



# Trace And Toxic Metals In Honey: Assessing Nutritional Benefits Versus Health Risks

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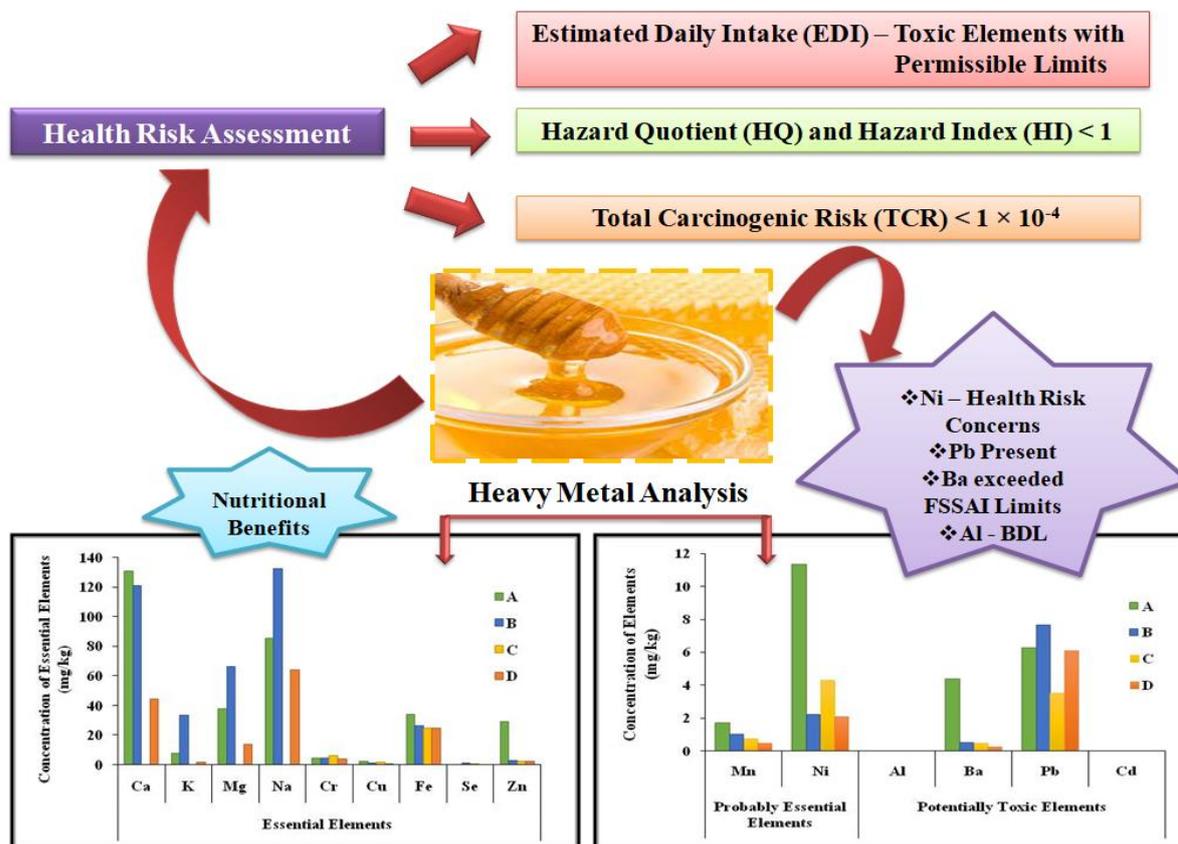
**Abstract:** This study aimed to evaluate the concentrations of heavy metals in honey samples collected from Agra, Uttar Pradesh, India, utilizing ICP-OES and to conduct a health risk assessment. Results indicated that essential elements such as Ca, K, Mg, Na, Cr, Cu, Fe, Se, and Zn were present in concentrations ranging from 44.5-130.25 mg/kg, 0.16-33.9 mg/kg, 14.0-66.7 mg/kg, 64.0-132.5 mg/kg, 3.7-6.5 mg/kg, 0.5-2.0 mg/kg, 24.2-33.7 mg/kg, 0.5-1.0 mg/kg and 2.2-29.75 mg/kg, respectively suggesting significant nutritional benefits. Mn and Ni ranging from 0.5-1.7 mg/kg and 2.0-11.2 mg/kg, considered probably essential elements, were also detected, with Ni levels raising potential health concerns. Conversely, toxic elements like Al, Ba, and Pb were found in varying amounts. Estimated Daily Intake (EDI) values (mg/kg) for the trace metals analyzed in all honey samples were below the maximum tolerable daily intake. Hazard Quotient and Hazard Index values were less than one. Target Carcinogenic Risk (TCR) values for Pb and Cr in all honey samples indicated the lowest carcinogenic risks, ranging from  $7.1 \times 10^{-7}$  to  $1.1 \times 10^{-6}$ . Consequently, there are no significant non-carcinogenic or carcinogenic risks to human health associated with trace metal exposure from such honey consumption.

**Index Terms** - Honey, Heavy metals, Health risks, Environmental monitoring

## Highlights

- [1] Honey samples contained essential minerals (Ca, K, Mg, Na, Cr, Cu, Fe, Se, Zn) within beneficial ranges, highlighting their nutritional value.
- [2] Mn and Ni were detected, with Ni levels (2.0–11.2 mg/kg) being comparatively higher, raising possible health concerns.
- [3] Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) values were all below safety thresholds; carcinogenic risk (TCR for Pb and Cr) was minimal, indicating no significant health risks from honey consumption.

## Graphical Abstract



## I. Introduction

Honey is a highly viscous, nutrient-rich food composed mainly of carbohydrates—fructose (25–45%), glucose (25–37%), maltose (2–12%), sucrose (0.5–3%)—and water (15–18%). It also contains minor constituents that contribute to its wide-ranging biological activities, including enzymes (invertase, glucose oxidase), organic acids (e.g., gluconic acid), amino acids (notably proline), vitamins (vitamin C, B-complex), and minerals (K, Ca, Mg). Phenolic compounds and flavonoids such as quercetin and kaempferol enhance its antioxidant potential, while organic and volatile compounds influence flavor and antimicrobial effects. Hydroxymethyl furfural (HMF) serves as a key indicator of honey quality, and traces of pollen and propolis further support its nutritional and therapeutic value. These diverse constituents collectively give honey its antimicrobial, antioxidant, antiviral, antiparasitic, anti-inflammatory, anti-mutagenic, anticancer, and immunosuppressive properties. However, honey quality may be compromised by contaminants introduced through environmental pollution or residues from pharmacological treatments. Among these, metal contaminants are particularly concerning, often originating from soil or nectar-producing plants. Environmental pollution and other anthropogenic sources contribute significantly to the accumulation of metals in honey. Additionally, honey can be contaminated with transition metals during processing due to the equipment and tools used by beekeepers, as well as the processing environment. After extensive evaluation studies on food additives and their toxicity, the World Health Organization (WHO) has determined that even low levels of certain metals, such as lead (Pb) and cadmium (Cd), can cause various diseases in humans [4, 5]. Heavy metal pollution impacts the quality of agricultural products, as well as the atmosphere and water, posing a threat to the health and life of humans and animals through the food chain. Besides its environmental significance, monitoring heavy metals is crucial for the quality control of honey, one of the most complex food products [6]. The results of such studies can aid in preventing the aforementioned problems and promote healthy honey consumption. These findings can lead to identifying the origins of honey contaminants, such as soil type and air pollution, thereby enhancing food safety in health policy. Ensuring the best quality of food will protect public health and maintain consumer confidence. However, determining metal concentrations in sugar-rich foodstuffs has been a challenging analytical task due to matrix interference. Sample pre-treatment is typically required to break down the organic matrix and extract the metal ions bound in organic complexes. The selection of the digestion procedure must consider the analytes, the sample matrix, and the time requirements of the chosen analytical technique. Several techniques have been proposed for determining heavy metals in honey and other sweeteners, but most of these methods necessitate matrix mineralization [3, 7].

Flame atomic absorption spectrometry (FAAS), owing to its relatively low cost and satisfactory analytical performance, has been widely used to determine various metals in honey. The conventional approach for these determinations involves a mineralization stage to produce a final solution suitable for introduction into the flame nebulizer. However, a limitation arises due to the narrow linear response range of AAS [8, 9]. However, inductively coupled plasma (ICP)-based techniques such as ICP-Atomic Emission Spectroscopy (AES)/ Optical Emission Spectroscopy (OES) and ICP-Mass Spectrometer (MS) have been employed as multi-elemental approaches for analyzing heavy metals in honey and other sweeteners. ICP-OES is particularly appealing for trace analysis due to its satisfactory sensitivity and ability to simultaneously determine multiple metals at various spectral lines. However, a significant drawback is the need for sample digestion, either dry or wet. Consequently, samples are typically digested using wet-acid or dry ashing by heating in a microwave oven or a furnace [10, 11, 12].

Therefore, the aim of this study was to assess the levels of metals such as aluminum (Al), barium (Ba), calcium (Ca), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn) through ICP-OES, followed by conducting a health risk assessment on honey samples collected from Agra, Uttar Pradesh, India.

## II. Materials and Methods

### 2.1. Sample Collection

A total of four samples of honey named as A, B, C and D in triplicates were collected from study site. Samples A & B were procured commercially from the market while C & D was collected from beehive keepers. All samples were collected in clean and closed glass jars and immediately transferred to the laboratory of Department of Chemistry at Dayalbagh Educational Institute; all samples were stored in glass bottles and kept at 4–8 °C in dark until analysis.

### 2.2. Sample Preparation

Approximately 1 g of each honey sample were placed in a digestion vessel utilizing 10 ml of Aqua Regia (a mixture of HCl and HNO<sub>3</sub> in a 3:1 ratio). The digestion was carried out with the Microwave digestion system (Multiwave GO Plus). The digested samples were subsequently filtered using Whatman filter paper and adjusted to a volume of 25 ml using ultrapure water. Process blanks were also prepared in a similar manner (Figure 1). All samples were stored in polytetra-fluoroethylene (PTFE) bottle until further analysis.

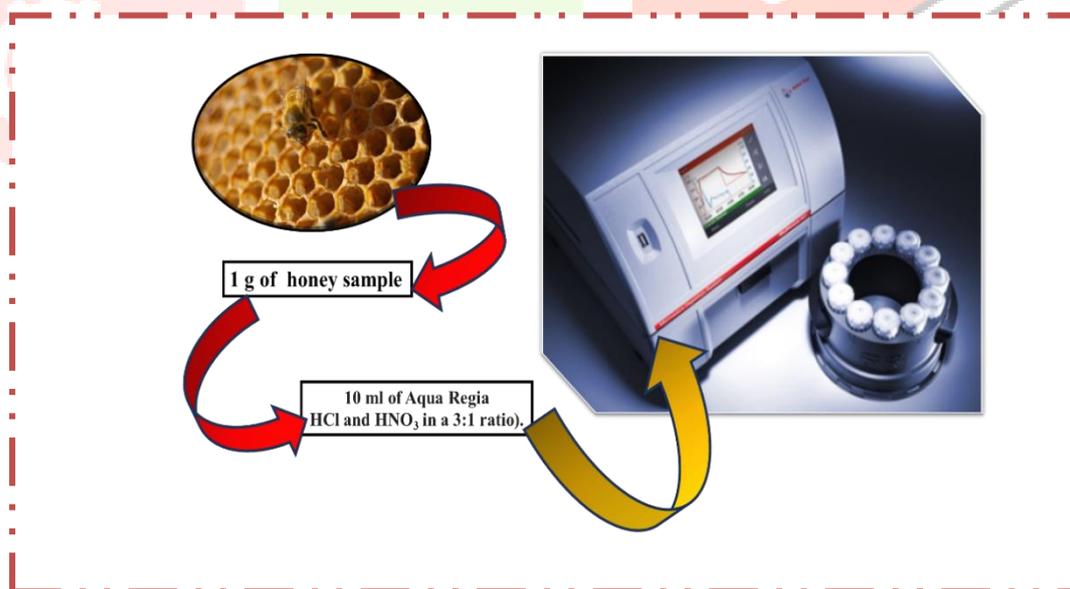


Figure 1. Flow chart showing metals extraction using microwave digestion

### 2.3. Elemental Analysis

Following the sample preparation, elemental analysis was conducted using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) with an Agilent 5110 instrument. Prior to analysis, the instrument was calibrated using a standard solution containing a mixture of major and trace metals within the range of 1 to 50 ppm (parts per million). The ICP-OES technique, known for its excellent sensitivity, high sample throughput, precision, and accuracy in multi-elemental analysis, was used to determine the heavy metals of interest in honey samples.

## 2.4. Health Risk Assessment

Risk assessment is the systematic process of evaluating the probability that a certain number of adverse health effects may occur within a specified time frame. During a health risk assessment, contaminants are analyzed to determine their potential carcinogenic or non-carcinogenic properties. Generally, risk is influenced by the following factors: (1) the concentration of a chemical present in various media (e.g., soil, water, air), food, or products; (2) the degree of an individual's exposure to the environmental pollutant; and (3) the chemical toxicity [13-17]. The human health risk for potential consumers of honey from such sources was evaluated using different parameters explained below.

### 2.4.1. Calculation of Estimated Daily Intake of Elements (EDI)

The mean daily elemental exposure for a specific body weight was determined by calculating the EDI of elements using the equation 1 –

$$EDI = \frac{C \times F_{IR}}{BW} \dots\dots\dots (1)$$

Where, C is the elemental concentration (mg/kg),  $F_{IR}$  is the honey ingestion rate quantified as the daily per capita honey consumption, expressed in kilograms per individual per day (1 g or 0.001 kg per individual per day), BW is the average body weight (70 kg for adults and 15 kg for Children) [17-20].

### 2.4.2. Non-carcinogenic Risk Assessment

The hazard quotient (HQ), a metric for assessing non-carcinogenic risk associated with exposure to toxic elements, was calculated for each element. HQ represents the ratio of the estimated daily exposure (EDI) to an element relative to its oral reference dose (RfD) [15]. The cumulative non-carcinogenic risk, or hazard index (HI), was subsequently determined using equations 2 and 3, respectively.

$$HQ = \frac{EDI}{RfD} \dots\dots\dots (2)$$

$$HI = \sum HQ_{Pb} + HQ_{Se} + HQ_{Mn} + HQ_{Cu} + HQ_{Zn} + HQ_{Cr} + HQ_{Cd} + HQ_{Ni} \dots\dots\dots (3)$$

The RfD represents the reference dose of toxic elements via oral ingestion in mg/kg/day which has been given for Pb, Se, Mn, Cu, Zn, Cr, Cd and Ni [16, 17, 19, 20] in Table 1.

**Table 1.** Table depicting oral reference dose (RfD) values of different elements

Elements	Oral Reference Dose (RfD) (mg/kg/day)
Pb	$3.5 \times 10^{-3}$
Se	$5.0 \times 10^{-3}$
Mn	$1.4 \times 10^{-1}$
Cu	$4.0 \times 10^{-2}$
Zn	$3.0 \times 10^{-1}$
Cr	$1.5 \times 10^0$
Cd	$1.0 \times 10^{-3}$
Ni	$2.0 \times 10^{-2}$

A HQ value greater than or equal to unity indicates a potential for adverse human health effects resulting from trace metal exposure via honey consumption. Conversely, a HI value less than one suggests a negligible risk of non-carcinogenic health hazards associated with trace metal ingestion through honey intake [16, 20, 21].

The total cancer risk (TCR) associated with cumulative exposure to multiple carcinogenic elements were quantified using equation 4. TCR was calculated using the oral cancer slope factor (CSF), expressed in  $(\text{mg/kg/day})^{-1}$ , as presented in Table 2. This factor represents the carcinogenic potency of a specific contaminant, defined as the increased cancer risk per unit of lifetime average dose normalized to body weight and time [15, 17, 22-24].

$$TCR = EDI \times CSF \dots\dots\dots (4)$$

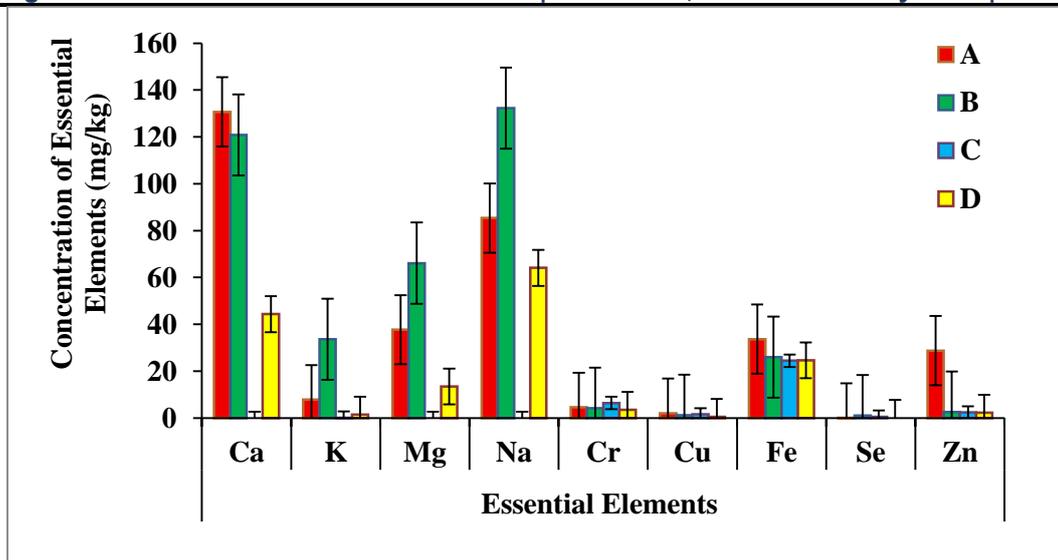
Where, EDI is the estimated daily intake of elements via oral ingestion and CSF quantifies the carcinogenic potency of a toxic element via oral ingestion, expressed as the increased cancer risk per milligram of the element per kilogram body weight per day i.e.  $(\text{mg/kg/day})^{-1}$ . CSF = 0.0085, 0.5, 0.38  $(\text{mg/kg/day})^{-1}$  for Pb, Cr and Cd [22-25]. Human exposure is considered safe if the calculated TCR is less than or equal to  $1.0 \times 10^{-4}$  [16, 17].

The cumulative cancer risk arising from exposure to multiple contaminants within a specific honey sample can be approximated by the summation of the incremental lifetime cancer risks associated with each individual metal [26, 27].

### III. Results & Discussion

#### 3.1. Elemental Analysis in Honey Samples

The aim of this study was to determine the concentrations of heavy metals in honey samples collected from Agra, Uttar Pradesh, India. The samples were analyzed for assessing the levels of metals such as aluminum (Al), barium (Ba), calcium (Ca), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn) which were further categorized into three categories. These categories depending upon the health risk factors were classified as essential elements (Ca, K, Mg, Na, Cr, Cu, Fe, Se and Zn), probably essential elements (Mn and Ni) and potentially toxic elements (Al, Ba, Pb and Cd). In the honey samples (A, B, C and D), the essential elements like Ca, K, Mg, Na, Cr, Cu, Fe, Se and Zn concentrations ranged from 44.5-130.25 mg/kg, 0.16-33.9 mg/kg, 14.0-66.7 mg/kg, 64.0-132.5 mg/kg, 3.7-6.5 mg/kg, 0.5-2.0 mg/kg, 24.2-33.7 mg/kg, 0.5-1.0 mg/kg and 2.2-29.75 mg/kg, respectively [Table S1; Figure 2]. Calcium (Ca) levels in the honey range from 44.5 to 130.25 mg/kg, indicating that honey can be a good source of calcium, which is essential for bone health and various metabolic functions. Potassium (K) with concentrations from 0.16-33.9 mg/kg is vital for heart health, muscle function, and maintaining fluid balance. Magnesium (Mg) ranging from 14.0-66.7 mg/kg is important for muscle and nerve function, as well as bone health. Sodium (Na) at 64.0-132.5 mg/kg, such levels are important for nerve function and fluid balance, although excessive sodium intake should be avoided. Chromium (Cr) ranging from 3.7-6.5 mg/kg is important for insulin function and glucose metabolism. Copper (Cu) with levels from 0.5-2.0 mg/kg is essential for iron metabolism and the formation of red blood cells. Iron (Fe) ranging from 24.2-33.7 mg/kg is crucial for oxygen transport in the blood and preventing anemia. Selenium (Se) at 0.5-1.0 mg/kg is important for antioxidant defense and thyroid function. Zinc (Zn) with concentrations from 2.2-29.75 mg/kg is essential for immune function, wound healing, and DNA synthesis. The presence of these essential & trace elements also serves as an indicator of honey quality. Honey with a rich profile of essential elements is often considered to be of higher quality and more beneficial for health. These values can help in comparing different honey samples and determining their suitability for health-conscious consumers [12, 28]. When compared to previously reported literature values, the Ca concentrations in this study are consistent with the range of 50-140 mg/kg reported in studies done in Abruzzo region (Italy) [29]. Similarly, K concentrations are slightly lower than the upper ranges of 10-40 mg/kg found in studies in area Abruzzo region (Italy) [29]. The Mg and Na levels in this study fall within the reported ranges of 10-70 mg/kg and 50-150 mg/kg, respectively. The Cr and Cu concentrations observed are slightly higher but still comparable to the ranges of 2-7 mg/kg and 0.2-2.0 mg/kg reported in the literature obtained from samples collected from Sindhi, Pakistan and Kano South Senatorial District of Kano State, Nigeria [30, 31]. The Fe, Se, and Zn concentrations in this study align closely with the ranges of 15-40 mg/kg, 0.3-1.2 mg/kg, and 3-30 mg/kg reported in studies conducted on Northern Part of Nigeria [32, 33]. These findings indicate that the elemental composition of the honey samples analyzed in this study is generally consistent with previously reported values, with some variations that could be attributed to differences in geographical origin and floral sources of the honey. Overall, the concentrations of these essential elements in the honey samples suggest that they can provide significant health benefits and nutritional value, making them a valuable addition to the diet. However, it is essential to monitor these levels to ensure they remain within safe and beneficial ranges.

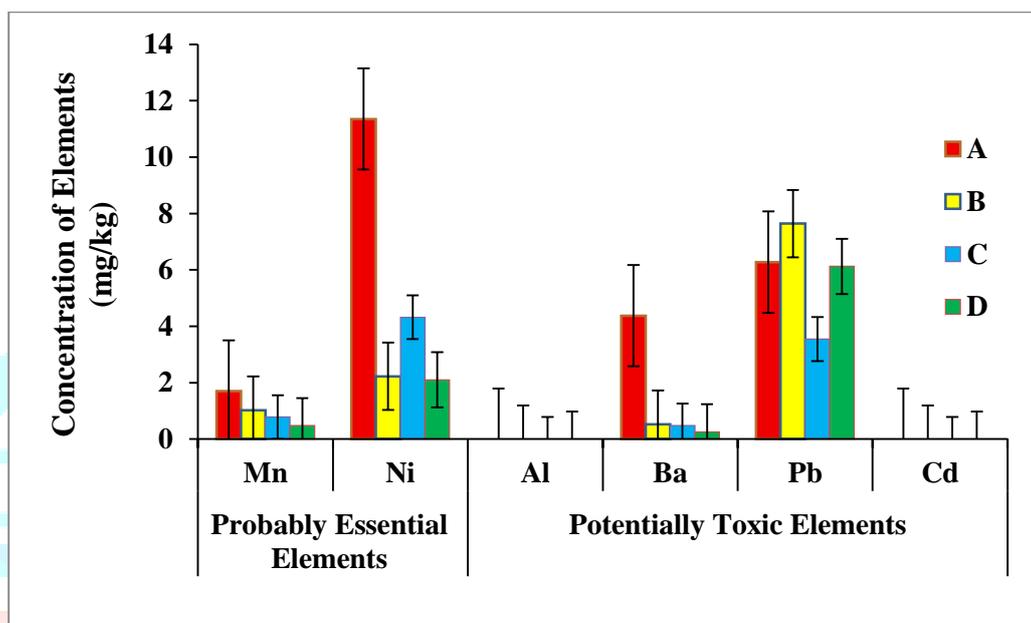


**Figure 2. Concentrations (mg/kg) of essential elements in honey samples**

The probably essential elements like Mn and Ni ranged from 0.5-1.7 mg/kg and 2.0-11.2 mg/kg in honey samples [Table S2; Figure 3]. The manganese (Mn) concentrations in this study, ranging from 0.5 to 1.7 mg/kg, are consistent with the previously reported range of 0.2 to 2.0 mg/kg [34, 35]. Similarly, the nickel (Ni) concentrations, spanning from 2.0 to 11.2 mg/kg, align with the reported values of 0.5 to 12.0 mg/kg in studies conducted in regions of Kosovo and Haryana, India [36, 37]. These results indicate that the Mn and Ni levels in the analyzed honey samples fall within the expected ranges documented in the literature, suggesting that their elemental composition is typical and comparable to previously reported values. Variations in these concentrations are likely attributable to differences in the geographical origin and botanical sources of the honey. The nutritional benefits of manganese (Mn) include its essential role as a trace element in bone formation, blood clotting, and reducing inflammation. The levels found in the honey samples indicate that honey could be a modest source of manganese, contributing to daily nutritional needs. The levels in honey are well below the upper intake levels for manganese, which is 11 mg/day for adults according to health guideline set by the Institute of Medicine (IOM) and the European Food Safety Authority (EFSA). Therefore, the amounts in honey are unlikely to pose a risk of manganese toxicity. Nickel's essential role in humans is still being studied, but it is thought to aid in iron absorption and metabolism. The concentrations of nickel (Ni) in these honey samples are relatively high; while small amounts can be beneficial, excessive intake may pose health risks. The higher end of the nickel range (11.2 mg/kg) in these honey samples is a concern because nickel can be toxic at higher levels. The tolerable upper intake level for nickel is generally around 1 mg/day for adults as established by the EFSA. Consumption of honey with high nickel content could contribute significantly to daily intake and potentially exceed safe levels, leading to adverse health effects like dermatitis, respiratory issues, or other nickel sensitivity reactions [38].

The honey samples were also found to contain some potentially toxic elements such as aluminum (Al), barium (Ba), and lead (Pb). Barium concentrations ranged from 0.5 to 4.5 mg/kg, while lead concentrations were found to be between 3.7 and 7.7 mg/kg. Cadmium (Cd) and Al was below the detection limit of the instrument [Figure 3]. When compared to previously reported literature, the Ba concentrations in this study are consistent with the range of 0.1 to 5.0 mg/kg reported by other researchers in northeast area of Portugal [39, 40]. Similarly, the Pb concentrations observed align with the reported ranges of 0.5 to 10.0 mg/kg found in studies conducted in different harvest season and varied honey samples like chilean honey [41, 42]. The absence of Cd and the low levels of Al are also in agreement with the findings of previous investigations where Cd was often undetectable and Al was found at minimal concentrations [43, 44]. These findings suggest that the elemental composition of the analyzed honey samples in terms of potentially toxic elements is generally consistent with previously reported values, indicating that the samples fall within the expected safety limits. The variations in these concentrations could be attributed to environmental factors, including pollution and soil composition in the regions where the honey was harvested. According to the Food Safety and Standards Authority of India (FSSAI) guidelines, the permissible limits for heavy metals are 1.0 mg/kg for lead (Pb) and 1.5 mg/kg for cadmium (Cd). The concentrations of lead (Pb) ranging from 3.7 to 7.7 mg/kg significantly exceed the permissible limit of 1.0 mg/kg set by the FSSAI. This poses serious health risks, including neurological damage, especially in children, and potential cardiovascular, renal, and reproductive issues in adults. While barium (Ba) concentrations ranged from 0.5 to 4.5 mg/kg, there is no specific FSSAI

limit for barium in honey. However, high levels of barium can cause gastrointestinal disturbances and muscle weakness, and in severe cases, it can affect the cardiovascular system. Although aluminum (Al) was below the detection limit, its presence in trace amounts could still contribute to cumulative exposure, which has been linked to neurotoxicity and potential connections to Alzheimer's disease. The high levels of lead far exceed the FSSAI permissible limits, indicating significant contamination. This necessitates urgent regulatory intervention to identify and mitigate sources of contamination. The absence of cadmium (Cd) is positive, as it means there is no immediate risk from this particular heavy metal, which is known for its toxicity even at low concentrations. The findings indicate a critical need for action to address the contamination of honey with toxic elements, particularly lead [38]. Regulatory bodies must enforce compliance with safety standards, and honey producers must adopt rigorous quality control measures to ensure the safety and trustworthiness of their products. Consumer health education and awareness are also vital to mitigate potential risks associated with heavy metal contamination in honey.



**Figure 3. Concentrations (mg/kg) of probably essential and potentially toxic elements in honey samples**

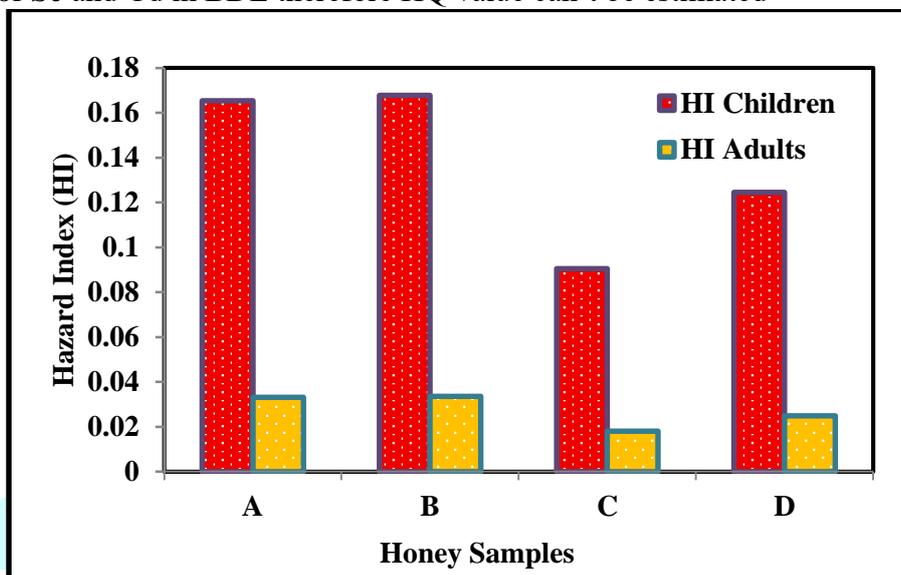
### 3.2. Health Risk Assessment

The summarized data for Estimated Daily Intake (EDI), Hazard Quotient (HQ), and non-carcinogenic health risk (Hazard Index, HI) values of toxic elements in commercially obtained and beekeeper-sourced honey samples are presented in Tables 2, 3 and S3. The analysis revealed that the EDIs for Pb, Se, Cu, Zn, Cr, Cd, Ni, and Mn (Table 2) were below the recommended dietary allowances established by regulatory agencies [45-52]. These low EDI levels suggest minimal or no potential health risks for consumers of the honey samples analyzed in this study.

**Table 2. Estimated Daily Intake (EDI) values obtained for different toxic elements in honey samples**

Samples	Estimated Daily Intake (EDI)							
	A		B		C		D	
	Children	Adults	Children	Adults	Children	Adults	Children	Adults
Elements (mg/kg)								
Pb	$4.1 \times 10^{-4}$	$8.3 \times 10^{-5}$	$5.0 \times 10^{-4}$	$1.0 \times 10^{-4}$	$2.3 \times 10^{-4}$	$4.7 \times 10^{-5}$	$4.1 \times 10^{-4}$	$8.1 \times 10^{-5}$
Se	$3.3 \times 10^{-6}$	$6.6 \times 10^{-7}$	$6.8 \times 10^{-5}$	$1.3 \times 10^{-5}$	$3.6 \times 10^{-5}$	$7.2 \times 10^{-6}$	--	--
Cu	$1.4 \times 10^{-4}$	$2.7 \times 10^{-5}$	$8.2 \times 10^{-5}$	$1.6 \times 10^{-5}$	$1.0 \times 10^{-4}$	$2.1 \times 10^{-5}$	$3.2 \times 10^{-5}$	$6.4 \times 10^{-5}$
Zn	$1.9 \times 10^{-3}$	$3.8 \times 10^{-4}$	$1.7 \times 10^{-4}$	$3.4 \times 10^{-5}$	$1.6 \times 10^{-4}$	$3.2 \times 10^{-5}$	$1.5 \times 10^{-4}$	$3.0 \times 10^{-5}$
Cr	$3.0 \times 10^{-4}$	$6.0 \times 10^{-5}$	$2.8 \times 10^{-4}$	$5.6 \times 10^{-5}$	$4.2 \times 10^{-4}$	$8.5 \times 10^{-5}$	$2.3 \times 10^{-4}$	$4.6 \times 10^{-5}$
Cd	--	--	--	--	--	--	--	--
Ni	$7.5 \times 10^{-4}$	$1.5 \times 10^{-4}$	$1.4 \times 10^{-4}$	$2.9 \times 10^{-5}$	$2.8 \times 10^{-4}$	$5.7 \times 10^{-5}$	$1.4 \times 10^{-4}$	$2.8 \times 10^{-5}$
Mn	$1.1 \times 10^{-4}$	$2.2 \times 10^{-5}$	$6.8 \times 10^{-5}$	$1.3 \times 10^{-5}$	$5.2 \times 10^{-5}$	$1.0 \times 10^{-5}$	$3.1 \times 10^{-5}$	$6.3 \times 10^{-5}$

In all samples, Hazard Quotient (HQ) and Hazard Index (HI) values for toxic elements were higher in children than adults, reflecting their greater susceptibility due to lower body weight and less efficient metabolic pathways. No health risks from cadmium (Cd) were detected in either commercial or beekeeper-sourced honey. All HQ values remained below 1, indicating no significant risk to consumers, consistent with reports from other countries. Similarly, HI values for both children and adults were below 1, confirming the absence of adverse health effects from the studied elements. These findings agree with studies from Ghana and Iran, which also reported HI values under the EPA safety threshold [16]. Concentrations of Se and Cd in BDL therefore HQ value can't be estimated



**Figure 4. Hazard Index (HI) values obtained for different honey samples**

Table 2 presents the Total Carcinogenic Risk (TCR) for lead (Pb) and chromium (Cr) in the honey samples. The New York State Department of Health Center for Environmental Health [55, 56] categorizes TCR as follows: a  $TCR \leq 1.0 \times 10^{-6}$  is considered low;  $1.0 \times 10^{-4}$  to  $1.0 \times 10^{-3}$  is moderate;  $1.0 \times 10^{-3}$  to  $1.0 \times 10^{-1}$  is high; and  $\geq 1.0 \times 10^{-1}$  is very high. Carcinogenic risk estimates the probability that an individual will develop cancer over a 55-year lifespan. Risk values greater than  $1.0 \times 10^{-4}$  are deemed intolerable, those smaller than  $1.0 \times 10^{-6}$  pose no adverse health effects, and risks between  $1.0 \times 10^{-4}$  and  $1.0 \times 10^{-6}$  are generally considered within the safe range [57, 58]. As shown in Table 5, the TCR values for Pb in all honey samples, for both children and adults, were below the maximum safe threshold ( $TCR < 1.0 \times 10^{-4}$ ) established by the EPA [16], indicating no potential risk of Pb-induced carcinogenicity over a lifetime. Similar findings have been reported for honey from other countries [19, 20]. Pb is a toxic heavy metal, and dietary exposure poses significant health risks, including the development of renal cell carcinoma (kidney cancer) and malignant tumors in the brain, larynx, and bladder tissues. Although the carcinogenic mechanisms of dietary Pb ingestion are not fully understood, they likely involve disruption of cellular tumor regulation genes and impairment of the DNA repair system, leading to DNA damage [26].

Specifically, the TCR values for Cr ranged from  $2.26 \times 10^{-4}$  to  $1.1 \times 10^{-4}$  for children and from  $3.04 \times 10^{-5}$  to  $2.33 \times 10^{-5}$  for adults placing them within the moderate risk range. Cr exists in different oxidation states, with Cr (III) occurring naturally in various foods and dietary supplements [59]. Studies indicate that Cr (III) compounds exhibit low oral toxicity due to poor absorption, and although they can interact with DNA in cellular systems, limited cellular access restricts or prevents genotoxicity [59, 60].

The cumulative  $\Sigma TCR$  values for Pb and Cr ranged from  $1.5 \times 10^{-4}$  to  $1.2 \times 10^{-4}$  for children and from  $3.1 \times 10^{-5}$  to  $2.4 \times 10^{-5}$  for adults, placing them within the moderate risk range.

#### IV. Conclusions

Studies on honey from Agra, Uttar Pradesh, reveal key insights into environmental contamination and food safety. Honey samples contained essential elements (Ca, K, Mg, Na, Cr, Cu, Fe, Se, Zn) in nutritionally beneficial ranges, indicating their dietary value. Probably essential elements like Mn were present at safe levels, while elevated Ni suggested potential health concerns. Toxic elements (Al, Ba, Pb) were also detected, with Pb concentrations (3.7–7.7 mg/kg) exceeding the FSSAI limit of 1 mg/kg, posing risks of neurological, cardiovascular, and developmental effects.

Despite this, health risk assessments showed that Estimated Daily Intake (EDI) values for metals such as Pb, Se, Cu, Zn, Cr, Cd, Ni, and Mn remained below recommended dietary allowances. Hazard Quotient (HQ) and Hazard Index (HI) values were higher for children but remained below 1 for all groups, indicating no significant non-carcinogenic risks. Target Carcinogenic Risk (TCR) values for Pb were below concern levels, while Cr fell within a moderate risk range but is mitigated by low toxicity and limited absorption.

Overall, the honey samples did not pose significant carcinogenic or non-carcinogenic health risks. The findings highlight the need for continuous environmental monitoring, stricter regulatory enforcement, sustainable agricultural practices, and increased consumer awareness to safeguard honey quality and protect public health in Agra.

#### V. Acknowledgments

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#### VII. Authors Contribution

**Gunjan Goswami**- Data Acquisition, Formal Analysis, Methodology, Data Interpretation, Writing Original Draft

**Priya Kumari**- Conception, Data Acquisition

**Anita Lakhani**-Supervision, Validation, Funding, Writing-Reviewing

#### VIII. Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

#### IX. Declaration

Declaration is not applicable.

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