution of 1000 mg L^{-1} (ICP IV, Merck). In both cases 5 point calibration process was used for which standard solutions were diluted with 0.1 M HNO_3 prepared in ultrapure water.

The concentration of 11 additional trace elements (As, Ce, Cd, Co, Cr, Cs, Ni, Pb, Rb, Sb and V) was measured with inductively coupled plasma mass spectrometry (8800 ICP-MS, Agilent Technologies). For the analysis ASX-520 Autosampler (Teledyne CETAC Technologies, Omaha, USA) and MicroMist® type nebulizer were used. Sample solutions for ICP-MS measurements were diluted tenfold. Standard solutions were made from mono-element spectroscopic 1000 mg L^{-1} stock solutions (Merck). During the measurement 5 point calibration was used with quality check (50 $\mu\text{g L}^{-1}$) solutions. The ICP-MS measurement conditions are indicated in the **Supplementary Table 3 and 4**.

2.3. Sample preparation for isotope ratio analysis and MC-ICP-MS measurement

The sample preparation was done in a Class 1000 cleanroom at the Isotope Climatology and Environmental Research Centre at the HUN-REN Institute for Nuclear Research (ATOMKI) in Debrecen, Hungary. For both lead and strontium isotope ratio analysis briefly, 0.5 g of honey was microwave digested in 5 mL concentrated HNO_3 (ETHOS Up microwave digestion system, Milestone, Italy). Residues were dried and treated twice with 67% HNO_3 (Suprapure, Merck) and dried again, then dissolved in $4 \times 1 \text{ mL } 8 \text{ M } \text{HNO}_3$. For the strontium isotope ratio analysis ion-exchange chromatography (column chemistry) was applied where Sr-Spec Resin was used (100–150 μm particle size, Triskem International, France). Following the column chemistry, samples were treated with $2 \times 1 \text{ mL } 67\% \text{ HNO}_3$, dried, and dissolved in 1 mL 3% HNO_3 for

strontium isotope analysis. Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) were measured with Neptune Plus multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS, Thermo Fischer Scientific, Waltham USA) equipped with an Aridus-3 desolvation system (Teledyne CETAC Technologies, Omaha, USA). Measured isotopic ratios are corrected for instrumental mass discrimination using $^{88}\text{Sr}/^{86}\text{Sr} = 8.375209$, as well as by applying an interference correction for $^{87}\text{Sr}^+$ and $^{86}\text{Sr}^+$ with $^{85}\text{Rb}^+$ and $^{83}\text{Kr}^+$, respectively. The measured ratios were calibrated against the standard NBS987 (NIST SRM 987) to the reported value of 0.710248 (McArthur et al., 2020).

For the lead isotope ratio measurement, the microwave digested samples were used with ion-exchange chromatography. Crown ether-based Sr-Spec Resin (50–100 μm particle size), sourced from Triskem International, France, was employed for the procedure. The resin was packed into 2 mL polypropylene columns, which served as chromatographic columns. A polyethylene frit was placed atop the resin bed. Prior to use, the resin was pre-cleaned with 6 M hydrochloric acid (HCl) and ultrapure water (UPW). The digested honey samples were reconstituted in 8 M HNO_3 and loaded onto the pre-cleaned and conditioned columns to isolate lead from other matrix elements. Matrix components were eluted using 8 M HNO_3 , followed by 3 M HCl to establish a hydrochloric environment suitable for stripping the lead from the resin. The lead fraction was then eluted with 8 M HCl. This collected fraction was evaporated and digested again in 14 M HNO_3 , followed by a second evaporation to dryness. Final the lead fractions were taken up in 3% HNO_3 . Samples were measured with the same MC-ICP-MS instrument described previously based on the method of Horváth et al. (2023). The primary results were normalized to a standard solution of 35 $\mu\text{g L}^{-1}$ prepared from the NIST SRM 981 international Pb standard. All standards and samples were doped with Tl of known isotope ratio, adjusting the Tl concentration to obtain a $^{208}\text{Pb}/^{205}\text{Tl}$ signal ratio of approximately 2, thereby ensuring comparable ion beam intensities of Pb and Tl and enabling stable Tl-based mass bias correction during MC-ICP-MS analysis. The measured Pb isotope ratios were corrected for the instrument mass discrimination using the measured and nominal values of the $^{203}\text{Tl}/^{205}\text{Tl}$ ratio (Baker et al., 2004; Nagaishi et al., 2021). NIST SRM 981 standard solution was measured after every three samples, with the measurements performed in low resolution mode. Amplification with 10^{11} Ohm resistors was primarily used, and only the Faraday cup at mass 202 was amplified with 10^{13} Ohm resistor to monitor ^{202}Hg to correct for potential ^{204}Hg interference on ^{204}Pb . The measurement conditions are indicated in **Supplementary Table 5**.

2.4. Statistical analysis

To compare the elemental analytical results Student's *t*-test and ANOVA were used and Tukey's multiple comparison test was applied to identify significant differences, with a *p* value of less than 0.05 indicating statistical significance. The homogeneity of variances was analyzed using Levene test. Linear relationships between variables were evaluated using Pearson's correlation analysis. Canonical Discriminant Analysis (CDA) was applied to separate the samples based on the botanical and geographical origin. ANOVA, Student's *t*-test, Levene test, Pearson correlation analysis and CDA tests were carried out in SPSS software package (SPSS Statistic IBM 22). To compare genuine and fraudulent honeys independent samples *t*-test was performed, along with Principal Component Analysis (PCA) using Past 3.21 software. Graphs were made in Origin Pro 2018 software. It should be noted that the relatively small sample sizes ($N \geq 3$) for some groups may limit the statistical robustness of the results and should therefore be interpreted with caution.

Throughout the manuscript, values are reported as mean (standard deviation), unless stated otherwise.

3. Results and discussion

3.1. Elemental fingerprint

From the 121 honey samples the concentration of 27 elements (Al, B, Ba, Bi, Ca, Cu, Fe, K, Li, Mg, Mn, Na, P, S, Sr, Zn, As, Ce, Cd, Co, Cr, Cs, Ni, Pb, Rb, Sb and V) was determined by ICP-OES and ICP-MS techniques. Among the analyzed honey samples, only one specimen of unknown botanical origin from Albany County (sample No. 49) contained several toxic metals (Cr, Ni and Pb) in concentration above the health limit 0.1 mg kg^{-1} (Codex Alimentarius, 2019). The elevated levels were likely caused by contamination during handling or storage, or by human-related pollution in the collection area.

From the detected macro elements, potassium is the most abundant in honey samples resulting from the plant origin (Sajtos et al., 2019, 2022; Varga et al., 2020). Although soils in the southeastern U.S. are relatively low in potassium compared to other regions of North America (USGS Scientific Investigations Report 2017–5118, 2025), potassium was still the most abundant element in the honey samples, likely due to the plant-based origin of the nectar (D. B. Smith et al., 2013). In line with this, our study found no correlation between the amount of potassium and geographic location - potassium concentration in honeys shows no dependence on the latitude or longitude which confirms the fact that honey potassium is mostly dependent on the botanical origin (Sajtos et al., 2019). In the analyzed samples the K concentration varies widely between 161 and 3339 mg kg^{-1} , the highest concentration is measured in Tupelo (*Nyssa sp. L.*) honey from the state of West Virginia while the lowest in a Bluegrass honey (*Poa pratensis L.*) from the state of Kentucky. The K concentration of the studied samples shows a significant ($p < 0.01$) positive correlation with P ($r = 0.755$), S ($r = 0.745$), Mg ($r = 0.716$), Rb ($r = 0.649$), Al ($r = 0.543$) and shows a strong positive correlation with almost all the other macroelements except for sodium.

Looking at the botanical origin as a grouping factor ($N \geq 3$) we can conclude that Sourwood (*Oxydendrum arboreum (L.) DC.*) honeys have the highest concentration of potassium ($1560 (693) \text{ mg kg}^{-1}$) and Clover (*Dalea sp. L.*) honeys have the lowest ($381 (169) \text{ mg kg}^{-1}$). The trend aligns with the summarized elemental concentration (Fig. 2) proving potassium as the highest contributing element to the mineral content, respectively 67–87% based on our results, with the lowest contribution to Clover honeys, and the highest to Sourwood honeys. Among all samples Sourwood honeys had the highest elemental concentration

($1797 (758) \text{ mg kg}^{-1}$) (Fig. 3). In all cases, the elemental concentrations measured in honey samples from the U.S. East Coast were lower than those reported for Malaysian Sourwood honeys, where the overall elemental concentration exceeded 5000 mg kg^{-1} (Moniruzzaman et al., 2014). This type of honey is predominantly produced in the U.S. Appalachian region namely in the states of Tennessee, Georgia and North-Carolina where the sourwood tree is native (Coder, 2011). There is no available data according to Sourwood honey from the US to make comparisons, so far this is the first study to describe the elemental composition of certain honey types from the U.S.

Aluminium is the only element in the honey samples which shows a positive correlation with both the longitude ($p < 0.05$, $r = 0.247$) and the latitude ($p < 0.01$, $r = 0.187$). This spatial association suggests a link to regional geological or soil-related characteristics. Although soil properties are discretely distributed and not strictly spatially auto-correlated, the observed trends broadly correspond to large-scale mineralogical patterns across the United States (USGS Scientific Investigations Report 2017–5118: Geochemical and Mineralogical Maps, with Interpretation, for Soils of the Conterminous United States). The Al content in the samples is lowest in the Palmetto (*Serenoa repens (W. Bartram) Small*) honeys $0.480 (0.21) \text{ mg kg}^{-1}$ and in average highest in the Tupelo honeys $5.40 (1.1) \text{ mg kg}^{-1}$. Two Sourwood honeys from Tennessee showed exceptionally high Al concentrations compared to the other samples (48.1 mg kg^{-1} in No. 101 and 18.1 mg kg^{-1} in No. 102); these values were taken out from the average calculation due to the high variance. Aluminium content also shows regional trends in examined counties - samples from Pennsylvania had the lowest Al concentrations $0.232 (0.05)$ and honeys from Tennessee had the highest $5.36 (2.7) \text{ mg kg}^{-1}$, even without Sample No. 101 and 102. These results show good correspondence with Brazilian honeys, and the concentration is lower than in Turkish and New Zealand honeys (Batista et al., 2012; Vanhanen et al., 2011; Yücel & Sultanoğlu, 2013). For the human body aluminium is nonessential; but compared to the 1950s, our daily intake of Al has increased a hundredfold, for which the sources vary from cosmetics and packaging materials to industrial exhaust (Exley, 2013). Our results indicate that aluminium concentration in honey is influenced by geographical origin, with the botanical origin also contributing to the observed variation. The primary source of aluminium is most likely the soil which would be introduced to the nectar by dry deposition and dust; however, contamination from storage containers, handling, and processing may also play a role in elevated Al levels in honeys (Díaz et al., 2019).

Compared to other foodstuffs, honey can be considered rich in rubidium given its similarity to potassium, which is an important macronutrient for plants (Anke et al., 2005). Rubidium is an alkali metal found in the analyzed honeys in various concentrations ($0.173\text{--}9.82 \text{ mg kg}^{-1}$). The highest average value is from the state of Tennessee $3.83 (2.6) \text{ mg kg}^{-1}$, while the lowest is from New Jersey $0.780 (0.40) \text{ mg kg}^{-1}$. Regarding botanical origin, Sourwood honeys had the highest average Rb concentration $5.85 (1.7) \text{ mg kg}^{-1}$ followed by Gallberry (*Ilex glabra (L.) A. Gray*) honeys $2.13 (1.6) \text{ mg kg}^{-1}$. The sample with the highest Rb concentration is an unknown botanical origin honey from Florida (Sample No. 20), suspected to be a Sourwood or Honeydew honey based on the high elemental content. In a previous study with honeys also originating from the U.S., Rb was found in a range of $0.12\text{--}0.29 \text{ mg kg}^{-1}$ from the states of Montana, North and South Dakota (Weilert et al., 2022). Although the current study does not include samples from the above-mentioned states, the observation is noteworthy, given that, similarly to potassium, rubidium tends to be less abundant in the soils of the East Coast compared to those of the Midwest (USGS Scientific Investigations Report 2017–5118: Geochemical and Mineralogical Maps, with Interpretation, for Soils of the Conterminous United States). Globally, higher concentrations of Rb in honeys have been reported from Northwestern Italy $0.80\text{--}23.0 \text{ mg kg}^{-1}$ by Squadrone et al. (2020) and in Bracatinga Honeydew honeys from Brazil by Silva et al., 2021 in a concentration range $15.4\text{--}42.2 \text{ mg kg}^{-1}$. Batista et al.

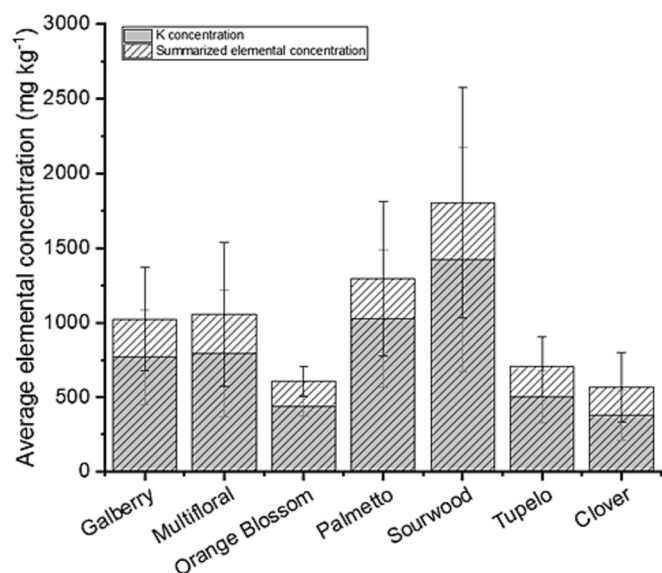


Fig. 2. Average potassium and summarized elemental concentration of the measured 27 elements in different honey species ($\text{mg kg}^{-1} \pm \text{SD}$).

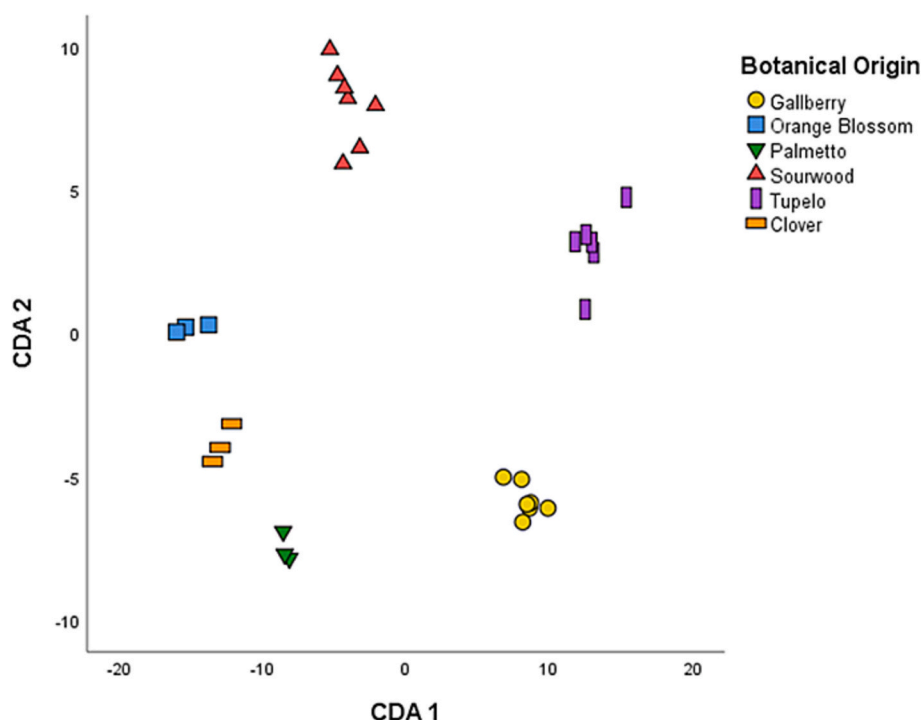


Fig. 3. CDA biplot shows the relationship between the botanical origin and the elemental composition of honey samples.

(2012) analyzed 42 elements in Brazilian honeys and found Rb in a range 0.06–15.8 mg kg⁻¹.

In the analyzed samples, Rb exhibited a significant positive correlation with K ($p < 0.001$, $r = 0.649$), the latter typically accounting for more than 50% of the total mineral content and representing the most abundant element in honey (Peng Kek et al., 2017). Rb also showed positive associations with Ba, Mg, P and S. In contrast, a statistically significant negative correlation was observed between Rb and V ($p = 0.038$, $r = -0.189$). Given the chemical similarity between Rb and K and their partially shared environmental and biological pathways, this inverse relationship may reflect complex interactions within the soil–plant–honey continuum. However, as discussed above, V may originate from multiple sources, including environmental uptake as well as potential handling- or storage-related contributions, and the present dataset does not allow these pathways to be unambiguously separated. Previous studies have shown that V can interfere with nutrient uptake processes in plants, including K transport, under controlled experimental conditions (AL-Huqail et al., 2024; Tehseen et al., 2024). While such mechanisms may contribute to the observed pattern, the correlation between V and Rb in honey is interpreted here as an associative relationship rather than evidence of a direct causal plant-physiology effect. Consequently, the negative V–Rb correlation likely reflects the combined influence of soil geochemistry, environmental exposure, and sample-specific factors, rather than a single mechanistic pathway.

Vanadium was present above the LoD (1.00 µg kg⁻¹) in 38 samples from the 121 analyzed honeys, in a range of 1.30–71.3 µg kg⁻¹ with average 14.0 (15.7) µg kg⁻¹. Although the number of samples is insufficient to draw definitive conclusions regarding botanical or geographical patterns for this element, the vanadium concentrations observed in our dataset exhibit a strong and statistically significant correlation with iron ($p < 0.001$, $r = 0.403$). Vanadium is a nonessential trace element, but its presence in honeys can be attributed to steel alloy constituents, correlating with iron potentially introduced during storage and handling. As well as it shows a positive correlation with Sb ($p = 0.005$, $r = 0.253$), which also can indicate anthropogenic origin. Squadrone et al. (2020) reported V concentrations in Italian honey samples in a range (17 (49) µg kg⁻¹) that are comparable to the levels observed in the present

study. On a global scale, the analyzed samples generally fall within the average concentration range of 10–50 µg kg⁻¹ showing no substantial deviation (Solayman et al., 2016; Squadrone et al., 2020). The V content in the analyzed samples showed a positive correlation with their Na concentrations as well ($p = 0.002$, $r = 0.273$). This relationship can be attributed to their common geochemical origin and environmental mobility. Both elements are often released simultaneously from mineral weathering in soils and may be present in similar concentrations depending on local geology and soil chemistry. Factors such as pH and redox conditions influence the solubility and bioavailability of both vanadate and sodium ions, thereby affecting their uptake by plants and subsequent incorporation into nectar and honey (Cappuyns & Slabbinck, 2012). Additionally, anthropogenic inputs, such as sodium-based fertilizers or industrial emissions, can contribute to elevated concentrations of both elements in agricultural soils (Chen et al., 2021). This co-occurrence and parallel mobility in the environment likely explain the observed correlation in honey composition.

Antimony was present above the LoD (1.00 µg kg⁻¹) in 42 samples in a range of 1.22–3.89 µg kg⁻¹. Antimony is a nonessential toxic metalloid, and has been reported in the literature as a technologically critical element (TCE) and as a tracer associated with traffic-related emissions, particularly non-exhaust sources such as brake and tire wear (Goddard et al., 2019; Nuss & Blengini, 2018; Pleijel et al., 2023; Parviainen et al., 2020). In our dataset, Sb concentrations differed significantly among states (ANOVA: $p < 0.001$, $F = 5.926$), with the highest mean values observed in samples from Florida. However, no significant correlation was found between Sb concentrations and either county- or state-level population density. Furthermore, although Cu/Sb and Ba/Sb ratios have been proposed as indicators of non-exhaust traffic emissions and are often elevated in urban or metropolitan environments, no significant correlations were observed between Sb and Cu or Ba, nor between their elemental ratios, in the analyzed honey samples. The absence of characteristic elemental relationships and spatial patterns typically associated with traffic-related pollution suggests that the data do not provide strong support for traffic-related Sb sources as a dominant contributor to Sb concentrations in honey. Instead, the observed Sb levels are more likely to reflect background concentrations influenced by geogenic

sources and soil-related uptake rather than anthropogenic traffic inputs. Our results indicate that, although antimony emissions have been reported to increase in recent decades, Sb concentrations in honey are generally low and frequently close to the analytical detection limit. This suggests limited bioavailability under current environmental conditions, but also highlights the need for continued monitoring and further research into its potential accumulation in the food chain (Pleijel et al., 2023). According to the World Health Organization's (WHO) risk assessment $6 \mu\text{g kg}^{-1}$ bw/day is the guidance value for Sb in diet (Kowalczyk et al., 2022). Based on the mean Sb concentration measured in honey ($0.00073 \text{ mg kg}^{-1}$) and the average honey consumption of 1.74 g/day , the estimated daily Sb intake from honey is approximately $0.0013 \mu\text{g/day}$ (Sugar and Sweeteners Yearbook Tables - Visualization: Meeting honey demand in the United States, 2026). This corresponds to about 0.0003% of the WHO tolerable daily intake for antimony ($6 \mu\text{g kg}^{-1}$ body weight/day), indicating that honey represents a negligible contribution to overall dietary Sb exposure (Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda, 2026).

Lead contamination in honey primarily originates from well-documented traffic-related pollution, particularly from historical tetraethyl lead (TEL) use. Additionally, it may still be introduced through aviation gasoline (AVGAS) emissions, industrial discharges, or accidental release events, such as the fire at the Notre Dame Cathedral (Godebo et al., 2025; Gulson et al., 2016; K. E. Smith et al., 2020; K. E. Smith & Weis, 2020, 2022). In a time series analysis of archived Hungarian honey samples, lead concentrations exhibited a clear declining trend over the years, correlating with the reduction of anthropogenic emissions - most notably the phase-out of leaded gasoline (Sajtos et al., 2022). In the present study lead was only above the limit of detection in 4 samples, which were also above the health limit (0.1 mg kg^{-1}) (Codex Alimentarius, 2019). The highest concentration (3.04 mg kg^{-1}) was detected in a sample of unknown botanical origin from Albany County, NY. The other three samples of unknown or multifloral botanical origin from Florida, Georgia, and South Carolina, showed concentrations approximately twice the health limit.

The soil is richer in lead in the northern part of the East Coast (D. B. Smith et al., 2013), but in our samples lead probably was from anthropogenic origin, as the lead isotope ratio results suggest discussed later. In a previous study US honey's lead concentration was found with average $8.0 \mu\text{g kg}^{-1}$ with the highest lead concentration as 0.451 mg kg^{-1} in a sample from North Carolina (Godebo et al., 2025). Smith and Weis (2020) also analyzed the Pb concentration and isotope ratio of North American honey samples and found the average Pb concentration below $135 \mu\text{g kg}^{-1}$ which aligns with our results; the lead concentration was below $179 \mu\text{g kg}^{-1}$ in 117 of the 121 honey samples.

3.2. Multivariate statistical characterization

Chemometric tools are useful in identifying relationships between the composition of honeys and their botanical and geographical origin (Batista et al., 2012). To analyze the dependence of the elemental concentration on the time of collection, the samples were grouped by the year of harvest, respectively to 2017, 2018 and 2019. The groups did not separate in the CDA and PCA plots, indicating that this short time difference does not affect the composition of the honeys drastically; however, the variables (like different botanical and geographical origin) in this diverse sample collection can also complicate the results. In a previous study, we were able to group honey samples according to their decade of origin, with fewer variables: the samples were from one foraging area and the same botanical origin, harvested and stored by the same beekeeper yearly for 25 years (Sajtos et al., 2022; Varga et al., 2020).

3.2.1. Botanical origin and elemental concentration

The multivariate statistical analysis (CDA) of the elemental content

shows a separation based on both the botanical and geographical origin. Fig. 3 illustrates a distinct clustering of honeys corresponding to six plant taxa. Since the composition of multifloral and undefined origin honeys varies widely those samples were not part of this biplot. The first function accounts for 65.8% of the discriminating ability of the discriminating variables while the second accounts for 20.9%. The canonical correlation values are 0.996 and 0.988, respectively. The cumulative percentages are 65.8 (CDA1) and 86.7 (CDA2). According to ANOVA six variables showed significant values ($p \leq 0.05$) Ba, Co, K, Na, Rb and $^{87}\text{Sr}/^{86}\text{Sr}$ between the honey types. However, these elements alone were not enough to see visual separation between the groups using CDA; we observed a better separation with using the total elemental composition of the samples.

3.2.2. Geographic origin and elemental concentration

Performing CDA on all honey samples based on their state of origin has revealed no separation. Indicating that botanical origin might have a higher impact than the geographical origin on the elemental composition of honeys.

However, after dividing the samples into smaller geographic regions (counties), clear separation was seen between the six groups (Fig. 4.) According to ANOVA, the variables As, Ca, Co, Cu, Mn, and Sb show statistically significant differences ($p \leq 0.05$) between the groups. The separation in the biplot is described by the following: the first function accounts for 91.2% of the discriminating ability of the discriminating variables while the second accounts for 6.0%. The canonical correlation values are 0.999 and 0.991, respectively. The cumulative percentages are 91.2 (CDA1) and 97.2 (CDA2).

Similar to the previous observation, by considering only one honey type, multifloral honeys are grouped according to their geographic origin into states. Elemental composition can indicate the botanical origin and also the nectar producing region, as seen in Fig. 5. A clear separation can be observed according to the states of origin indicating the relationship between the elemental composition and the geographic origin of the samples. The first function accounts for 80.1% of the discriminating ability of the discriminating variables while the second accounts for 14.2%. The canonical correlation values are 0.998 and 0.991, respectively. The cumulative percentages are 80.1 (CDA1) and 94.3 (CDA2). Between the groups significant elements ($p \leq 0.05$) were B, Ca, Na, Cd, and Sb but the separation is visibly clearer with using all the variables of the elements with concentration above the LOD of the methods. It is likely that the better separation is due to the grouping of samples within one honey type according to nectar producing areas, thus excluding botanical origin as factor of confounding variable.

3.3. Adulterated honeys

We analyzed the differences in elemental composition between pure and adulterated samples to evaluate whether these elemental profiles can provide insights into honey adulteration (Fig. 6.a). A recent study on the sample series using $^{13}\text{C}/^{12}\text{C}$ ratio analysis and the AOAC 978.17–1979 standard method detected 10 adulterated honeys from the 121 samples (Varga et al., 2024). In those cases, a carbon isotopic ratio higher than -23.5% ($\delta^{13}\text{C}$ vs. PDB) was observed, which means greater than 13% corn based sugar contribution in the honeys (Fig. 6.b) (Varga et al., 2024). It is common for beekeepers to add supplemental feed to their colonies during time periods when natural nectar availability is limited. Most commercially available supplements are corn-based, and this is the most likely pathway for higher ^{13}C to enter the honey samples, but we cannot rule out the possibility that some honey could have corn syrup added during the finishing stage to increase profits.

Independent samples *t*-test shows significant differences ($p \leq 0.05$) in the concentration of Cu, Co, Cd, Rb and Zn between the genuine and fraudulent samples. However, the principal component analysis (PCA) biplot based on the elemental composition of the honey samples shows no separation of the adulterated honeys from the pure samples. Since the

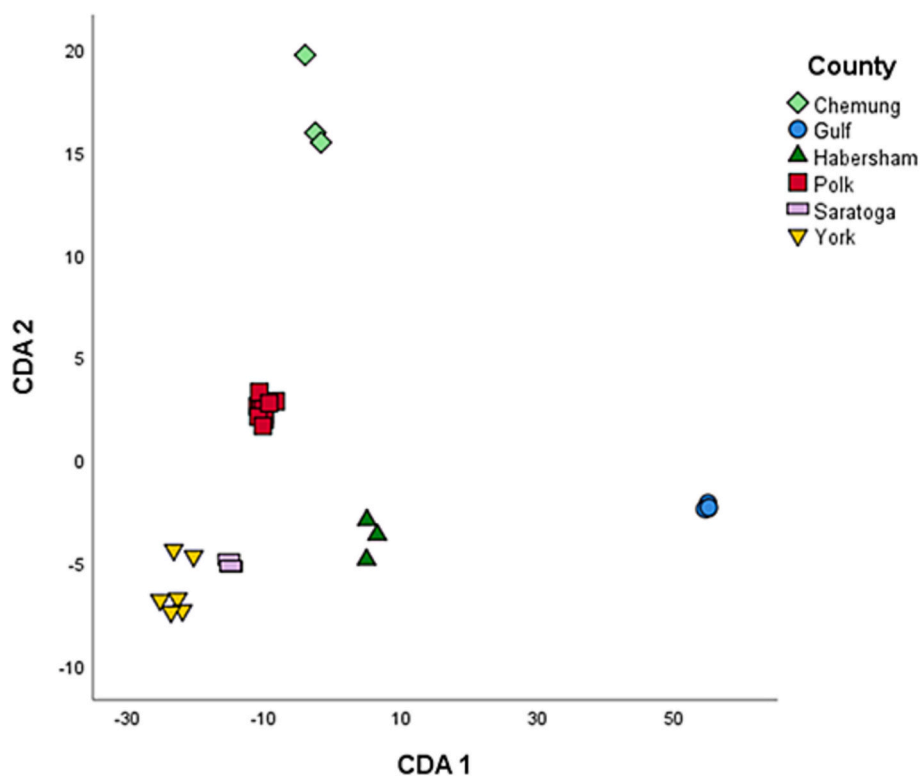


Fig. 4. CDA biplot of the analyzed honey samples based on their nectar producing counties.

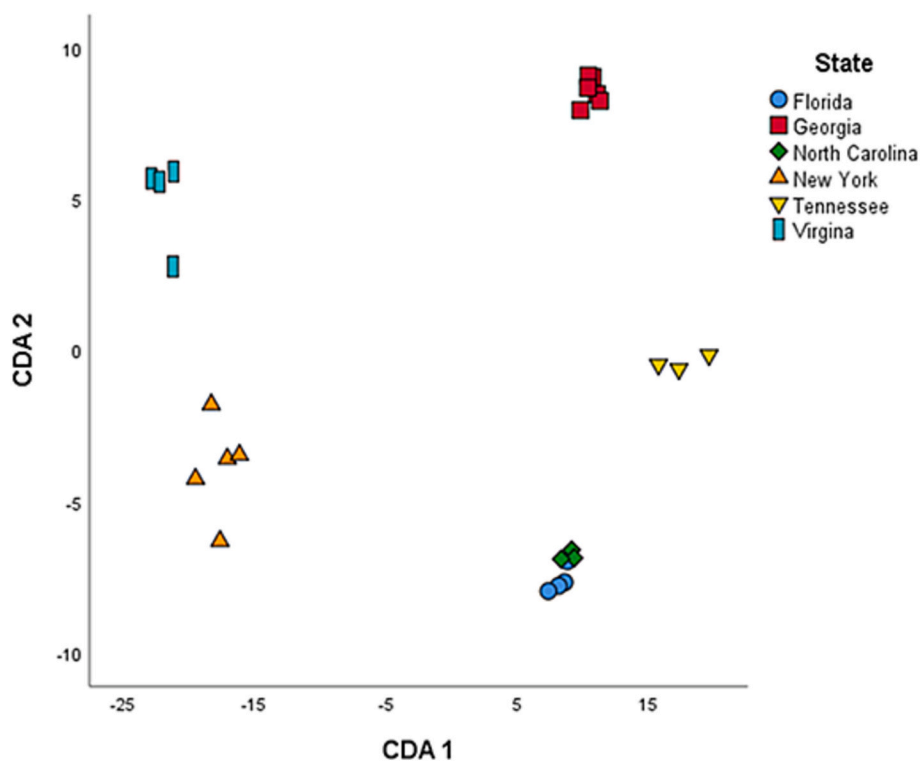


Fig. 5. CDA biplot if the multifloral honeys grouped according to their states of origin.

adulterated honeys were from multiple different types (some of them with unknown botanical and/or geographical origin), the natural variability of the elemental concentration is too high - especially for the multifloral honeys - to be able to make any definite predictions based on

the elemental composition of the samples according to their authenticity (Fig. 6.a). In cases when the botanical origins of the honeys are the same, their geographical origins differ, which also plays a major role in the elemental composition, therefore it cannot be concluded that the

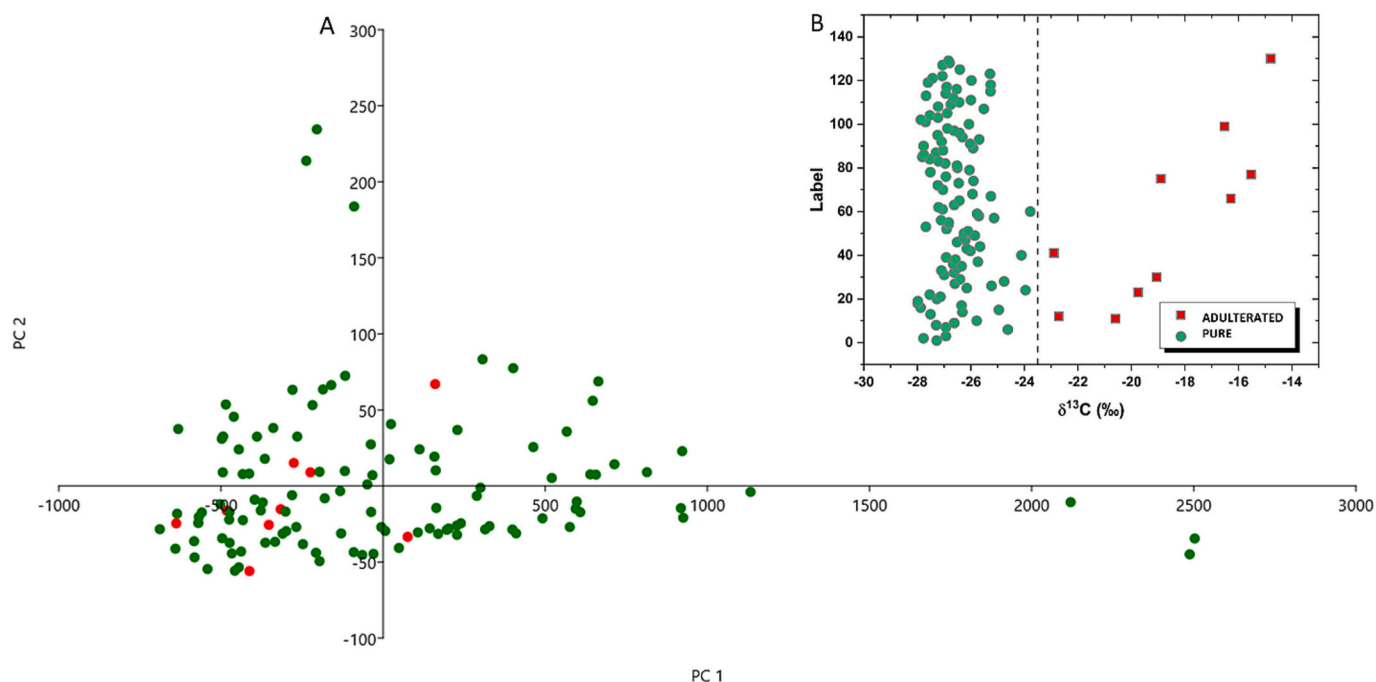


Fig. 6.a. PCA biplot of the analyzed adulterated and pure samples. Honeys suspected of adulteration showed no statistically significant difference either in the concentration of the analyzed elements. **Fig. 6.b** Stable carbon isotope composition of honey samples in the eastern part of the USA (dashed line: reference value of adulteration with more than 13% corn-based sugar; > -23.5 ‰ ($\delta^{13}\text{C}$) indicates adulterated honey). Replicated with permission from Varga et al. (Varga et al., 2024).

differences in concentrations are due solely to adulteration. Consequently, our results confirmed that elemental analysis can be a useful tool to identify adulterations in combination with other methods like NMR, FTIR, etc. (Rhee et al., 2023) but it is not a reliable source itself.

3.4. Isotope ratio analysis

3.4.1. Strontium isotope ratio

Strontium isotope ratio analysis has proved to be a useful tool in food authentication - especially in the case of wine and, coupled with elemental analytical data can give a fingerprint-like identification of origin to these products (Almeida & Vasconcelos, 2001; Di Paola-Naranjo et al., 2011; Geană et al., 2017; Rapa et al., 2023). Honey is similar to wine in that it is a natural-origin foodstuff, and authentication and identifying adulteration are of key importance. Our study is the first one to analyze the strontium isotope ratios in a large number of honey

samples from the U.S.

Honey samples had $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.7070 and 0.7238 with an average of 0.7116 (0.0030) (Fig. 7). Qualitatively, our results match well with a preexisting bioavailable Sr isoscape of the eastern USA and with the geology of the eastern USA (Reich et al., 2021). Low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are found in Florida within young carbonate terranes, higher ratios are found around the southern region of Appalachian Mountains with older siliciclastic Phanerozoic sediments, and coastal areas show ratios lower than 0.715 likely due to the addition of marine sulfates with low $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 8). A low value hotspot can be observed in New Jersey and Delaware states, around Philadelphia and Atlantic City. This pattern may reflect the effect of the coastal region and modern seawater, which has a $^{87}\text{Sr}/^{86}\text{Sr}$ of ~ 0.7092 (McArthur et al., 2001; Peucker-Ehrenbrink & Fiske, 2019), or anthropogenic pollution (Horacek, 2022). Although $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were significantly different between states ($p = 0.005$, $F = 2.671$), substantial overlap was observed. Additionally, no

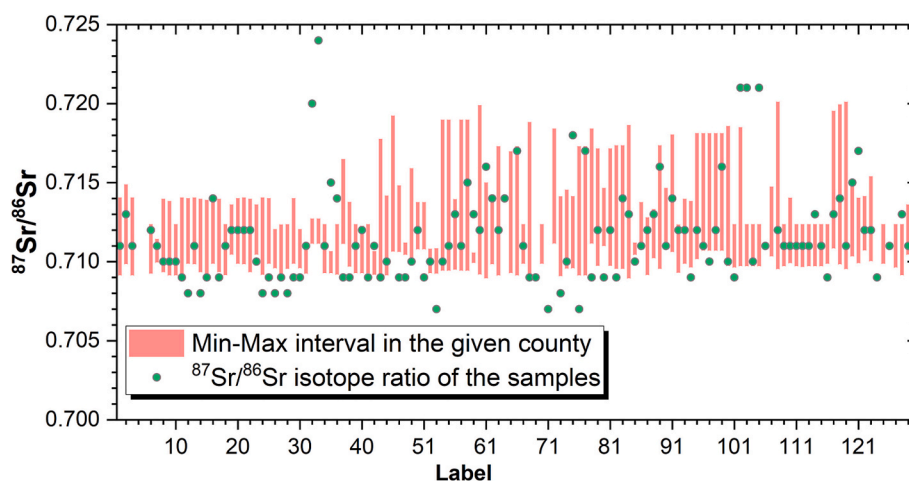


Fig. 7. $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio of US honeys compared to the min-max interval in the given county, where the honey was collected.

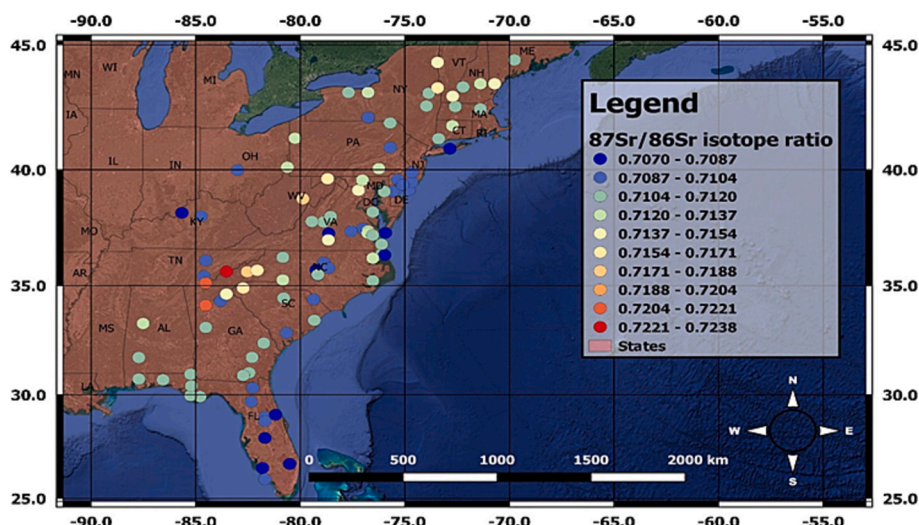


Fig. 8. Map of $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios measured in U.S. honey samples.

significant differences could be found at the county level ($p = 0.130$, $F = 1.911$). Correlation was detected between the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and the Sr concentration ($r = -0.179$, $p = 0.05$). Neither the dominant Sr source, nor a state- or county-level classification of the samples was possible to determine based on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

The inability of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to distinguish honey origin in this study may be explained by two limitations. First, our samples were not accompanied by geographic coordinates. Instead, the available location data in this present study is the center of the county where the samples and nectar were collected. Strontium isotope ratios can change rapidly at small spatial scales and can vary substantially within a given county. To accommodate for this limitation, we extracted the minimum and maximum predicted bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of each county from the preexisting Sr isotope (Reich et al., 2021). While the minimum and maximum $^{87}\text{Sr}/^{86}\text{Sr}$ ratios did not always cover wide ranges, these ranges generally overlapped, reducing the potential for $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to be able to distinguish between honeys from different counties (Fig. 7). However, despite this additional quantification of spatial variance, the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 54 samples did not fall within the min-max ratios modelled for the given sample collection county (Fig. 7), and the isotope predications explained only a small proportion of the variance ($R^2 < 0.150$). Based on our results, it is clear that the location data of honey samples are not precise enough for exact comparison of the samples and available Sr isotope maps.

Second, the geolocation potential of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios may be limited by bee behavior and agricultural practices. Bees can forage over relatively large, geochemically diverse areas (several km^2) during nectar collection, potentially crossing county borders. In addition, beehives are commonly transported between sites within a single harvesting period, which may cause honey to reflect a much broader geographical area than the bees' natural foraging range. Based on this, the element and isotopic composition of the honeys are mixtures of several flowers and plants from a wide area, limiting the geolocation potential of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Lastly, many bee hives are placed in or around agricultural regions where the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of soils are heavily influenced by fertilization and liming (Frei et al., 2020; Thomsen & Andreassen, 2019). The bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ isotope from Reich et al. (2021) was generated using exclusively plants collected from areas that are minimally influenced by industry and agriculture. As a result, honey $^{87}\text{Sr}/^{86}\text{Sr}$ might not be directly comparable to this bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ isotope.

3.4.2. Lead isotope ratio

Lead isotope ratios have been widely used to trace environmental Pb

sources and to distinguish between anthropogenic and geogenic contributions in complex environmental and biological matrices. Previous studies have shown that honey, as well as other biomonitoring materials such integrates lead inputs from atmospheric deposition and the surrounding environment, supporting its applicability as an indicator of regional Pb sources (Đurđić et al., 2020, 2021; Smith & Weis, 2020). Several honey-based studies further indicate that Pb isotope compositions can reflect spatial and temporal variations in local emission patterns, land use, and anthropogenic activity (Hoppstock-Mattson et al., 2025; Zhou et al., 2018).

In this study the lead isotope ratios of the four honey samples – which had Pb concentrations above the LoD – were analyzed by MC-ICP-MS technique. Since these interpretations are based on a limited number of samples should therefore be interpreted with caution. The measured $^{206}\text{Pb}/^{207}\text{Pb}$ ratio (range: 1.123–1.197) falls within the range of honeys from continental USA by previously published research (K. E. Smith & Weis, 2020). The lead isotope ratios fit into the global Pb array as defined by previous regional and city-scale honey studies as well as anthropogenic and natural Pb isotopic compositions measured in consumer products and aerosols (Smith et al., 2021; Smith & Weis, 2020). **Supplementary Fig. 1** illustrates the lead isotope ratios of the honey samples analyzed in this study in comparison with literature-reported data, providing a broader contextual framework for interpretation (Smith et al., 2019).

The $^{206}\text{Pb}/^{207}\text{Pb}$ vs. $^{208}\text{Pb}/^{206}\text{Pb}$ ratios shows US gasoline origin of the Pb in the No. 96 sample. The $^{206}\text{Pb}/^{207}\text{Pb}$ vs. $^{208}\text{Pb}/^{206}\text{Pb}$ ratios of sample No. 20 and 49 are at the border of the natural and anthropogenic (gasoline) source signatures, but the elevated Pb concentration can show the anthropogenic origin. However, sample No. 49 also has a Sr isotope ratio that shows possible seawater contribution, so the Pb isotopic composition could also be affected by the seawater. Elevated $^{208}\text{Pb}/^{206}\text{Pb}$ ratios similar to the sample No. 31 were measured by Smith et al. (2019) in honeys from Vancouver. In this sample, US gasoline origin also can be possible (Smith et al., 2019; Wang et al., 2019).

4. Conclusions

In this study, we analyzed the elemental composition of 121 honey samples collected between 2017 and 2019 from the eastern part of the United States. Compared to other countries, honey elemental analysis is severely underrepresented in the U.S., resulting in a limited understanding of the composition of the most common types produced in the country. In this gap filling study, we were one of the first to describe the elemental composition of the most common honey varieties, analyzing

the trace element and toxic metal content as well as the strontium and lead isotope ratios.

The geographical and geological diversity of the United States, combined with the small sample set, limits the ability to draw broad conclusions about the national market. Considering the measured 27 elements, among all samples the group of Sourwood honeys had the highest, and Clover honeys the lowest elemental concentration. Potassium was the most abundant element, accounting for 67–87% of total mineral content. There was only one sample (from Albany County, NJ), which exceeded the health limit for several toxic metals (Cr, Ni, Pb). Aluminium concentrations showed spatial trends that may reflect a combination of environmental and regional factors. Multivariate statistical analyses (CDA, PCA) enabled classification by botanical and geographic origin.

In light of previously published $^{13}\text{C}/^{12}\text{C}$ ratio measurements on this sample set, our elemental analysis results indicate that elemental profiling alone may not provide conclusive evidence for detecting adulteration due to its high natural variability.

Based on our results, the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio in honey reflects a qualitative relationship with the bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ in the United States. However, the georeferencing of the honey samples along with the influence of the agricultural landscape on honey $^{87}\text{Sr}/^{86}\text{Sr}$ makes it challenging to compare with existing $^{87}\text{Sr}/^{86}\text{Sr}$ isotope isoscape maps. The lead isotope ratios observed in the samples suggest that U.S. gasoline was the predominant source of Pb.

Our findings highlight the relevance of honey elemental analysis in the case of food safety and environmental monitoring purposes.

CRediT authorship contribution statement

Ágota Zsófia Ragyák: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Tamás Varga:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology. **Nassar Almonther Khaled Ahmed:** Investigation, Formal analysis. **Mihály Braun:** Investigation, Formal analysis. **Anikó Horváth:** Investigation, Formal analysis. **Zsuzsa Lisztes-Szabó:** Writing – review & editing. **Szilárd Szabó:** Writing – review & editing, Visualization, Data curation. **James Kaste:** Writing – review & editing, Resources, Conceptualization. **Clément P. Bataille:** Writing – review & editing. **Megan S. Reich:** Writing – review & editing. **Edina Baranyai:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Conceptualization. **Zsófi Sajtos:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foodchem.2026.149254>.

Data availability

Data will be made available on request.

References

- AL-Huqail, A. A., Alghanem, S. M. S., Alhathloul, H. A. S., Abbas, Z. K., AL-Balawi, S. M., Darwish, D. B. E., ... Javed, S. (2024). Selenium mitigates vanadium toxicity through enhanced nutrition, photosynthesis, and antioxidant defense in rice (*oryza sativa* L.) seedlings. *BMC Plant Biology*, 24(1), 1–18. <https://doi.org/10.1186/S12870-024-05790-2>
- Almeida, C. M., & Vasconcelos, M. T. S. D. (2001). ICP-MS determination of strontium isotope ratio in wine in order to be used as a fingerprint of its regional origin. *Journal of Analytical Atomic Spectrometry*, 16(6), 607–611. <https://doi.org/10.1039/B100307K>
- Anke, M., Angelow, L., Müller, R., & Anke, S. (2005). Recent progress in exploring the essentiality of the ultratrace element rubidium to the nutrition of animals and man. *Biomedical Research on Trace Elements*, 16(3), 203–207. <https://doi.org/10.11299/BRT.16.203>
- Aoyama, K., Nakano, T., & Shin, K. C. (2017). Variation of strontium stable isotope ratios and origins of strontium in Japanese vegetables and comparison with Chinese vegetables. *Food Chemistry*, 237, 1186–1195. <https://doi.org/10.1016/J.FOODCHEM.2017.06.027>
- Baker, J., Peate, D., Waight, T., & Meyzen, C. (2004). Pb isotopic analysis of standards and samples using a 207Pb–204Pb double spike and thallium to correct for mass bias with a double-focusing MC-ICP-MS. *Chemical Geology*, 211(3–4), 275–303.
- Baroni, M. V., Podio, N. S., Badini, R. G., Inga, M., Ostera, H. A., Cagnoni, M., ... Wunderlin, D. A. (2015). Linking soil, water, and honey composition to assess the geographical origin of Argentinean honey by multielemental and isotopic analyses. *Journal of Agricultural and Food Chemistry*, 63(18), 4638–4645. <https://doi.org/10.1021/jf5060112>
- Bataille, C. P., Crowley, B. E., Wooller, M. J., & Bowen, G. J. (2020). Advances in global bioavailable strontium isoscapes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 555, Article 109849. <https://doi.org/10.1016/J.PALAEO.2020.109849>
- Batista, B. L., da Silva, L. R. S., Rocha, B. A., Rodrigues, J. L., Berretta-Silva, A. A., Bonates, T. O., ... Barbosa, F. (2012). Multi-element determination in Brazilian honey samples by inductively coupled plasma mass spectrometry and estimation of geographic origin with data mining techniques. *Food Research International*, 49(1), 209–215. <https://doi.org/10.1016/j.foodres.2012.07.015>
- Capo, R. C., Stewart, B. W., & Chadwick, O. A. (1998). Strontium isotopes as tracers of ecosystem processes: Theory and methods. *Geoderma*, 82(1–3), 197–225. [https://doi.org/10.1016/S0016-7061\(97\)00102-X](https://doi.org/10.1016/S0016-7061(97)00102-X)
- Cappuyns, V., & Slabbinck, E. (2012). Occurrence of vanadium in Belgian and European alluvial soils. *Applied and Environmental Soil Science*, 2012(1), Article 979501. <https://doi.org/10.1155/2012/979501>
- Chen, L., Liu, J.-r., Hu, W.-f., Gao, J., & Yang, J.-y. (2021). Vanadium in soil-plant system: Source, fate, toxicity, and bioremediation. *Journal of Hazardous Materials*, 405, Article 124200. <https://doi.org/10.1016/J.JHAZMAT.2020.124200>
- Čirić, J., Spirić, D., Baltić, T., Lazić, I. B., Trbović, D., Parunović, N., ... Dordević, V. (2021). Honey bees and their products as indicators of environmental element deposition. *Biological Trace Element Research*, 199(6), 2312–2319. <https://doi.org/10.1007/s12011-020-02321-6>
- Coder, K. D. (2011). *Sourwood (Oxydendrum arboreum): The honey tree*. Warnell School of forestry and natural resources, The University of Georgia, Native Tree Series (WSFNRI11–13).
- Codex Alimentarius. (2019). *Codex Alimentarius - standard for honey CXS 12–1981*. Food and Agriculture Organization of the United Nations.
- Crane, E. (1984). *Bees, honey and pollen as indicators of metals in the environment*. Bee World (UK). [Doi: 10.3/JQUERY-ULJS](https://doi.org/10.3/JQUERY-ULJS).
- Cunningham, M. M., Tran, L., McKee, C. G., Ortega Polo, R., Newman, T., Lansing, L., ... Marta Guarna, M. (2022). Honey bees as biomonitors of environmental

- contaminants, pathogens, and climate change. In *Ecological Indicators*. <https://doi.org/10.1016/j.ecolind.2021.108457> (Vol. 134). Elsevier B.V.
- Di Paola-Naranjo, R. D., Baroni, M. V., Podio, N. S., Rubinstein, H. R., Fabiani, M. P., Badini, R. G., ... Wunderlin, D. A. (2011). Fingerprints for main varieties of argentinean wines: Terroir differentiation by inorganic, organic, and stable isotopic analyses coupled to chemometrics. *Journal of Agricultural and Food Chemistry*, 59(14), 7854–7865. <https://doi.org/10.1021/JF2007419>
- Díaz, S., Paz, S., Rubio, C., Gutiérrez, Á. J., González-Weller, D., Revert, C., ... Hardisson, A. (2019). Toxic metals and trace elements in artisanal honeys from the canary islands. *Biological Trace Element Research*, 190(1), 242–250. <https://doi.org/10.1007/S12011-018-1538-0>
- Durdić, S., Stanković, V., Razić, S., & Mutić, J. (2020). Lead isotope ratios as tool for elucidation of chemical environment in a system of *macrolepiota procera* (Scop.) singer - soil. *Environmental Science and Pollution Research*, 28(42), 59003–59014. <https://doi.org/10.1007/S11356-020-07947-6>
- Durdić, S., Stanković, V., Razić, S., & Mutić, J. (2021). Is a lead isotope ratios in wine good marker for origin assessment? *Frontiers in Chemistry*, 9, Article 746695. <https://doi.org/10.3389/FCHEM.2021.746695/BIBTEX>
- Exley, C. (2013). Human exposure to aluminium. *Environmental Science: Processes & Impacts*, 15(10), 1807–1816. <https://doi.org/10.1039/C3EM000374D>
- Frank, A. B., Frei, R., Moutafi, I., Voutsaki, S., Orgeoleto, R., Kristiansen, K., & Frei, K. M. (2021). The geographic distribution of bioavailable strontium isotopes in Greece – A base for provenance studies in archaeology. *Science of the Total Environment*, 791. <https://doi.org/10.1016/j.scitotenv.2021.148156>
- Frei, R., Frei, K. M., & Jessen, S. (2020). Shallow retardation of the strontium isotope signal of agricultural liming - implications for isoscapes used in provenance studies. *Science of the Total Environment*, 706, Article 135710. <https://doi.org/10.1016/J.SCITOTENV.2019.135710>
- Geană, E. I., Sandru, C., Stanciu, V., & Ionete, R. E. (2017). Elemental profile and ⁸⁷Sr/⁸⁶Sr isotope ratio as fingerprints for geographical traceability of wines: An approach on romanian wines. *Food Analytical Methods*, 10(1), 63–73. <https://doi.org/10.1007/S12161-016-0550-2>
- Goddard, S. L., Williams, K. R., Robins, C., & Brown, R. J. C. (2019). Determination of antimony and barium in UK air quality samples as indicators of non-exhaust traffic emissions. *Environmental Monitoring and Assessment*, 191(11), 1–12. <https://doi.org/10.1007/S10661-019-7774-8>
- Godebo, T. R., Stoner, H., Taylor, P., & Jeuland, M. (2025). Metals in honey from bees as a proxy for environmental contamination in the United States. *Environmental Pollution*, 364, Article 125221. <https://doi.org/10.1016/J.ENVPOL.2024.125221>
- Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. (2026). Retrieved 15 January. from <https://www.who.int/publications/i/item/9789240045064>.
- Gulson, B., Chiaradia, M., Davis, J., & O'Connor, G. (2016). Impact on the environment from steel bridge paint deterioration using lead isotopic tracing, paint compositions and soil deconstruction. *Science of the Total Environment*, 550, 69–72. <https://doi.org/10.1016/J.SCITOTENV.2016.01.083>
- Hiraoka, H., Morita, S., Izawa, A., Aoyama, K., Shin, K. C., & Nakano, T. (2016). Tracing the geographical origin of onions by strontium isotope ratio and strontium content. *Analytical Sciences*, 32(7), 781–788. <https://doi.org/10.2116/ANALSCI.32.781>
- Holt, E., Evans, J. A., & Madgwick, R. (2021). Strontium (⁸⁷Sr/⁸⁶Sr) mapping: A critical review of methods and approaches. *Earth-Science Reviews*. <https://doi.org/10.1016/j.earscirev.2021.103593>
- Hong, L., Wang, W., Su, Y., Zhang, G., Su, Y., Zhang, C., ... Wang, J. (2022). Identifying the geographical origin of tobacco leaf by strontium and lead isotopic with mineral elemental fingerprint. *International Journal of Chemical Engineering*, 2022. <https://doi.org/10.1155/2022/5949770>
- Hoppstock-Mattson, B., Weis, D., Maton, J., Hublet, G., & Mattielli, N. (2025). Local honey reflects environmental changes in metal concentrations and lead isotope ratios during COVID-19 restrictions in Brussels, Belgium, and Vancouver, Canada. *Science of the Total Environment*, 959, Article 178077. <https://doi.org/10.1016/J.SCITOTENV.2024.178077>
- Horacek, M. (2022). The need to consider geochemistry when interpreting Sr-isotopes. Comment on Gregorčič et al. The Provenance of Slovenian Milk Using ⁸⁷Sr/⁸⁶Sr Isotope Ratios. *Foods* 2021, 10, 1729. *Foods*, 11(4), Article 564. <https://doi.org/10.3390/foods11040564>
- Horváth, A., Bajnóczi, B., Györkös, D., & Palcsu, L. (2023). Comparison of rapid preparation methods for pb isotope analysis of high-pb ceramic glazes: A case study of late medieval Besztercebánya/Banská bystrica-type stove tiles. *Archaeometry*, 65(5), 1004–1017. <https://doi.org/10.1111/arc.12872>
- Kaste, J. M., Volante, P., & Elmore, A. J. (2021). Bomb ¹³⁷Cs in modern honey reveals a regional soil control on pollutant cycling by plants. *Nature Communications*, 12(1), 1–7. <https://doi.org/10.1038/s41467-021-22081-8>
- Kowalczyk, E., Givélet, L., Amlund, H., Sloth, J. J., & Hansen, M. (2022). Risk assessment of rare earth elements, antimony, barium, boron, lithium, tellurium, thallium and vanadium in teas. *EFSA Journal*, 20(S1). <https://doi.org/10.2903/J.EFSA.2022.E200410>
- Machado De-Melo, A. A., Almeida-Muradian, L. B. d., Sancho, M. T., & Pascual-Maté, A. (2017). Composition and properties of *Apis mellifera* honey: A review. *Journal of Apicultural Research*, 57(1), 5–37. <https://doi.org/10.1080/00218839.2017.1338444>
- McArthur, J. M., Howarth, R. J., & Bailey, T. R. (2001). Strontium isotope stratigraphy: LOWESS version 3: Best fit to the marine Sr-isotope curve for 0–509 ma and accompanying look-up table for deriving numerical age. *The Journal of Geology*, 109(2), 155–170. <https://doi.org/10.1086/319243>
- McArthur, J. M., Howarth, R. J., Shields, G. A., & Zhou, Y. (2020). Strontium isotope stratigraphy. In *Geologic time scale 2020* (pp. 211–238). Elsevier. <https://doi.org/10.1016/B978-0-12-824360-2.00007-3>
- Moniruzzaman, M., Chowdhury, M. A. Z., Rahman, M. A., Sulaiman, S. A., & Gan, S. H. (2014). Determination of mineral, trace element, and pesticide levels in honey samples originating from different regions of Malaysia compared to manuka honey. *BioMed Research International*, 2014, 1–10. <https://doi.org/10.1155/2014/359890>
- Nagaishi, K., Nakada, R., & Ishikawa, T. (2021). High-throughput isotope analysis of sub-nanogram sized lead using MC-ICP-MS with on-line thallium doping technique and desolvating nebulizer system. *Gaochemical Journal*, 55(1), 1–9. <https://doi.org/10.2343/geochemj.2.0612>
- Nuss, P., & Blengini, G. A. (2018). Towards better monitoring of technology critical elements in europe: Coupling of natural and anthropogenic cycles. *Science of the Total Environment*, 613–614, 569–578. <https://doi.org/10.1016/j.scitotenv.2017.09.117>
- Parviainen, A., Papasilioti, E. M., Casares-Porcel, M., & Garrido, C. J. (2020). Antimony as a tracer of non-exhaust traffic emissions in air pollution in Granada (s Spain) using lichen bioindicators. *Environmental Pollution*, 263, Article 114482. <https://doi.org/10.1016/J.ENVPOL.2020.114482>
- Peng Kek, S., Ling Chin, N., Wei Tan, S., Aniza Yusof, Y., & Suan Chua, L. (2017). Classification of honey from its bee origin via chemical profiles and mineral content. *Food Analytical Methods*. <https://doi.org/10.1007/s12161-016-0544-0>
- Peucker-Ehrenbrink, B., & Fiske, G. J. (2019). A continental perspective of the seawater ⁸⁷Sr/⁸⁶Sr record: A review. *Chemical Geology*, 510, 140–165. <https://doi.org/10.1016/J.CHEMGEO.2019.01.017>
- Pleijel, H., Klingberg, J., Strandberg, B., Sjöman, H., & Wallin, G. (2023). Accumulation of antimony and lead in leaves and needles of trees: The role of traffic emissions. *Heliyon*, 9(2), Article e13548. <https://doi.org/10.1016/j.heliyon.2023.e13548>
- Poszwa, A., Ferry, B., Dambrine, E., Pollier, B., Wickman, T., Loubet, M., & Bishop, K. (2004). Variations of bioavailable sr concentration and ⁸⁷Sr/⁸⁶Sr ratio in boreal forest ecosystems: Role of biocycling, mineral weathering and depth of root uptake. *Biogeochemistry*, 67(1), 1–20. <https://doi.org/10.1023/B: BIOG.0000015162.12857.3E/METRICS>
- Rapa, M., Ferrante, M., Rodushkin, I., Paulukat, C., & Conti, M. E. (2023). Heavy metals, rare earth elements and isotopic fingerprint of venetian protected designation of origin sparkling wines. *British Food Journal*, 125(7), 2644–2662. <https://doi.org/10.1108/BJFJ-06-2022-0483>
- Reich, M. S., Flockhart, D. T. T., Norris, D. R., Hu, L., & Bataille, C. P. (2021). Continuous-surface geographic assignment of migratory animals using strontium isotopes: A case study with monarch butterflies. *Methods in Ecology and Evolution*, 12(12), 2445–2457. <https://doi.org/10.1111/2041-210X.13707>
- Rhee, Y., Shilliday, E. R., Matviychuk, Y., Nguyen, T., Robinson, N., Holland, D. J., ... Johns, M. L. (2023). Detection of honey adulteration using benchtop 1H NMR spectroscopy. *Analytical Methods*, 15(13), 1690–1699. <https://doi.org/10.1039/D2AY01757A>
- Ryan, S. E., Snoeck, C., Crowley, Q. G., & Babechuk, M. G. (2018). ⁸⁷Sr/⁸⁶Sr and trace element mapping of geosphere-hydrosphere-biosphere interactions: A case study in Ireland. *Applied Geochemistry*, 92(July 2017), 209–224. <https://doi.org/10.1016/j.apgeochem.2018.01.007>
- Saar de Almeida, B., Fedele, L., D'Antonio, M., Morra, V., Mercurio, M., Stevenson, R., & Widory, D. (2023). Characterizing wine terroir using strontium isotope ratios: A review. *Isotopes in Environmental and Health Studies*, 59(4–6), 327–348. <https://doi.org/10.1080/10256016.2023.2245122>
- Sajtos, Z., Herman, P., Harangi, S., & Baranyai, E. (2019). Elemental analysis of hungarian honey samples and bee products by MP-AES method. *Microchemical Journal*, 149. <https://doi.org/10.1016/j.microc.2019.103968>
- Sajtos, Z., Varga, T., Gajdos, Z., Burik, P., Csontos, M., Lisztes-Szabó, Z., ... Baranyai, E. (2022). Rape, sunflower and forest honeys for long-term environmental monitoring: Presence of indicator elements and non-photosynthetic carbon in old hungarian samples. *Science of the Total Environment*, 808, Article 152044. <https://doi.org/10.1016/J.SCITOTENV.2021.152044>
- Schuette, H. A. (1932). Report on honey. *Journal of AOAC International*, 15(2), 177–181. <https://doi.org/10.1093/JAOAC/15.2.177>
- Schuette, H. A., & Huenink, D. J. (1937). Mineral constituents of honey II. Phosphorous, calcium, magnesium. *Journal of Food Science*, 2(6), 529–538. <https://doi.org/10.1111/J.1365-2621.1937.TB17825.X>
- Schuette, H. A., & Remy, K. (1932). Degree of pigmentation and its probable relationship to the mineral constituents of honey. *Journal of the American Chemical Society*, 54(7), 2909–2913. <https://doi.org/10.1021/JA01346A032>
- Schuette, H. A., & Triller, R. E. (1938). Mineral constituents of honey. *Journal of Food Science*, 3(5), 543–547. <https://doi.org/10.1111/J.1365-2621.1938.TB17090.X>
- Silva, B., Valdomiro Gonzaga, L., França Maltz, H., Samochvalov, K. B., Fett, R., & Oliveira Costa, A. C. (2021). Elemental profiling by ICP-MS as a tool for geographical discrimination: The case of bracinga honeydew honey. *Journal of Food Composition and Analysis*, 96, Article 103727. <https://doi.org/10.1016/j.jfca.2020.103727>
- Smith, D. B., Smith, S. M., & Horton, J. D. (2013). History and evaluation of national-scale geochemical data sets for the United States. *Geoscience Frontiers*, 4(2), 167–183. <https://doi.org/10.1016/J.GSF.2012.07.002>
- Smith, K. E., & Weis, D. (2020). Evaluating spatiotemporal resolution of trace element concentrations and pb isotopic compositions of honeybees and hive products as biomonitors for urban metal distribution. *GeoHealth*, 4(7). <https://doi.org/10.1029/2020GH000264>
- Smith, K. E., & Weis, D. (2022). Metal and pb isotope characterization of particulates encountered by foraging honeybees in metro Vancouver. *Science of the Total Environment*, 826, Article 154181. <https://doi.org/10.1016/j.scitotenv.2022.154181>

- Smith, K. E., Weis, D., Amini, M., Shiel, A. E., Lai, V. W. M., & Gordon, K. (2019). Honey as a biomonitor for a changing world. *Nature Sustainability*, 2(3), 223–232. <https://doi.org/10.1038/S41893-019-0243-0>
- Smith, K. E., Weis, D., Chauvel, C., & Moulin, S. (2020). Honey maps the pb fallout from the 2019 fire at Notre-dame cathedral, Paris: A geochemical perspective. *Environmental Science & Technology Letters*, 7(10), 753–759. <https://doi.org/10.1021/acs.estlett.0c00485>
- Smith, K. E., Weis, D., Scott, S. R., Berg, C. J., Segal, Y., & Claeys, P. (2021). Regional and global perspectives of honey as a record of lead in the environment. *Environmental Research*, 195, Article 110800. <https://doi.org/10.1016/J.ENVRES.2021.110800>
- Solayman, M., Islam, M. A., Paul, S., Ali, Y., Khalil, M. I., Alam, N., & Gan, S. H. (2016). Physicochemical properties, minerals, trace elements, and heavy metals in honey of different origins: A comprehensive review. *Comprehensive Reviews in Food Science and Food Safety*, 15(1), 219–233. <https://doi.org/10.1111/1541-4337.12182>
- Squadrone, S., Brizio, P., Stella, C., Pederiva, S., Brusa, F., Mogliotti, P., ... Abete, M. C. (2020). Food chain trace and rare earth elements in monofloral and multifloral honeys from northwestern Italy; A first attempt of characterization by a multi-elemental profile. <https://doi.org/10.1016/j.jtemb.2020.126556>
- Sugar and Sweeteners Yearbook Tables - Visualization: Meeting honey demand in the United States. (2026). *Economic Research Service*. Retrieved 15 January. from <https://www.ers.usda.gov/data-products/sugar-and-sweeteners-yearbook-tables/visualization-meeting-honey-demand-in-the-united-states>
- Tehseen, M., Attia, H., Khaliq, A., Saleh, M. A., Zia Ul Haq, M., Alamer, K. H., ... Hussain, S. (2024). Biochemical, physiological, and nutrient acquisition response of wheat cultivars to nickel and vanadium toxicity. *Journal of Plant Growth Regulation*, 43(12), 4532–4555. <https://doi.org/10.1007/S00344-024-11416-6/METRICS>
- Tesauro, M., Moroni, G., Gianelle, V., Consonni, M., Petrelli, F., & Tovaglieri, B. (2023). 12 years of honey surveys in northern Italy: How anthropic activities can influence honey quality. *Environmental Pollution*, 331, Article 121940. <https://doi.org/10.1016/J.ENVPOL.2023.121940>
- Thomsen, E., & Andreassen, R. (2019). Agricultural lime disturbs natural strontium isotope variations: Implications for provenance and migration studies. *Science Advances*, 5(3). <https://doi.org/10.1126/SCIADV.AAV8083>
- Tong, S. S. C., Morse, R. A., Bache, C. A., & Lisk, D. J. (1975). Elemental analysis of honey as an indicator of pollution. *Archives of Environmental Health: An International Journal*, 30(7), 329–332. <https://doi.org/10.1080/00039896.1975.10666715>
- United States Department of Agriculture (USDA). (1980). *Beekeeping in the United States. Agriculture Handbook No. 335*. Washington, DC: U.S. Government Printing Office.
- USGS Scientific Investigations Report 2017–5118. (2025). *Geochemical and Mineralogical Maps, with Interpretation, for Soils of the Conterminous United States*. Retrieved 11 July. from https://pubs.usgs.gov/sir/2017/5118/sir20175118_element.php?el=19.
- Vanhanen, L. P., Emmertz, A., & Savage, G. P. (2011). Mineral analysis of mono-floral New Zealand honey. *Food Chemistry*, 128(1), 236–240. <https://doi.org/10.1016/j.foodchem.2011.02.064>
- Varga, T., Sajtos, Z., Baranyai, E., Lisztes-Szabó, Z., Ragyák, Á., Molnár, M., ... Kaste, J. M. (2024). Isotopic study of honey documents widespread plant uptake of old carbon in north america. *Science of the Total Environment*, 947, Article 174691. <https://doi.org/10.1016/j.scitotenv.2024.174691>
- Varga, T., Sajtos, Z., Gajdos, Z., Jull, A. J. T., Molnár, M., & Baranyai, E. (2020). Honey as an indicator of long-term environmental changes: MP-AES analysis coupled with 14C-based age determination of hungarian honey samples. *Science of the Total Environment*, 736. <https://doi.org/10.1016/j.scitotenv.2020.139686>
- Voerkelius, S., Lorenz, G. D., Rummel, S., Quérel, C. R., Heiss, G., Baxter, M., ... Ueckeremann, H. (2010). Strontium isotopic signatures of natural mineral waters, the reference to a simple geological map and its potential for authentication of food. *Food Chemistry*, 118(4), 933–940. <https://doi.org/10.1016/j.foodchem.2009.04.125>
- Wang, Z., Dwyer, G. S., Coleman, D. S., & Vengosh, A. (2019). Lead isotopes as a new tracer for detecting coal fly ash in the environment. *Environmental Science & Technology Letters*, 6(12), 714–719. <https://doi.org/10.1021/acs.estlett.9b00512>
- Weilert, T. M., Ray, C. L., Gawenis, J. A., & Brockman, J. D. (2022). Neutron activation analysis and ICP-MS for provenance of honey collected from american Midwest region. *Journal of Radioanalytical and Nuclear Chemistry*, 331(12), 4971–4981. <https://doi.org/10.1007/s10967-022-08532-6>
- Widga, C., Walker, J. D., & Boehm, A. (2017). Variability in bioavailable 87Sr/86Sr in the north american midcontinent. *Open Quaternary*, 3(1), 4. <https://doi.org/10.5334/oq.32>
- Yücel, Y., & Sultanoğlu, P. (2013). Characterization of Hatay honeys according to their multi-element analysis using ICP-OES combined with chemometrics. *Food Chemistry*, 140(1–2), 231–237. <https://doi.org/10.1016/j.foodchem.2013.02.046>
- Zhou, X., Taylor, M. P., Davies, P. J., & Prasad, S. (2018). Identifying sources of environmental contamination in european honey bees (apis mellifera) using trace elements and lead isotopic compositions. *Environmental Science and Technology*, 52(3), 991–1001. <https://doi.org/10.1021/ACS.EST.7B04084>