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Elevated Metal Levels in U.S. Honeys: Is There a Concern for Human Health?

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Abstract

Honey is a bioactive food used for millennia to improve health and treat diseases. More recently, researchers employ honey as a tool to assess local environmental pollution. Honeybees effectively ‘sample’ their environment within a ~ 7 km radius, actively collecting nectar, pollen, and water to bring to their hive. Foraging honeybees also sample the air as dust particles accumulate on their pubescence, adding to the hive’s contaminant load. Many studies from around the world report elevated metal levels in honey, with the most reports from Iran, Italy, and Turkey, but only two reports have measured metal levels in honey from the United States (U.S.). We report levels of 20 metals from 28 honeys collected from 15 U.S. states between 2022–2023. We then focus on four toxic metals recognized as hazards in foodstuffs when the concentrations are above safety recommendations – lead, cadmium, arsenic, and mercury. Two of these metals (lead and mercury) are regulated in honey by the European Union (EU), though the U.S. currently lacks defined regulations for metal levels in honey. We consider the levels of these toxic metals by state, then compare the U.S. mean honey level for these metals against the provisional tolerable weekly intake (PTWI). Our results suggest U.S. honey have levels metal that exceed the PTWI and EU regulations and may be hazardous to human health. Further research is needed to determine if the

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effects of these toxic metal at measured levels outweigh the health benefits from consumption of honey.

Keywords

Honey; Metal pollution; Honeybees; United States; Food safety; One Environmental Health

Introduction

Honey is a sweet natural food produced by bees (*Apis mellifera*, Family: Apidae). Briefly, the bees collect nectar from flowers that is ripened in the honeycomb by diastase and invertase enzymes from their midgut. The nectar is then matured by evaporating water content by the bees fanning with their wings, until the stored nectar reaches ~ 18% water content. Harvested honey is typically a mixture of matured nectar collected from a wide variety of flora and contains over 200 substances that reflect the botanical and geographical origin. Sugar content is predominantly fructose ($45 \pm 5\%$) and glucose ($35 \pm 3\%$), while other components include organic acids (e.g. succinic, acetic, formic), minerals (e.g. calcium, potassium, zinc, copper, iron, manganese, phosphorus), vitamins (e.g. ascorbic acid, pantothenic acid, niacin, riboflavin), polyphenols (e.g. gallic acid, apigenin, chrysin, kaempferol), and flavonoids (e.g. pinocembrin, quercetin, galangin, tocopherols) [1, 2]. Honey is the only food produced by an insect that humans consume.

Honey is a natural food and medicine that humans have harvested and prized for time immemorial. The earliest archaeological evidence of humans harvesting honey dates to the Mesolithic period (around 9600–4000 BCE) and the earliest evidence of apiculture was found in the sun temple of Neuserre, Abu Ghorab (around 2400 BCE). References to the health-giving properties of honey are prominent in medical and religious texts spanning global written history and continue to advance and expand in modern texts and practices [3–6]. Much of the health benefits from honey are attributed to the polyphenols and flavonoids as active ingredients serving anti-inflammatory, antioxidative, anti-fungal, and wound-healing effects [1, 2, 7]. Today, beekeeping is a multi-billion dollar industry worldwide, and much of our agriculture depends on bee pollination services expanding the value of the beekeeping industry beyond bee products. Global honey production was approximately 1.72 million metric tons and is currently a \$50 billion market expected to grow significantly each year [8, 9]. The character and quality of honeys are strictly defined and lawfully enforced by federal governments across the globe, to combat the prevalence of honey adulterated with other sweeteners. However, the chemical quality of honey is often overlooked and may be a critical oversight in protecting human health against other honey contaminants, such as pesticides, PCBs, PFAS, or metals [10–13]. Metals are the most commonly reported contaminant in honey [14].

Metal contamination continues to be a hot topic in food security and public health, as evidenced by recent recalls with baby foods, packaged apple sauces, and many other similar instances [15–17]. Common metals of concern include lead (Pb), arsenic (As), cadmium (Cd), and mercury (Hg) due to these contributing to a wide range of health issues including

risk of cancer, neurological issues, kidney or liver toxicity, and cardiovascular disease [18–20]. Currently there are no maximum contaminant levels (MCLs) for metals in honey defined by the World Health Organization (WHO) or the U.S. Environmental Protection Agency (EPA), though there are two Commission Regulations from the European Union (EU) that define a maximum residue level (MRL) in honey of 0.01 and 0.10 mg/kg for mercury and lead, respectively [21, 22]. Over 100 studies from at least 38 countries have described metal contamination in honey, with the majority from Turkey, Iran, Poland, and Iran [11, 12, 23, 24]. The highest reported level for Pb was 79.815 mg/kg from Ghana; for Cd was 3.810 mg/kg from Romania; for Hg was 0.852 mg/kg from Turkey; and for As was 5.146 mg/kg from Kosovo [25–28]. One study published from the U.S. reported lead levels in honey from central Kentucky as high as 5.65 mg/kg, with 56% of tested honeys higher than 0.05 mg/kg [29].

Metals can also threaten the health of bees and their colony, and are a significant concern for honeybee populations [30, 31]. Bees can be exposed to metals through the food and water they harvest, from dust particles in the air, or from pesticides applied near or directly onto the hive. Many metals (e.g., As, Cu, Pb) are present in licensed pesticides used worldwide and a recent study found most glyphosate-based herbicides contain harmful levels of As, Cr, Co, Ni, and Pb [32]. Given the ubiquity of honeybees and environmental metal pollution, bees are an ideal model species for One Environmental Health [33]. The core principle of the One Environmental Health perspective is recognizing the health of humans, wildlife, and ecosystems are all interconnected and are collectively threatened by environmental pollution. Honeybees are essential pollinators for 80% of flowering plants globally and produce a highly profitable food source for humans, hence they are a critical species to consider within the One Environmental Health framework [34].

Given the lack of data on metal contaminants in U.S. honeys and no reports on essential metals, we sought to investigate metal levels in honeys across the continental U.S. to establish metal levels for 28 honeys from 14 different states collected between 2022–23 (Table 1). We first report metal levels from all honeys for 20 metals (Fig. 1), then report levels for Pb, Cd, Hg, and As by state (Fig. 2) and consider these toxic metal data with a geographic map of the U.S. Critically, we found the vast majority of U.S. honeys greatly exceed MRLs set by EU, indicating a significant concern for metal contamination in U.S. honeys. Finally, we calculated an estimate for daily metal exposure assuming daily consumption of 300 mg honey/kg body mass per day and compared these data against the provisional tolerable weekly intake (PTWI) (Table 2).

Materials & Methods

Honey Samples

The 28 samples of honey were purchased from small business beekeepers across the U.S. between 2022–2023 (Table 1). Twenty of the honeys were labeled as wildflower honey, two were labeled tupelo honey, and one each labeled sourwood, peach flower, start thistle, Russian olive, blackberry/blueberry, and turnip. Honeys were assigned a digital latitude and longitude based on the center of the zip code or city/town listed on the label unless otherwise

indicated by the vendor (we provide the zip code below). The honey samples were stored in 1.5 mL plastic microcentrifuge tubes in a dark box at room temperature until analysis.

Benchtop X-Ray Fluorescence Methodology

We used the Epsilon 4 (Malvern Panalytical, Marlborough, MA) benchtop x-ray fluorescence equipment with a 15-W x-ray tube and 50 kV max tube voltage to perform elemental analyses of honeys. As performed routinely with XRF analysis, the Epsilon 4 software has standard deconvolution protocols that use a series of gaussians along with a polynomial background to identify net counts associated with each element of interest [35–38]. The samples were placed in the center of a 30 mm XRF cup and covered with a 4 µm thin polypropylene film. Importantly, for XRF analysis the honeys do not need to be homogenized or digested [39, 40]. For our metal measurements, we utilized the full energy beam at 50 kV and 300 µA and collected data for 7.5-min for each honey sample.

As measured in previous studies, standard phantoms were doped with known concentrations of metals of interest to appropriately calibrate the machine for elemental quantification [38, 41, 42]. Phantoms were made of varying thicknesses and masses to match the potential variations in our sampling and measurement procedure [43]. Subsequently, samples were measured and the strength of characteristic spectra peaks for metals of interest were translated into metal concentrations based on the formula derived from calibrating the system with standard phantoms. Successful quantification, therefore, depends on the strength of the machine, precise calibration with phantom samples, and a valid normalization approach. Previous research validated the use of phantom samples and the normalization approach utilized here [37, 38, 42, 44]. The normalization approach is based on the Compton scattering peak, which was shown to correct for the mass and thickness variations within samples that would otherwise influence the accuracy of the approach [42, 45]. For this calibration, results from the benchtop XRF were reported in micrograms per gram (µg/g) of material, which is the standard reporting unit from ICP-MS.

Estimated Weekly Intake (EWI)

The safety of honey for adult consumption was estimated by comparing the Estimated Weekly Intake (EWI) to the Provisional Tolerable Weekly Intake (PTWI) proposed by JECFA for the toxic metals As, Pb, Cd, Hg, and Al, and for the essential metals Cu, Mn, Zn, and Se. For the EWI we used the following equation:

$$EWI = \frac{\text{dailyhoneyconsumption} \times \text{metalconcentration}}{\text{bodymass}} \times 7$$

For these calculations, we assumed 300 mg/kg daily honey consumption (~ 15.3 mL or 1.03 US tablespoons) and an average adult body mass of 70 kg. This daily honey dose is commonly used in therapeutic studies in rodents and is below the daily honey dose used in many human studies (1–2 g/kg) [46–49].

Sample Mapping

ArcGIS mapping of the locations of U.S. honey samples were mapped using GPS coordinates based on the zipcode with ArcGIS Pro version 3.2.2 (Environmental Systems Research Institute, Redlands, CA). The specific map used was the Charted Territory basemap provided in the program, which was developed for the program using data from Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community.

Results

Metal Levels in U.S. Honeys Reveal Distinct Differences in Select Metals

We report levels of 20 elements present in 28 honeys from across the continental U.S (Fig. 1). Eleven metals within are reported in the range of 0–1 $\mu\text{g/g}$ (Fig. 1A), four metals in the range of 0–15 $\mu\text{g/g}$ (Fig. 1B), three metals in the range of 0–300 $\mu\text{g/g}$ (Fig. 1C), and two metals in the range of 0–500 $\mu\text{g/g}$ (Fig. 1D). Five metals were present at relatively the same level across all honeys sampled (mean $\pm$ SEM); sodium ($406.8 \pm 1.8 \mu\text{g/g}$), calcium ($234.8 \pm 2.1 \mu\text{g/g}$), copper ($3.61 \pm 0.01 \mu\text{g/g}$), arsenic ($0.06 \pm 0.0 \mu\text{g/g}$), and vanadium ($0.02 \pm 0.0 \mu\text{g/g}$). The three metals with the highest mean level were sodium, calcium, and zinc ($75.91 \pm 12.2 \mu\text{g/g}$), while the lowest three metals detected in the honeys were vanadium, titanium ($0.056 \pm 0.01 \mu\text{g/g}$), and germanium ($0.035 \pm 0.01 \mu\text{g/g}$). Thirteen metals were detected in all honeys; silicon ($0.19 \pm 0.02 \mu\text{g/g}$), titanium, vanadium, arsenic, selenium ($0.51 \pm 0.03 \mu\text{g/g}$), gallium ($0.14 \pm 0.01 \mu\text{g/g}$), manganese ($2.33 \pm 0.37 \mu\text{g/g}$), copper ($3.61 \pm 0.01 \mu\text{g/g}$), bromine ($4.82 \pm 0.45 \mu\text{g/g}$), iron ($31.33 \pm 7.23 \mu\text{g/g}$), zinc ($75.9 \pm 12.18 \mu\text{g/g}$), calcium ($234.8 \pm 2.15 \mu\text{g/g}$), and sodium ($406.8 \pm 1.58 \mu\text{g/g}$).

Levels of Toxic Metals in Honeys Varies Across Geographical Locations

We next considered differences in metal levels by state for four toxic metals: Pb, Cd, Hg, and As (Fig. 2). Many of the U.S. honeys we assessed exceeded the EU regulations for Pb ($0.10 \mu\text{g/g}$) and Hg ($0.01 \mu\text{g/g}$). The three highest levels of lead were observed in honeys from Tennessee ($0.918 \mu\text{g/g}$), Massachusetts ($0.820 \mu\text{g/g}$), and New Mexico ($0.367 \mu\text{g/g}$), which are 9.18x, 8.2x, and $3.67 \times$ higher than the EU safety limit (Fig. 2A). The three highest levels of Cd were observed in honeys from Tennessee ($0.918 \mu\text{g/g}$), Massachusetts ($0.820 \mu\text{g/g}$), and Vermont ($0.350 \mu\text{g/g}$). The three highest levels of Hg were observed in honeys from Massachusetts ($8.94 \mu\text{g/g}$), Tennessee ($7.04 \mu\text{g/g}$), and New Mexico ($6.92 \mu\text{g/g}$), which were 894x, 704x, and $692 \times$ higher than the EU safety limit. The three highest levels of As were observed in honeys from Oregon ($0.067 \mu\text{g/g}$), Indiana ($0.065 \mu\text{g/g}$), and Arkansas ($0.065 \mu\text{g/g}$).

We further generated ArcGIS maps to illustrate the distribution of these four metals in U.S. honeys (Fig. 3). Through this analysis and mapping, we found no distinct clustering of elevated levels of any of these toxic metals. However, the highest levels of all four toxic metals were observed in Tennessee and Massachusetts.

Estimated Daily Metal Intake from U.S. Honeys

Honey has been used to attenuate metal toxicity in a variety of studies using a daily dose of 85–300 mg honey/kg body mass [46–49]. We estimated daily metal intake for five toxic metals and four essential metals considering the most common daily honey dose reported in therapeutic studies, 300 mg/kg, and compared these results against the relevant PTWI (Table 2). The daily intake for all toxic metals exceeded levels considered safe in other food sources. For example, the estimated daily intake for arsenic was 0.128 mg/kg, which is 64x above the PTWI of 0.002 mg/kg. The levels of the estimated daily intake for essential metals compared to the PTWI were metal-dependent. For example, the estimated daily intake for Mn was 0.699 mg/kg, which is 3.7x lower than the PTWI of 2.5 mg/kg while the estimated daily intake for Zn was 22.77 mg/kg, which is 3.3 × above the PTWI of 7 mg/kg.

Discussion

We assessed levels of 20 metals in U.S. honeys from 15 different states, which is the most thorough report on contaminants in U.S. honeys reported thus far. Sodium ($406.8 \pm 8.3 \mu\text{g/g}$) and calcium ($234.8 \pm 11.35 \mu\text{g/g}$) were the highest metals we measured, with relatively similar levels regardless of U.S. state of origin; while vanadium ($0.021 \pm 0.004 \mu\text{g/g}$) and titanium ($0.056 \pm 0.039 \mu\text{g/g}$) were the lowest metals measured. We then focused our analyses on four toxic metals (Pb, Hg, As, Cd) and regional differences by state, and found honey samples from Massachusetts and Tennessee exhibited the highest of these metals. Notably, the majority of samples assessed were well above levels considered safe by the EU, implying a potential metal contamination concern for U.S. honeys. We then considered the U.S. mean levels of these metals in the context of JECFA PTWI values, assuming daily consumption of 300 mg/kg (15–20 mL). For each toxic metal, the estimated weekly metal intake greatly exceeded the recommended PTWI values set by JECFA.

Honey is a useful indicator of local environmental contamination. Honeybees forage their local environment within an ~ 7 km radius, effectively sampling the local flora, air, and water. Hence, contaminants measured in honey can give us a view of local environmental contamination and provide valuable monitoring data and insight into areas in need of remediation. In many cases, honey contamination can be isolated to a single point source (e.g., major highway, factory, agriculture), as may be the case for our honey sample from Boxboro, MA which is within 5 km of U.S. Interstate-495. In other cases, further investigation may be required to determine sources based on the land history or geogenic sources, such as our honey sample from Tennessee, which was from a very rural area with no major roadways or industry that could contribute to the high metal levels we observed.

Metal contamination in honey can also challenge the health of bees and the success of their hive [30, 31]. Certain metals honeybees can detect in nectar with their antennae or proboscis and avoid or reject that nectar source, such as Cu, As, Pb, or Zn [50–52]. Exposure to As, Cd, Pb, or a combination can impair honeybee's short- and long-term memory for odor discrimination, resulting in impaired cognitive flexibility [53–56]. Honeybee exposure to Ni, Pb or Mn resulted in shorter and less frequent flights to visiting flowers [57–60].

Critically, honey has been used in medicine for thousands of years to treat a variety of diseases and recent reports suggest it can improve health for liver, cardiovascular, reproductive, metabolic, and neurological health [5, 47, 49]. Further, a recent review summarized 19 reports describing honey's ability to alleviate metal toxicity for Pb, Cd, and As across many organs including the liver, kidney, brain, and testes [46]. However, none of these studies reported metal levels in the honeys used for such therapeutic effects. Critically, our results and similar reports from other groups suggest there is a significant potential for metal toxicity from honey consumption [61, 62]. Further research is needed to determine if these levels of these toxic metals outweigh the health benefits of daily honey consumption.

In conclusion, our study is the most extensive to date for metal contamination in U.S. honeys and our results suggest there is a critical concern for metal contamination. Similar or worse metal contamination has been reported in 38 other countries, most often from Italy, Iran, and Turkey. Metal contamination is an important consideration, as honey is a significant commercial industry in the U.S. with about \$296 million in annual revenue and with over 565 million pounds consumed in 2022 [63]. Metals may threaten the health of honeybees and the fitness of their hive. Additionally, honey is a bioactive food that can improve health outcomes for multiple organ systems and many disease states which may be exacerbated by metal exposures. Results from our study indicate the levels of many toxic metals in U.S. honeys may result in metal exposures that exceed the recommended PTWI from JECFA when assuming ~ 15 mL (1 U.S. tablespoon) of honey consumption per day. Hence, further investigation is necessary to understand the extent and the threat of metal toxicity from honey consumption and if metal contamination outweighs the health benefits from honey.

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Data Availability

No datasets were generated or analysed during the current study.

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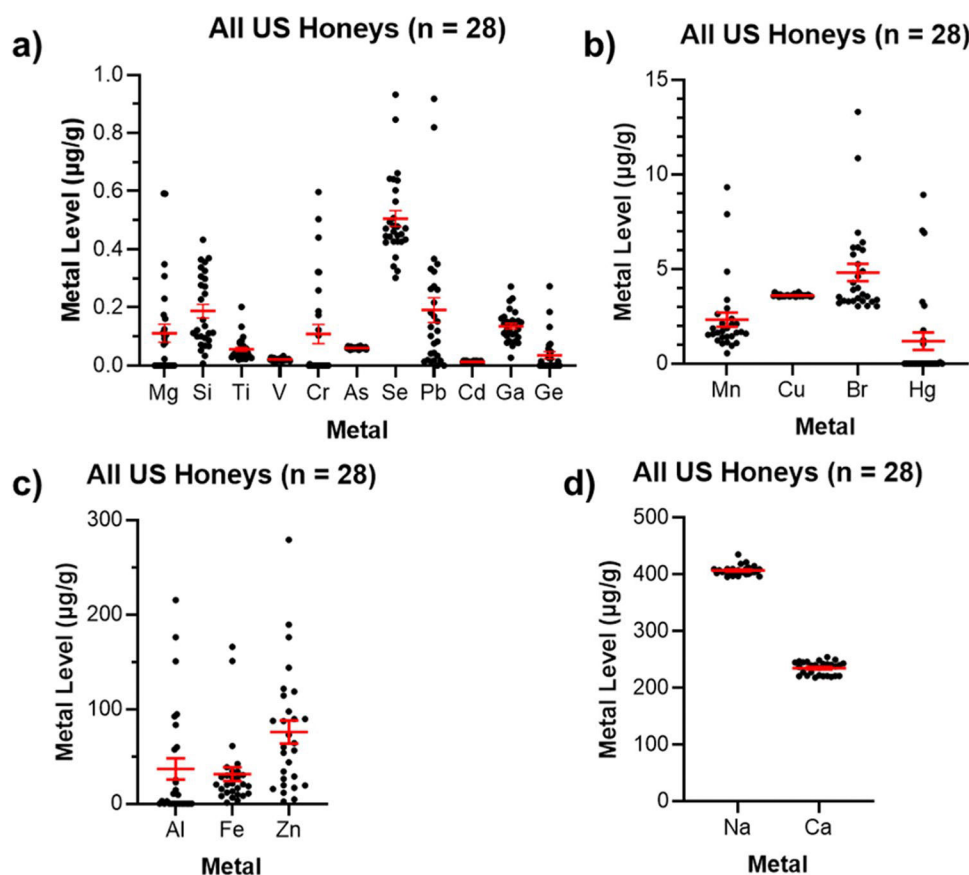


Fig. 1. Metal Levels in U.S. Honeys. These data represent levels of 20 metals in 28 honeys sampled from across the U.S. Metals were separated by relative concentration for easier comparison; **(a)** less than 1 µg/g, **(b)** 1–15 µg/g, **(c)** less than 300 µg/g, **(d)** 200–500 µg/g

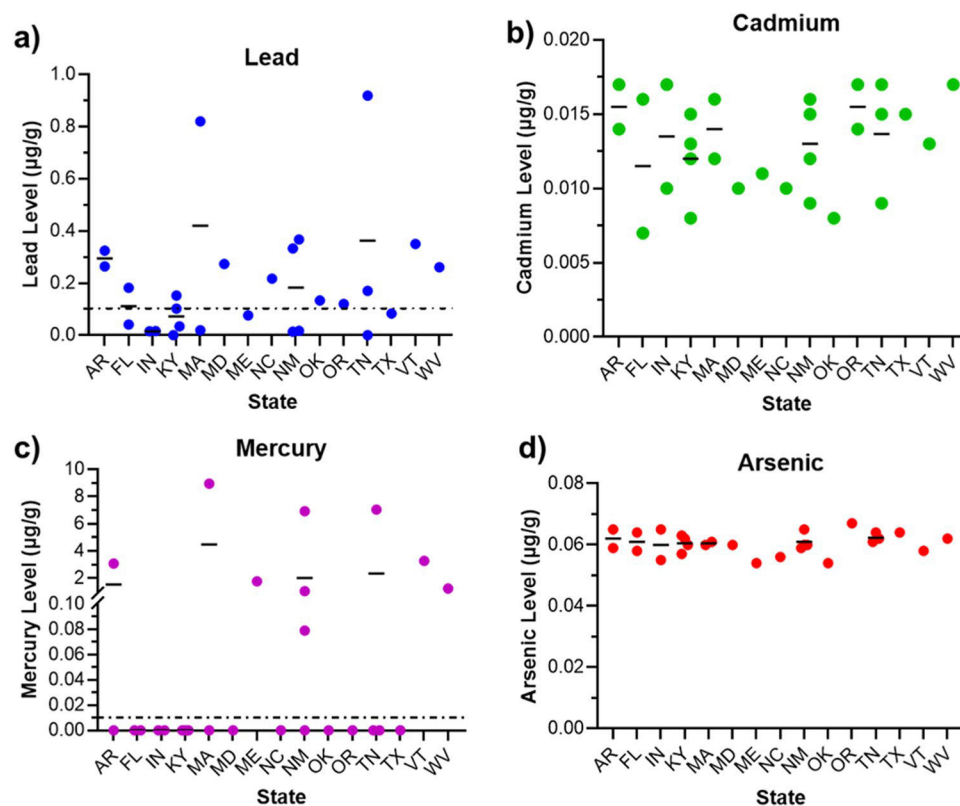


Fig. 2. Regional Analysis of Toxic Metals in U.S. Honeys. Levels of toxic metals in U.S. honeys by state (hash represents state mean); **(a)** lead, **(b)** cadmium, **(c)** mercury, and **(d)** arsenic. We included dashed lines to represent maximum permissible limits set by the EU for lead (0.01 $\mu\text{g/g}$) and mercury (0.01 $\mu\text{g/g}$). Based on these data, the vast majority of U.S. honey exceed EU regulations for lead levels in honey and many of them exceed limits for mercury

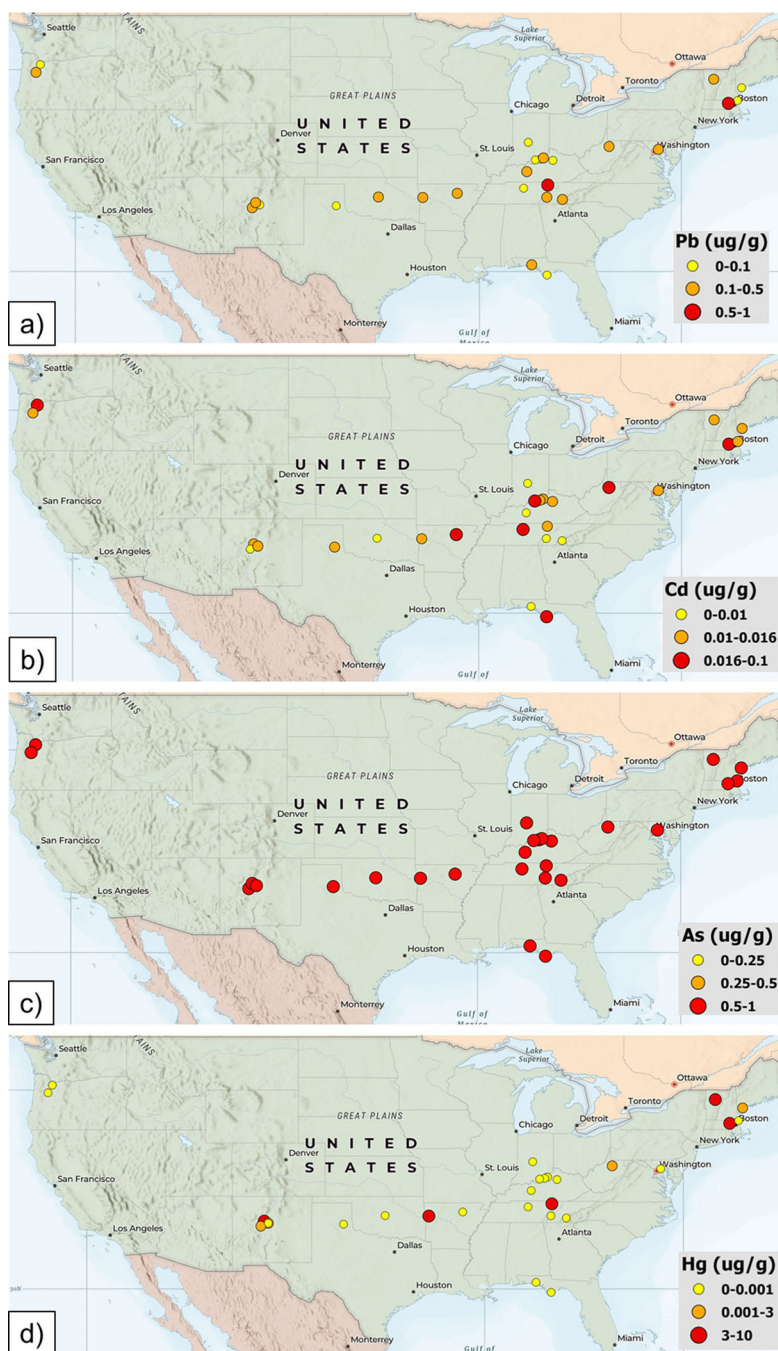


Fig. 3. Geographical Map of Toxic Metal Levels in U.S. Honeys. Visual representation for the levels of **(a)** lead, **(b)** cadmium, **(c)** arsenic, and **(d)** mercury. Increasing metal levels are indicated by yellow, orange, and red circles, with larger circles indicating higher levels of metals

Table 1

Sources and Floral Source of Honey Samples Analyzed

Floral Source	State	Zip Code/Locale
Wildflower	Arkansas	72501
Wildflower	Arkansas	72921
Tupelo	Florida	32320
Tupelo	Florida	32439
Wildflower	Indiana	47150
Wildflower	Indiana	46158
Wildflower	Kentucky	40324
Wildflower	Kentucky	40014
Wildflower	Kentucky	40055
Wildflower	Kentucky	42721
Wildflower	Maine	04093
Wildflower	Maryland	21113
Wildflower	Massachusetts	01938
Wildflower	Massachusetts	01719
Wildflower	New Mexico	87107
Turnip	New Mexico	87059
Russian Olive	New Mexico	87059
Desert wildflower	New Mexico	87031
Sourwood	North Carolina	28771
Wildflower	Oklahoma	73105
Star Thistle	Oregon	97068
Blueberry/Blackberry	Oregon	97392
Wildflower	Tennessee	38556
Wildflower	Tennessee	37206
Wildflower	Tennessee	37321
Peach Flower	Texas	79237
Wildflower	Vermont	05602
Wildflower	West Virginia	26301

Table 2

Estimated Weekly Metal Exposure When Consuming 300 mg/kg Daily

Metal	US Honey Mean (mg metal/kg honey)	Weekly Metal Consumption (mg metal/kg body mass)	JECFA PTWI (mg metal/kg body mass)
<i>Toxic Metals</i>			
As	0.060	0.128	0.002
Pb	0.178	0.401	0.025
Cd	0.132	0.027	0.007
Hg	3.710	2.504	0.005
Al	64.36	77.233	2.000
<i>Essential Metals</i>			
Cu	3.612	1.084	3.500
Mn	2.330	0.699	2.500
Zn	75.91	22.77	7.000
Se	0.509	0.015	0.066