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Occurrence and Health Risk Assessment of Heavy Metals in Lychee (*Litchi chinensis* Sonn., Sapindaceae) Fruit Samples

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Abstract: This study aimed to assess the occurrence of eight heavy metals in lychee (*Litchi chinensis* Sonn.) fruit samples collected from orchards of the Dehradun and Haridwar districts in Uttarakhand, India. Lychee fruit samples were collected from ten (10) sampling locations from May to June 2023 and analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES). Results showed that lychee fruit samples showed varying levels of selected heavy metals, i.e., Cd (0.009–0.095 mg/kg), Cr (0.079–0.960 mg/kg), Cu (0.095–0.258 mg/kg), Fe (0.254–0.531 mg/kg), Pb (0.000–0.011 mg/kg), Mn (0.862–1.903 mg/kg), Ni (0.166–0.310 mg/kg), and Zn (0.076–0.149 mg/kg). It was observed that lychee fruit sampling sites near urban and industrial areas had higher concentrations of heavy metals as compared to those in rural and agricultural areas. In addition, principal component analysis (PCA) and clustered heatmap dendrogram results showed that several sites had significant similarities in terms of heavy metal availability. Overall, the levels of all heavy metals were below the safe limits as suggested by health risk studies. The selected indices such as daily intake of metals (DIM), health risk index (HRI), and target hazard quotient (THQ) did not exceed the standard limit which indicated consumption of lychee fruit was safe at all sampling sites. The results of this study emphasize the need to regularly monitor lychee heavy metal levels and implement sustainable agricultural and environmental practices to reduce contamination sources.

Keywords: fruits; heavy metals; industrial pollution; safety assessment; toxic elements; urban areas

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1. Introduction

Lychee (*Litchi chinensis* Sonn.) is a fruit rich in carbohydrates and vitamins; it is highly marketable owing to its sweetness and good medicinal properties. Lychee fruit originates from southwestern China and northern Vietnam and its global production amounted to 3.5 million tons in 2018, of which 80% was produced by China alone [1]. As of 2023, the newest reports depicted lychee's global market value at USD 6.73 billion and is forecasted to reach USD 8.79 billion (on an annual 5% CAGR) [2]. India ranks as the third world's biggest lychee producer after China and Vietnam. By 2019, Indian lychee production reached 0.72 million tons with a 29.0% increase compared to 2016 [3]. However, small amounts are being exported (147–150 tons in 2018) due to high local lychee consumption [1,4]. Moreover, less than 0.5% of Indian lychee production is used for processing, while the remaining amounts are consumed fresh. On the other hand, this sector faces serious limitations in the Indian subcontinent, i.e., high transport costs, bare use of advanced production technologies, gaps in supply chain integration, and lack of infrastructure for efficient marketing [4].

Lychee is an exceptional source of nutrients such as minerals, polysaccharides, polyphenols, and vitamins that mainly reside in the fruit's pulp [5]. In addition, sugars and reducing sugars account for 10–19.2 and 70% of lychee pulp composition, respectively [6]. Fructose, glucose, and sucrose are the main sugars found in lychee pulp, with approximately equal amounts of fructose and sucrose [7]. Phenolic compounds, especially anthocyanins, are also found in lychee fruit. These compounds are responsible for the fruit's red color at the pre-harvest stage, and for its enzymatic browning phenomenon after harvest [8]. Therefore, the high phenolic compounds found in lychee are considered the main reason behind its very short shelf-life during the postharvest stage, which makes exports extremely harsh. Lychee fruit also contains potential organic acids such as malic acid, which has the highest proportion (80%), followed by ascorbic, tartaric, and citric acids. As reported by Zhao et al. [9], ascorbic acid in lychee fruits is relative to the cultivar/species grown; it ranges between 21 and 36 mg/100 g fresh weight (FW). Other minerals are found in various concentrations, i.e., calcium (3.8–4.9 mg/100 g FW), magnesium (10.3–16.2 mg/100 g FW), potassium (140.2–180.0 mg/100 g FW), phosphorus (25.4–35.0 mg/100 g FW), and sodium (3.2–7.9 mg/100 g FW) [10,11]. Numerous medicinal properties of lychee were largely investigated. It was found that lychee pericarp, pulp, and seeds had a potential contribution to hemostasis, hepatoprotection, and treatment of bladder and prostate cancers, respectively [12–14]. Other anti-obesity and antioxidant effects were attributed to lychee fruit consumption [15,16]. However, over-consumption of lychee can lead to encephalitis among children besides anaphylactic reactions and inflammations mainly related to allergenic and proinflammatory proteins [17,18].

The mass use of soil fertilizers and the application of pesticides on lychee fruits lead to the bioaccumulation of numerous potentially toxic elements (heavy metals). As per FAO/WHO, these elements should not exceed some standard safe limits, i.e., 60 µg (cadmium; Cd), 35 µg (chromium; Cr), 3 mg (copper; Cu), 14 mg (iron; Fe), 3 mg (manganese; Mn), 214 µg (lead; Pb), and 60 mg (zinc; Zn) [19]. However, several studies have shown that the use of advanced nanotechnological approaches could mitigate the risk of heavy metal accumulation in crops [20–22]. A previous study on South African lychee fruit composition revealed the following decreasing order of heavy metals: Zn (0.42 mg/100 g FW) > Fe (0.31 mg/100 g FW) > Cu (0.17 mg/100 g FW) > Mn (0.05 mg/100 g FW) > Co (cobalt; 0.01 mg/100 g FW) > Ni (nickel; 0.002 mg/100 g FW) > Cr (0.0003 mg/100 g FW) [23]. Earlier, the analysis of lychee fruits belonging to several Hawaii (Bosworth-3, Groff, and Kaimana) and South African (Mauritius and McLean's Red) cultivars revealed a different heavy metal bioaccumulation trend: Fe (0.21–0.43 mg/100 g FW) > Zn (0.16–0.28 mg/100 g FW) > Cu (0.17–0.23 mg/100 g FW) > Mn (0.07–0.33 mg/100 g FW) [10,11]. Whereas the analysis of lychee juice from Pakistan revealed higher Cr (1.51 mg/kg) than Cu (0.14 mg/kg) contents [24]. In all cases, proper biomonitoring of heavy metal accumulation in lychee fruits and juices is still lacking and is currently being urged.

For safe human consumption of fruits and vegetables, health risk assessments are of high interest, demand, and value. Our research team has recently assessed the spatial distribution of heavy metals in some vegetables and fruits produced in India [25,26]; we found that all analyzed samples were safe for human consumption according to international and local standards. Therefore, the current study aimed to determine the heavy metals bioaccumulation in lychee fruits collected from Uttarakhand orchards and evaluate the associated health risks.

2. Materials and Methods

2.1. Description of Study Area

This research was conducted in two western districts, namely Dehradun (30°19′ N to 78°04′ E) and Haridwar (29°58′ N to 78°10′ E), of Uttarakhand state of India. Figure 1 shows the map of the Dehradun and Haridwar districts along with different sampling sites. Both these districts have plainlands as compared to other districts, which are mostly occupied by high mountains of Indian Himalaya making them unsuitable for lychee cultivation. The agro-climatic conditions of these districts support the cultivation of lychee fruit, which is largely consumed within the state and exported to other states. The selected research areas have well-drained load soils that support the efficient growth of lychee trees. The average annual rainfall of the Dehradun and Haridwar districts are 2065.7 and 1054 mm, respectively. The cultivated orchard land of Dehradun and Haridwar districts are 3700 and 1500 ha in size, producing 8400 and 3900 tons of lychee fruit, respectively [27,28]. These statistics make lychee one of the major horticulture crops for the state's agriculture and economy.

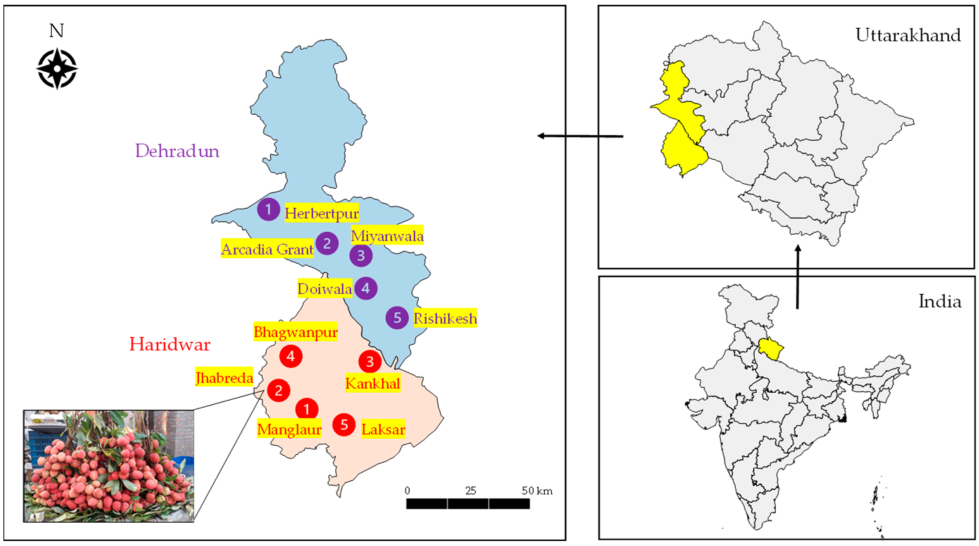

Figure 1. Map of the study area depicting locations of lychee (*L. chinensis*) orchards in the Dehradun and Haridwar districts of Uttarakhand, India.

2.2. Sample Collection and Processing

For this study, lychee fruit samples were collected from a total of ten (10) orchards, i.e., five (5) orchards from each district from May to June 2023. The names and geocoordinates of sampling locations are listed in Table 1. The altitude of selected orchards varied between 277.13 and 632.10 m. A random sampling approach was adopted to collect fruit samples from identified orchards by dividing each orchard into equal sections in order to minimize sampling bias. Fruit samples were manually picked from the tree branches, washed in distilled water, and then dried using blotting paper. Fruits were collected from both the inner and outer canopies of trees. Purposely, a total of five (5) samples were collected from each orchard in zip-locking plastic bags of 500 g capacity. After transporting them to the laboratory, the fruit was peeled to remove pulp and seed parts. Since pulp is the only edible part of lychee fruit, it was used for heavy metal analysis. The separated pulp sample was oven-dried at 60 °C until a constant weight was obtained and then converted into a fine powder using a mixer grinder. The fine powder of pulp was finally used for heavy metal analysis.

Table 1. List of orchard locations used for lychee (*L. chinensis*) fruit sample collection in Uttarakhand state, India.

District	Sampling Site	Code	Latitude (N)	Longitude (E)	Altitude (m)
Dehradun	Herbertpur (Agricultural)	D1	30°43′89.61″	77°74′00.04″	467.02
	Arcadia Grant (Rural)	D2	30°31′17.51″	77°95′84.25″	612.76
	Miyanwala (Urban)	D3	30°26′86.54″	78°08′19.24″	632.10
	Doiwala (Urban)	D4	30°17′00.00″	78°12′42.03″	497.70
	Rishikesh (Urban)	D5	30°06′37.63″	78°22′90.47″	358.87
Haridwar	Manglaur (Agricultural)	H1	29°79′53.67″	77°87′71.62″	277.23
	Jhabreda (Industrial)	H2	29°81′86.68″	77°77′23.18″	277.13
	Kankhal (Urban)	H3	29°92′75.77″	78°13′62.20″	302.67
	Bhagwanpur (Urban)	H4	29°93′69.14″	77°80′28.17″	297.27
	Laksar (Rural)	H5	29°75′01.20″	78°01′24.39″	259.11

2.3. Analytical Methods

Heavy metal contents of collected lychee fruit samples were analyzed using an inductively coupled plasma optical emission spectroscopy (ICP-OES, 7300 DV, Perkin Elmer, MA, USA). ICP-OES is a powerful analytical technique widely used to quantify heavy metal concentrations in various samples [29]. For this, 2 g of dried and powdered lychee pulp sample was mixed with 10 mL of digesting solution comprising 15 mL HNO_3 and 5 mL $HClO_4$ (70%; Sigma-Aldrich Chemicals Private Limited, Bangalore, India). This mixture was left overnight (12 h) for self-digestion and then digested at a temperature of 150 °C on a hot plate for 1 h to ensure complete dissolution of heavy metals. After cooling the mixture, the final volume was adjusted to 50 mL by the addition of 3% HNO_3 and then filtered through the Whatman filter paper number 41. ICP-OES instrument was pre-calibrated using a series of standardized and certified heavy metal solutions and specific analytical conditions were maintained as per the manufacturer's instructions and protocols. Several parameters such as plasma power, flow rates, and heavy metal wavelengths were optimized for maximum sensitivity and resolution [30]. Quality control (QC) measures were adopted to ensure the accuracy, precision, and traceability of heavy metal analysis results. ICP-OES was calibrated with standard heavy metal solutions (0–15 ppm) according to the dynamic range and verified using certified reference materials (CRM; Sigma-Aldrich Chemicals Private Limited, Bangalore, India) of analytical grade. Replicated analysis (n = 3) was performed to minimize bias and analytical errors. The spike recovery tests were performed and accepted in a range of 95.10–103.74%. The limits of detection for Cd, Cr, Cu, Fe, Pb, Mn, Ni, and Zn elements were 0.05, 2.00, 0.90, 0.70, 0.01, 0.02, 3.00, and 0.60 µg/L (ppb), respectively.

2.4. Data Analysis and Health Risk Assessment

In the present investigation, selected indices such as dietary intake of metals (DIM), health risk index (HRI), and target hazard quotient (THQ) were used in order to understand the non-carcinogenic risk associated with the consumption of heavy-metal-contaminated lychee fruit samples of selected orchards. DIM helps in determining the daily exposure level to heavy metals consumed by a particular population [31]. For this, DIM was calculated based on the formula given in Equation (1):

$$\mathrm{DIM} = (\mathrm{IR} \times \mathrm{C_{HM}} \times \mathrm{C_F})/\mathrm{B_W} \tag{1}$$

where, IR, CHM, CF, and BW refer to lychee fruit ingestion rate (0.265 kg per person per day), concentration of heavy metal in fruit sample (mg/kg dwt.), conversion factor (0.085), and body weight of consumer (70 kg), respectively [31]. Moreover, HRI is calculated by dividing the DIM of each individual heavy metal by the reference dose value (RfD). As per USEPA [32], standard RfD values for Cd, Cr, Cu, Fe, Pb, Mn, Ni, and Zn are 0.001, 1.500, 0.040, 0.007, 0.003, 0.033, 0.020, and 0.300 mg/kg/day, respectively. Normally, an HRI value of <1 indicates no health risk while >1 indicates health concerns. HRI was calculated by using Equation (2):

$$HRI = DIM/RfD \quad (2)$$

Moreover, THQ provides an overall health risk considering the cumulative exposure to multiple heavy metals [33]. THQ was calculated based on the models given in Equations (3) and (4):

$$THQ = [(EF \times E_D \times I_R \times C_{HM})/RfD \times B_W \times A_T)] \times 0.001 \quad (3)$$

$$\sum THQ = THQ_{Cd+Cr+Cu+Fe+Pb+Mn+Ni+Zn} \quad (4)$$

where, EF, ED, and AT refer to exposure frequency (365 days/year), exposure duration (70 years), and average exposure time (21,600 days), respectively. Herein, 0.001 is a conversion factor. On the other hand, principal component analysis (PCA) and hierarchical clustered heatmap analysis tools were used to understand the influence of sampling locations on heavy metal occurrence in lychee fruit samples [25]. The data obtained in this study were analyzed using Excel 365 (Microsoft Corp., Redmond, WA, USA) and OriginPro (version 2023a, OriginLab Corp., Northampton, MA, USA) software packages.

3. Results and Discussion

3.1. Concentration of Heavy Metals in Lychee (L. chinensis) Fruit Samples

The results of heavy metal concentrations in lychee fruit collected from different orchards of Uttarakhand state, India are reported in Table 2. Cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), and zinc (Zn) concentrations in lychee fruits collected were in the following respective ranges: 0.009–0.095, 0.079–0.960, 0.095–0.258, 0.254–0.531, <BLoD–0.011, 0.862–1.903, 0.166–0.310, and 0.076–0.149 mg/kg dwt. Such ranges denote the bioaccumulation of heavy metals within studied fruits in the following decreasing order: Mn > Cr > Fe > Ni > Cu > Zn > Cd > Pb. In this regard, Saha and Zaman [34] revealed that heavy metals bioaccumulated in lychee fruits collected from Rajshahi City, Bangladesh as follows: Cd > Mn > Pb > Cr. Moreover, all heavy metals detected in these fruits had higher average concentrations than observed in the present investigation (Cd: 2.143 > 0.041 mg/kg dwt, Mn: 2.467 > 1.244 mg/kg dwt, Pb: 1.204 > 0.004 mg/kg dwt, and Cr: 0.521 > 0.406 mg/kg dwt). Sajib et al. [35] revealed the following decreasing order of potentially toxic element concentrations bioaccumulated in lychee fruit collected from Dhaka city, Bangladesh: Fe > Cu > Zn > Mn, where the average Fe and Cu concentrations were similar to this study (0.39 = 0.383 mg/kg dwt) while Cu, Zn, and Mn concentrations were below those detected herein (0.10 < 0.172, 0.09 < 0.104, and 0.05 < 1.244 mg/kg dwt., respectively). Motalab et al. [36] found a similar heavy metal trend in lychee fruit as Sajib et al. [35], mostly because samples were collected from the same local markets of Dhaka city. However, it was observed that average Fe and Zn concentrations (0.45 and 0.11 mg/kg dwt, respectively) in collected samples were higher than denoted in the present investigation (0.383 and 0.104 mg/kg dwt, respectively). Contrarily, Cu and Mn concentrations showed the opposite scenario (0.16 < 0.172 and 0.07 < 1.244 mg/kg dwt, respectively).

Despite this, all lychee fruit samples collected from different sampling locations in Uttarakhand state had heavy metal concentrations below the safe limits set by USEPA [32] (0.10, 2.30, 40.0, 425.0, 0.20, 30.0, 1.50, and 50.0 mg/kg dwt for Cd, Cr, Cu, Fe, Pb, Mn, Ni, and Zn, respectively). H2 (Jhabreda) samples showed the highest Cd and Cr concentrations among studied samples, while H3 (Kankhal) samples revealed the highest Cu, Fe, Pb, Mn, Ni, and Zn concentrations. Jhabreda is mostly known as an industrial hotspot where many industrial activities occur around the year. Waste disposed of by industries into the environment can increase the transport of potentially toxic elements via water sources [37]. On the other hand, Kankhal is famous for its old temples (Chandi Devi, Mansa Devi, and Daksheswara Mahadev temples); temples generally generate huge loads of tourist and urban wastes, thus leading to infiltration into groundwater reservoirs [38]. Our findings showed that all studied locations were not polluted by natural phenomena or human activities and that lychee production within these regions is, for now, relatively safe. However, more focus should be given to the main sources of pollution by local and governmental authorities to avoid any future risks. Furthermore, the observation of the Kurtosis test results revealed both positive and negative values (−1.94 to 0.35); this depicts random symmetric distribution throughout the sampling locations. Contrarily, the results of the Skewness test depicted only positive values (0.02–1.05), and thereby a slight asymmetry exists.

Table 2. Average concentration (mg/kg dwt.) of heavy metals in lychee (*L. chinensis*) fruit samples collected from Uttarakhand state, India.

Sampling Site	Heavy Metals							
	Cd	**Cr**	**Cu**	**Fe**	**Pb**	**Mn**	**Ni**	**Zn**
D1	0.047	0.093	0.103	0.371	0.003	1.042	0.166	0.110
D2	0.026	0.081	0.178	0.406	0.004	0.970	0.172	0.098
D3	0.092	0.120	0.232	0.497	0.009	1.716	0.297	0.135
D4	0.009	0.079	0.190	0.285	0.005	1.136	0.204	0.107
D5	0.042	0.951	0.095	0.316	0.002	0.862	0.239	0.081
H1	0.014	0.103	0.148	0.254	0.005	0.989	0.191	0.076
H2	0.095	0.960	0.182	0.420	BLoD	1.150	0.184	0.083
H3	0.050	0.135	0.258	0.531	0.011	1.903	0.310	0.149
H4	0.011	0.840	0.201	0.331	0.001	1.410	0.258	0.090
H5	0.027	0.693	0.135	0.415	0.004	1.257	0.212	0.115
Average ± SD	0.041 ± 0.031	0.406 ± 0.399	0.172 ± 0.053	0.383 ± 0.089	0.004 ± 0.003	1.244 ± 0.339	0.223 ± 0.051	0.104 ± 0.024
Median	0.035	0.128	0.180	0.389	0.004	1.143	0.208	0.103
Range	0.009–0.095	0.079–0.960	0.095–0.258	0.254–0.531	BLoD–0.011	0.862–1.903	0.166–0.310	0.076–0.149
Kurtosis	−0.26	−1.94	−0.68	−0.70	0.35	0.18	−0.83	−0.28
Skewness	0.91	0.59	0.02	0.27	0.86	1.05	0.70	0.71
Safe Limit *	0.10	2.30	40.00	425.00	0.20	30.00	1.50	50.00

Values are presented as the mean of five replicates; * Sinha et al. [39] and USEPA [32,40]; BLoD: below the limit of detection.

3.2. PCA and HCA Results of Heavy Metals in Lychee (L. chinensis) Fruit Samples

Multivariate statistical analyses are helpful to understand complex data sets in a generalized manner [41]. Out of these, PCA helps in understanding the patterns in high-dimensional data. In the present investigation, PCA was applied to study concentrations of heavy metals in lychee fruit collected from different locations in Uttarakhand, India. The graphical representation of the relationship between heavy metal concentrations and sampling locations in a reduced dimensional space is depicted in Figure 2a. In this, points indicate the sampling locations while vectors refer to individual heavy metals where the length and direction of the vector correspond to high or low concentrations based on score loading values. PCA explained that the first two principal components (PC1 and PC2) showed variances of 60.12 and 37.93% with varying score loading values, as given in Table 3. Herein, PC1 encompasses a major source of variance while PC2 captures additional patterns. For instance, lychee fruit samples collected from several sites can be clustered together where heavy metal concentrations were mostly identical. Additionally, some heavy metals showed strong correlations at multiple sites, suggesting they share similar sources of pollution or have common geochemical structures. More specifically, D3 and H3 sites showed the highest dominance for Mn while H2, H4, and H5 for Cr. Other sites showed relatively different trends, i.e., clustered to specific biplot regions with negative score loading values. On the other hand, a clustered heatmap dendrogram is another visualization tool that helps reveal similarities between sampling sites [42]. The heatmap given in Figure 2b shows that several sites formed similar clusters which are indicated by color magnitude. Lychee fruit samples with similar heavy metal profiles at different sites are clustered on a dendrogram, revealing that H3-D3, H4-D5, H1-D4, and D1-D2 formed the most identical groups. However, H2 and H5 did not fit well within any specific cluster, which indicates high variability in lychee cultivation land and environmental condition. For the magnitude of heavy metals, Mn-Ni and Pb-Zn formed the most identical clusters. Such a high similarity between multiple sites might be due to specific geochemical and environmental conditions of the corresponding regions.

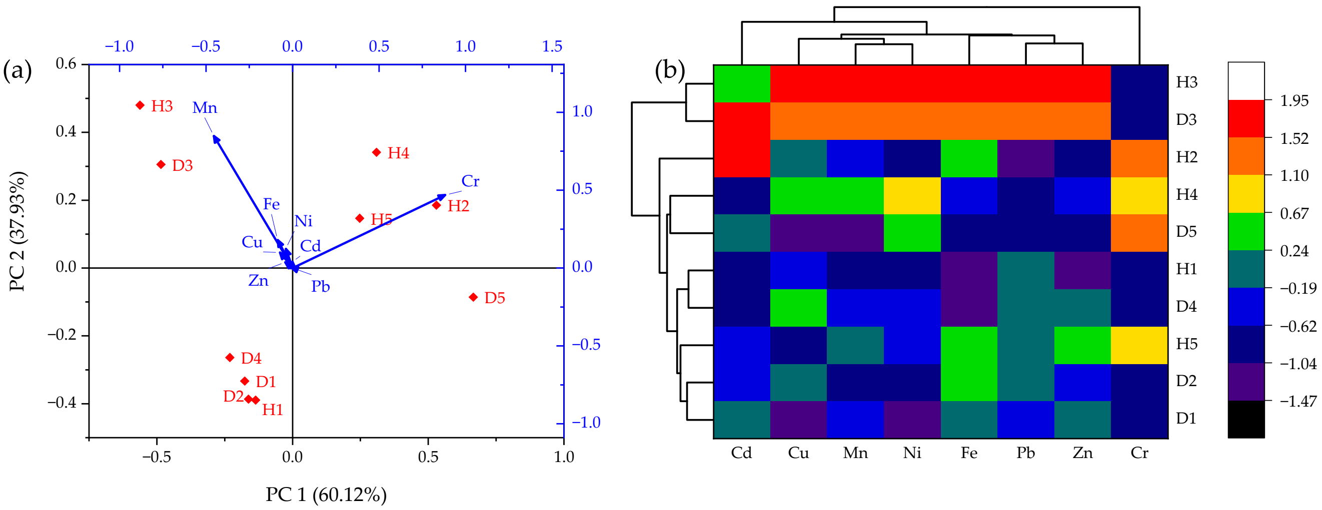

Figure 2. (**a**) PCA biplot and (**b**) clustered heatmap-dendrogram of heavy metals in lychee (*L. chinensis*) fruit samples collected from Uttarakhand state, India.

Table 3. Principal component (score loading) matrix of heavy metals in lychee (*L. chinensis*) fruit samples collected from Uttarakhand state, India.

Score Label		**Principal Component**	
		PC1	**PC2**
Eigenvalues		0.17	0.10
Variance (%)		60.12	37.93
Sampling Sites	D1	−0.18	−0.33
	D2	−0.16	−0.39
	D3	−0.48	0.31
	D4	−0.23	−0.26
	D5	0.67	−0.09
	H1	−0.14	−0.39
	H2	0.53	0.19
	H3	−0.56	0.48
	H4	0.31	0.34
	H5	0.25	0.15
Heavy Metals	Cd	−0.01	0.04
	Cr	0.88	0.47
	Cu	−0.07	0.10
	Fe	−0.09	0.18
	Pb	−0.01	0.00
	Mn	−0.45	0.85
	Ni	−0.04	0.12
	Zn	−0.04	0.04

Previous studies have shown that PCA and HCA are useful tools for analyzing complex datasets. Out of them, Gupta et al. [43] studied the occurrence of six heavy metals in selected fruits and vegetables in Durban, South Africa. They found that PCA and HCA tools were helpful in identifying major clusters of the highest heavy metal pollution sampling location. Similarly, Kumar et al. [44] studied the occurrence of five heavy metals (As, Cd, Cr, Hg, and Pb) in selected vegetable crops in urban and peri-urban areas of Delhi, India. Based on PCA, their findings revealed that urban areas had significantly higher heavy metal pollution than those in peri-urban areas. These studies suggest that heavy metal pollution in fruits and vegetables might be higher if sampling locations are affected by urban or industrial activities which supports the results obtained in the current study.

3.3. DIM, HRI, and THQ Results of Heavy Metals in Lychee (L. chinensis) Fruit Samples

The results of DIM and HRI studies given in Tables 4 and 5 showed that lychee fruit samples collected from Uttarakhand state showed no significant health concern related to their dietary consumption. Specifically, the average DIM values for selected heavy metals such as Cd, Cr, Cu, Fe, Pb, Mn, Ni, and Zn were recorded as 0.000015, 0.000147, 0.000062, 0.000139, 0.000002, 0.000451, 0.000081, and 0.000038 mg/kg/day, respectively. This suggests that the estimated amount of heavy metals consumed by individuals (RfD) is lower than daily acceptable limits [32]. These levels are helpful for protecting consumers against possible hazardous exposure to heavy metals. On the other hand, the calculated HRI values of selected heavy metals were found to be below 1, which indicates no significant health effects by the consumption of lychee fruits collected from all sampling locations of Uttarakhand, India. In particular, the HRI values of Cd, Cr, Cu, Fe, Pb, Mn, Ni, and Zn were recorded were 0.014978, 0.000098, 0.001561, 0.019822, 0.000532, 0.013666, 0.004049, and 0.000126, respectively. Since all values were below 1, it suggests that the exposure level did not exceed the safe limit in any sample and was thereby less likely to cause any adverse health impact.

Similarly, THQ is another important parameter that is used to estimate the cumulative health impact of heavy metals in foods and vegetables [45,46]. Herein, if the THQ value exceeds 1 when summed up together, the risk level is considered significant. However, THQ values of heavy metals in lychee fruit collected in this study did not exceed the safe limit of 1, as shown in Figure 3. The THQ values of heavy metals vary significantly with changes in sampling locations. However, the individual values of HRI and THQ were extremely low. The highest THQ values were recorded for Cd, Pb, and Ni, while the lowest was for Mn and Fe. Overall, the cumulative THQ of heavy metals was found to be highest at the D3 site, which is in line with results of heavy metal concentrations. However, the lowest THQ values were reported at the H1 site, identifying it as the least polluted site. Similar findings were reported by Gupta et al. [43] for THQ analysis of heavy metals in 33 fruit species samples collected from Durban City, South Africa. The results showed that cumulative THQ values of heavy metals exceed the safe limit of 1 in several fruit samples (banana, pineapple, guava, green grape, yellow orange, and kiwi fruit) which were collected from the polluted areas. However, the child group showed more susceptibility to heavy metal pollution in fruits than the adult group. Likewise, Chandorkar and Deota [47] reported that fruits and vegetable samples collected from Vadodara, Gujrat, India showed significant health risks associated with intake of Cd, Pb, and As heavy metals. The levels of heavy metals may also be induced by the source of irrigation supplies [48], which later could affect the HRI and THQ values. Therefore, urban and industrial activities at some sites taken in this study might be responsible for higher DIM, HRI, and THQ values.

Table 4. Results of DIM (mg/kg/day) for heavy metals in lychee (*L. chinensis*) fruit samples collected from Uttarakhand state, India.

Sampling Site	Heavy Metals							
	Cd	Cr	Cu	Fe	Pb	Mn	Ni	Zn
D1	0.000017	0.000034	0.000037	0.000135	0.000001	0.000378	0.000060	0.000040
D2	0.000009	0.000029	0.000065	0.000147	0.000001	0.000352	0.000062	0.000036
D3	0.000033	0.000044	0.000084	0.000180	0.000003	0.000622	0.000108	0.000049

Table 4. *Cont.*

Sampling Site	Heavy Metals							
	Cd	Cr	Cu	Fe	Pb	Mn	Ni	Zn
D4	0.000003	0.000029	0.000069	0.000103	0.000002	0.000412	0.000074	0.000039
D5	0.000015	0.000345	0.000034	0.000115	0.000001	0.000313	0.000087	0.000029
H1	0.000005	0.000037	0.000054	0.000092	0.000002	0.000359	0.000069	0.000028
H2	0.000034	0.000348	0.000066	0.000152	0.000001	0.000417	0.000067	0.000030
H3	0.000018	0.000049	0.000094	0.000193	0.000004	0.000690	0.000112	0.000054
H4	0.000004	0.000305	0.000073	0.000120	0.000001	0.000511	0.000094	0.000033
H5	0.000010	0.000251	0.000049	0.000151	0.000001	0.000456	0.000077	0.000042
Average	0.000015	0.000147	0.000062	0.000139	0.000002	0.000451	0.000081	0.000038

Values are presented as the mean of five replicates.

Table 5. Results of HRI for heavy metals in lychee (*L. chinensis*) fruit samples collected from Uttarakhand state, India.

Sampling Site	Heavy Metals							
	Cd	Cr	Cu	Fe	Pb	Mn	Ni	Zn
D1	0.017045	0.000022	0.000934	0.019221	0.000363	0.011451	0.003010	0.000133
D2	0.009429	0.000020	0.001614	0.021035	0.000484	0.010660	0.003119	0.000118
D3	0.033365	0.000029	0.002103	0.025749	0.001088	0.018859	0.005386	0.000163
D4	0.003264	0.000019	0.001723	0.014766	0.000604	0.012485	0.003699	0.000129
D5	0.015232	0.000230	0.000861	0.016372	0.000242	0.009473	0.004334	0.000098
H1	0.005077	0.000025	0.001342	0.013160	0.000604	0.010869	0.003463	0.000092
H2	0.034453	0.000232	0.001650	0.021760	0.000009	0.012638	0.003337	0.000100
H3	0.018133	0.000033	0.002339	0.027511	0.001330	0.020914	0.005621	0.000180
H4	0.003989	0.000203	0.001822	0.017149	0.000121	0.015496	0.004678	0.000109
H5	0.009792	0.000168	0.001224	0.021501	0.000484	0.013814	0.003844	0.000139
Average	0.014978	0.000098	0.001561	0.019822	0.000532	0.013666	0.004049	0.000126

Values are presented as the mean of five replicates.

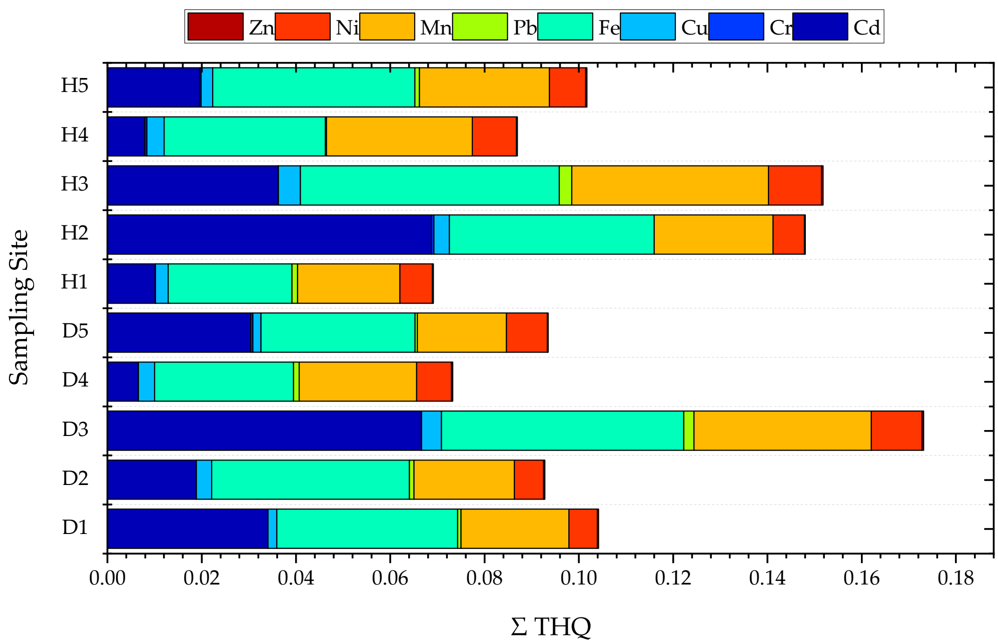

Figure 3. Individual and cumulative THQ of heavy metals in lychee (*L. chinensis*) fruit samples collected from Uttarakhand state, India.

4. Conclusions

The findings of the present study concluded that lychee fruit samples collected from orchards of Dehradun and Haridwar districts in Uttarakhand state, India showed the occurrence of all selected heavy metals (Cd, Cr, Cu, Fe, Pb, Mn, Ni, and Zn). The order of heavy metal concentration in lychee fruit samples was observed as follows: Pb < Cd < Zn < Cu < Ni < Fe < Cr < Mn. The results showed that sampling sites near urban and industrial localities showed higher levels of heavy metals than those in agricultural or rural areas. Overall, the levels of heavy metals in lychee fruit samples did not exceed the safe limits, as indicated by health risk studies. Addressing pollution sources at urban and industrial locations is crucial to mitigate the health risks associated with heavy metal exposure from lychee consumption. Further studies on assessing the long-term health effects of heavy metal exposure associated with lychee consumption in other areas of Uttarakhand state as well as to develop effective strategies to mitigate this potential health hazard are highly suggested.

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