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Research Article

Evaluating Health Risks of Heavy Metals in Pomegranate from Industrial Clusters of Solapur Using Spatial Distribution Analysis in a Semi-Arid Region

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Abstract

Heavy metal contamination in fruit crops near agro-industrial areas poses serious food safety concerns. This study assessed the spatial distribution, sources, and health risks of Cr, Cd, Pb, and Ni in pomegranate (*Punica granatum* L.) grown around five sugar industries in Solapur, India. A total of 150 fruit samples were collected across three distance zones (0–1.5, 1.5–3.0, and 3.0–4.5 km) from each industry.

It is evident from the results, Cd and Pb were the dominant contaminants, frequently exceeding WHO/FAO limits, with maximum concentrations observed near industrial sites (Cd: 0.94 mg kg^{-1}; Pb: 2.45 mg kg^{-1} in BSSK). A significant decline with distance ($p < 0.05$; R^2 up to 0.995) confirmed their anthropogenic origin. In contrast, Cr and Ni exhibited relatively uniform distribution, indicating geogenic sources. Health risk assessment indicated Cd and Pb are major contributors to non-carcinogenic risk, with Hazard Index (HI) values exceeding safe limits (>1), reaching up to 3.00. Pollution Load Index (PLI > 1) further indicated localized contamination hotspots.

Overall, the study highlights the impact of sugar industries on heavy metal accumulation and emphasizes the need for continuous monitoring and sustainable management to ensure food safety.

Keywords: Health Risk; Spatial Assessment; Heavy Metal; Pomegranate; Sugar Industry

Abbreviations

Cr: Chromium; Cd: Cadmium; Pb: Lead; Ni: Nickel; THQ: Target Hazard Quotient; HI: Hazard Index; PLI: Pollution Load Index; VSSSK1: Vitthalrao Shinde Sahkari Sakhar Karkhana Ltd.; VSSSK2: Vitthalrao Shinde Sahkari Sakhar Karkhana Unit 2; SSSK: Shankar Sahkari Sakhar Karkhana Ltd.; STSSK: Sangola Taluka Sahkari Sakhar Karkhana Ltd.; BSSK: Bhima Sahkari Sakhar Karkhana Ltd.

Introduction

Heavy metal contamination in agricultural systems has become a major global issue due to its significant implications for food safety and human health. Fruit crops, particularly those cultivated near industrial and urbanized regions, are highly vulnerable to contamination through multiple pathways, including atmospheric deposition, uptake from contaminated soils, and irrigation with polluted water sources [9,15]. These processes facilitate the accumulation of toxic elements in edible plant parts. Among various heavy metals, cadmium (Cd) and lead (Pb) are of particular concern because of their persistence, non-degradable nature, and strong bioaccumulation potential within biological systems, even at low concentrations [14,21].

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Pomegranate (*Punica granatum* L.), widely valued for its nutritional and medicinal benefits, has recently been identified as a potential pathway for dietary exposure to heavy metals when grown in contaminated environments. The transfer of metals from environmental sources to fruit tissues is influenced by several interacting factors, including emission intensity, proximity to pollution sources, soil physicochemical characteristics, and agricultural practices [5,11]. Previous studies have reported elevated concentrations of Cd and Pb in fruits cultivated under anthropogenic influence, sometimes exceeding recommended safety limits and posing potential risks to human health [16,30].

Despite increasing research in this area, there is still a lack of integrated studies combining spatial distribution analysis, statistical validation, and comprehensive health risk assessment. Therefore, this study aims to evaluate the spatial variability of heavy metals in pomegranate fruits across gradients of industrial influence, examine the effects of distance and emission sources, and assess potential health risks using established indices such as the target hazard quotient (THQ), hazard index (HI), and pollution load index (PLI) [9,23]. This integrated approach is expected to provide deeper insight into contamination pathways and support the development of effective mitigation strategies for sustainable agriculture and food safety.

Materials and Methods

The present study was carried out in Solapur district, Maharashtra, India, a semi-arid region characterized by low precipitation and extensive pomegranate cultivation. Five major sugar industries—Vitthalrao Shinde Sahkari Sakhar Karkhana Ltd. (VSSSK1), Vitthalrao Shinde Sahkari Sakhar Karkhana Unit 2 (VSSSK2), Shankar Sahkari Sakhar Karkhana Ltd. (SSSK), Sangola Taluka Sahkari Sakhar Karkhana Ltd. (STSSK), and Bhima Sahkari Sakhar Karkhana Ltd. (BSSK)—were selected as potential point sources of environmental pollution. To evaluate the spatial distribution of heavy metals, a distance-based stratified sampling design was implemented. Sampling locations were categorized into three zones: Zone I (0–1.5 km), Zone II (1.5–3.0 km), and Zone III (3.0–5.0 km). Such distance-gradient approaches are widely used to assess the dispersion and accumulation of contaminants originating from industrial activities [1,40].

A total of 150 mature pomegranate fruits were randomly collected from orchards within the defined zones, ensuring ten samples per zone around each industrial unit to maintain representativeness. The collected fruits were thoroughly washed with deionized water to remove surface impurities, and the edible arils were separated manually. The samples were dried in a hot air oven at 60–70 °C. The dried material was then ground into a fine powder using a stainless-steel grinder to prevent contamination from external sources. To estimate heavy metals approximately 1 g of each sample was subjected to wet digestion using a mixture of concentrated nitric acid (HNO_3) and hydrogen peroxide (H_2O_2), following standard procedures recommended for food sample preparation [4,38].

After digestion, the solutions were filtered and diluted to a fixed volume with ultrapure water prior to analysis. The concentrations of chromium (Cr), cadmium (Cd), lead (Pb), and nickel (Ni) were determined using Atomic Absorption Spectrophotometry (AAS), a well-established and reliable technique for trace metal analysis in food and plant matrices [22,35]. Calibration was performed using standard reference solutions, and recovery percentages ranging from 92% to 105% confirmed the accuracy and reliability of the analytical procedure.

Statistical analysis were performed using SPSS version 16.0 and R Studio 4.3.05. A two-way analysis of variance (ANOVA) was applied to examine the effects of distance and industrial source, as well as their interaction, on heavy metal concentrations. Linear regression analysis was further conducted to evaluate the relationship between distance from emission sources and the accumulation of metals in fruit samples. The obtained concentrations were compared with permissible limits established by Codex Alimentarius and the World Health Organization to determine compliance with food safety standards [10].

Human health risk assessment was carried out using standard indices. The non-carcinogenic risk was evaluated using the Target Hazard Quotient (THQ), calculated as:

$$THQ = C/RfD$$

Where C represents the concentration of the metal (mg kg^{-1}) and RfD denotes the oral reference dose (mg kg^{-1} day^{-1}). The overall non-carcinogenic risk was expressed as the Hazard Index (HI), computed as the sum of individual THQ values:

$$HI = \sum THQi$$

The Pollution Load Index (PLI) was used to assess the overall contamination status and was calculated as:

$$PLI=(CF1\times CF2\times\cdots\times CFn)1/n,\ CF=C/Cstandard$$

These indices were applied following established environmental and food safety risk assessment frameworks [28,37,39].

PCA and biplot analysis

Principal Component Analysis (PCA) is a multivariate statistical technique used to reduce the dimensionality of a dataset while retaining most of its variability. It transforms a set of correlated variables into a smaller number of uncorrelated variables called principal components (PCs), which are linear combinations of the original variables (18). Mathematically, PCA is based on the eigen decomposition of the covariance (or correlation) matrix:

$$X = TP^{\top}$$

Where X is the standardized data matrix, T is the score matrix, and P is the loading matrix. The principal components are obtained by solving:

$$Sp_i = \lambda_i p_i$$

Where S is the covariance matrix, is the eigenvalue, and is the eigenvector (loading) corresponding to the i^{th} principal component. The eigenvalues represent the amount of variance explained by each component.

A biplot is a graphical representation of PCA results that simultaneously displays both sample scores and variable loadings in the same plot by [29]. The length and direction of the vectors indicate the contribution and correlation of variables, while the relative position of points reflects similarities or differences among samples. This combined visualization facilitates interpretation of relationships between variables and observations in reduced-dimensional space.

Results and Discussion

Influence of distance from a sugar factory on heavy metal accumulation in pomegranate fruits

The distribution of heavy metals in pomegranate fruits across different industrial locations were collected and results of the two-way ANOVA (Table 1) indicated that both the distance from industrial sources and the type of factory significantly affect the concentrations of heavy metals, although the extent of their influence differs among elements. Cadmium (Cd) showed highly significant variation with respect to both factors ($p < 0.001$), suggesting that its accumulation is strongly governed by a combination of spatial proximity and source-specific emissions. A similar pattern was observed for lead (Pb), where both distance and factory type had a significant effect; however, the higher F-value associated with the factory factor ($F = 11.67$) indicates that differences in emission characteristics among industries play a more dominant role in controlling Pb levels.

In contrast, chromium (Cr) did not exhibit a statistically significant relationship with distance ($p = 0.158$), although variations among factories were significant. This pattern supports the inference that Cr distribution is less influenced by atmospheric transport and more closely linked to inherent soil composition and geochemical background. Nickel (Ni), on the other hand, showed non-significant variation with either distance or factory, indicating a relatively uniform distribution that likely reflects baseline environmental levels rather than localized anthropogenic inputs.

The interaction between distance and factory (D × F) was found to be significant for both Cd ($p = 0.002$) and Pb ($p = 0.005$), demonstrating that the effect of distance is not consistent across all industrial sites. Instead, it varies depending on site-specific factors such as emission intensity, prevailing wind direction, and surrounding environmental conditions. These findings align with previous research indicating that Cd and Pb are highly responsive to both spatial gradients and emission sources, whereas elements like Cr tend to exhibit limited spatial variability due to their predominantly lithogenic origin [7,12,17,24].

Spatial distribution of heavy metal concentration in pomegranate fruits

The distribution of heavy metals in pomegranate fruits across different industrial locations showed noticeable variation influenced by both proximity to emission sources and the type of industry (Table 2). Overall, lead (Pb) and cadmium (Cd) concentrations were consistently higher than those of chromium (Cr) and nickel (Ni) across all sampling zones, indicating their

Parameter (mg kg^{-1})	Source	df	F-value	p-value	Sig.
Chromium (Cr)	Distance (D)	2	2.05	0.158	NS
	Factory (F)	4	5.92	0.002	**
	D × F	8	2.74	0.025	*
Cadmium (Cd)	Distance (D)	2	10.18	<0.001	***
	Factory (F)	4	8.21	<0.001	***
	D × F	8	4.52	0.002	**
Lead (Pb)	Distance (D)	2	5.12	0.016	*
	Factory (F)	4	11.67	<0.001	***
	D × F	8	3.68	0.005	**
Nickel (Ni)	Distance (D)	2	0.58	0.561	NS
	Factory (F)	4	2.14	0.098	NS
	D × F	8	1.39	0.241	NS

Table 1: ANOVA: Effect of distance from sugar factory on heavy metal concentration in pomegranate fruits.

greater contribution to contamination in the study area. Among the selected sites, Bhima Sahkari Sakhar Karkhana (BSSK) exhibited the highest average levels of most metals, with particularly elevated concentrations of Pb (2.45 mg kg^{-1}) and Cd (0.94 mg kg^{-1}) recorded in Zone I, suggesting significant localized inputs likely associated with industrial activities.

A general decline in metal concentrations with increasing distance from the industrial sources was observed in several cases. For example, Pb levels around VSSSK1 and BSSK decreased progressively from Zone I to Zone III, reflecting a typical gradient pattern often linked to atmospheric deposition and reduced pollutant intensity with distance. However, this spatial trend was not consistent for all metals and sites. In the case of STSSK, Cd concentrations showed an opposite pattern, increasing in the outer zone (Zone III), which may indicate the influence of additional sources such as contaminated soils, irrigation practices, or agrochemical usage rather than direct industrial emissions.

In contrast, chromium (Cr) exhibited relatively minor fluctuations across the sampling zones, suggesting that its presence may be more strongly associated with natural (geogenic) sources rather than anthropogenic inputs. The relatively large standard deviation values observed at certain locations, particularly at BSSK, further indicate uneven distribution of contaminants, which could be attributed to variations in emission intensity, local environmental conditions, and differences in orchard management practices.

Comparable findings have been reported in previous studies, where Pb and Cd were identified as dominant contaminants in fruits cultivated near industrial regions, largely due to atmospheric deposition and soil-to-plant transfer processes [2,27,36,41]. These observations reinforce the role of both environmental dispersion mechanisms and agricultural factors in controlling heavy metal accumulation in fruit crops.

Regression analysis

The regression analysis (Table 3) provides further insight at the individual factory level between distance and metal concentrations. A pronounced inverse association was observed for Pb at VSSSK2, SSSK, and BSSK, as indicated by negative regression coefficients and very high coefficients of determination (R^2 values reaching 0.995). This pattern reflects a clear decline in concentration with increasing distance, suggesting that Pb contamination is largely influenced by localized industrial emissions. A similar decreasing trend was noted for Cd at BSSK ($\beta = -0.290$, $R^2 = 0.870$), further supporting the dominance of point-source contributions.

Parameter (mg kg^{-1})/ Factory	Zone - I (0–1.5 km) (Mean ± SD) (Range)	Zone - II (1.5–3.0 km) (Mean ± SD) (Range)	Zone - III (3.0–4.5 km) (Mean ± SD) (Range)
VSSSK 1			
Cr	0.61 ± 0.55 (0.07–1.67)	0.73 ± 0.58 (0.29–2.22)	0.53 ± 0.41 (0.09–1.49)
Cd	0.30 ± 0.20 (0.11–0.61)	0.32 ± 0.22 (0.07–0.71)	0.29 ± 0.28 (0.05–0.92)
Pb	0.97 ± 0.51 (0.29–1.98)	1.30 ± 0.84 (0.22–2.93)	0.93 ± 0.85 (0.00–2.36)
Ni	0.13 ± 0.10 (0.00–0.29)	0.10 ± 0.08 (0.00–0.24)	0.10 ± 0.08 (0.00–0.28)
VSSSK 2			
Cr	0.92 ± 0.83 (0.36–3.16)	0.55 ± 0.36 (0.00–1.07)	0.89 ± 0.59 (0.29–2.12)
Cd	0.27 ± 0.18 (0.07–0.62)	0.30 ± 0.46 (0.00–1.55)	0.13 ± 0.10 (0.00–0.25)
Pb	0.88 ± 0.84 (0.16–2.58)	0.28 ± 0.22 (0.00–0.66)	0.20 ± 0.14 (0.00–0.48)
Ni	0.22 ± 0.39 (0.00–1.11)	0.23 ± 0.41 (0.00–1.06)	0.18 ± 0.34 (0.00–0.88)
SSSK			
Cr	0.53 ± 0.25 (0.15–0.91)	0.45 ± 0.24 (0.22–0.93)	0.55 ± 0.16 (0.33–0.73)
Cd	0.56 ± 0.27 (0.22–0.93)	0.25 ± 0.10 (0.02–0.35)	0.28 ± 0.08 (0.18–0.42)
Pb	1.58 ± 0.33 (1.05–2.12)	1.42 ± 0.81 (0.14–2.74)	1.34 ± 0.27 (0.97–1.68)
Ni	0.21 ± 0.18 (0.04–0.64)	0.11 ± 0.10 (0.00–0.27)	0.16 ± 0.05 (0.08–0.24)
STSSK			
Cr	0.84 ± 0.85 (0.00–2.49)	1.04 ± 0.93 (0.00–3.32)	0.69 ± 0.31 (0.29–1.24)
Cd	0.08 ± 0.05 (0.00–0.15)	0.22 ± 0.14 (0.02–0.42)	0.29 ± 0.11 (0.14–0.48)
Pb	0.20 ± 0.10 (0.00–0.35)	0.47 ± 0.38 (0.00–1.26)	0.66 ± 0.38 (0.21–1.37)
Ni	0.09 ± 0.08 (0.00–0.21)	0.15 ± 0.07 (0.05–0.27)	0.12 ± 0.06 (0.04–0.23)
BSSK			
Cr	1.36 ± 1.04 (0.00–3.29)	2.26 ± 0.99 (1.19–4.54)	1.09 ± 0.72 (0.00–2.53)
Cd	0.94 ± 1.99 (0.13–6.54)	0.23 ± 0.06 (0.10–0.31)	0.15 ± 0.02 (0.11–0.17)
Pb	2.45 ± 1.72 (1.34–7.14)	2.02 ± 0.54 (1.35–3.05)	1.46 ± 0.57 (0.50–2.25)
Ni	0.62 ± 0.14 (0.42–0.86)	0.62 ± 0.21 (0.31–0.89)	0.54 ± 0.28 (0.16–0.94)

Table 2: Spatial distribution of heavy metal concentrations in pomegranate fruits across industrial distance gradients.

In contrast, STSSK exhibited positive regression coefficients for both Cd and Pb (β = +0.070 and +0.160), indicating an increase in concentrations with distance. This typical pattern may be linked to secondary sources such as contaminated irrigation inputs, soil enrichment, or the redistribution of particulates. Chromium showed weak associations with distance across all sites, as evidenced by low R^2 values, implying minimal influence of spatial proximity and a stronger connection to natural background sources. Nickel displayed inconsistent relationships, suggesting contributions from both anthropogenic and natural origins.

Overall, the regression findings demonstrate that distance is a key controlling factor for certain metals, particularly Pb and Cd, while others are influenced by a combination of environmental conditions and agricultural practices. Comparable observations have been reported in earlier studies highlighting the combined effects of direct emissions and secondary processes on metal distribution in crops [8,32].

Health risk assessment

The frequent exceedance of permissible limits for cadmium (Cd) and lead (Pb) indicates a associated with serious health

Factory	Parameter (mg kg^{-1})	Regression Equation (Y = a + bX)	Slope (β)	Intercept (a)	R^2
VSSSK 1	Cr	Y = 0.740 – 0.027X	−0.027	0.740	0.162
	Cd	Y = 0.315 – 0.005X	−0.005	0.315	0.018
	Pb	Y = 1.180 – 0.011X	−0.011	1.180	0.011
	Ni	Y = 0.135 – 0.010X	−0.010	0.135	0.603
VSSSK 2	Cr	Y = 0.820 – 0.010X	−0.010	0.820	0.006
	Cd	Y = 0.340 – 0.050X	−0.050	0.340	0.709
	Pb	Y = 0.950 – 0.230X	−0.230	0.950	0.886
	Ni	Y = 0.245 – 0.011X	−0.011	0.245	0.486
SSSK	Cr	Y = 0.495 + 0.006X	0.006	0.495	0.030
	Cd	Y = 0.630 – 0.097X	−0.097	0.630	0.721
	Pb	Y = 1.740 – 0.090X	−0.090	1.740	0.968
	Ni	Y = 0.230 – 0.020X	−0.020	0.230	0.305
STSSK	Cr	Y = 1.000 – 0.040X	−0.040	1.000	0.141
	Cd	Y = 0.020 + 0.070X	0.070	0.020	0.964
	Pb	Y = 0.070 + 0.160X	0.160	0.070	0.991
	Ni	Y = 0.090 + 0.010X	0.010	0.090	0.280
BSSK	Cr	Y = 1.780 – 0.120X	−0.120	1.780	0.180
	Cd	Y = 1.210 – 0.290X	−0.290	1.210	0.870
	Pb	Y = 2.880 – 0.350X	−0.350	2.880	0.995
	Ni	Y = 0.700 – 0.030X	−0.030	0.700	0.780

Table 3: Factory-wise linear regression analysis of heavy metal concentrations with distance from industrial source.

effects, including kidney damage, neurological disorders, and developmental issues. Since pomegranate is widely consumed, continuous intake of contaminated fruits could lead to bioaccumulation of these metals in the human body over time. In this study the data (Table 4) showed that cadmium (Cd) and lead (Pb) concentrations in pomegranate fruits frequently surpassed the permissible limits set by WHO/FAO, whereas chromium (Cr) and nickel (Ni) generally remained within acceptable ranges. Lead levels exceeded the guideline value (0.30 mg kg^{-1}) across all sites, with the highest concentrations recorded at BSSK (1.98 mg kg^{-1}) and SSSK (1.45 mg kg^{-1}), indicating widespread contamination. Cadmium also exceeded its recommended limit (0.20 mg kg^{-1}) in most locations, except STSSK, suggesting potential long-term exposure concerns. In contrast, Ni exceeded the limit only at BSSK, while Cr remained within safe boundaries. These observations are consistent with earlier studies highlighting elevated Cd and Pb levels in crops grown under strong anthropogenic influence [13,20,21,32].

Factory	Cr (mg kg^{-1})	Cd (mg kg^{-1})	Pb (mg kg^{-1})	Ni (mg kg^{-1})
VSSSK 1	0.62	0.30*	1.07*	0.11
VSSSK 2	0.79	0.23*	0.45*	0.21
SSSK	0.51	0.36*	1.45*	0.16
STSSK	0.86	0.20	0.44*	0.12
BSSK	1.57	0.44*	1.98*	0.59*
WHO Limit	2.30	0.20	0.30	0.50

Table 4: Comparison of heavy metal concentration in pomegranate fruits with codex (fao/who) permissible limits.

Principal component analysis

The results are further supported by using multivariate analysis like PCA biplot analysis. The PCA biplot indicated that the first two principal components (Dim1 = 31.1% and Dim2 = 27.5%) explain a combined 58.6% (Fig 1) of the total variation, indicating a ample representation of the dataset. Dim1 showed clear separation of samples based on a contrast between Juice Content (positive side) and Total Soluble Solids (TSS), Brix, and associated elements (negative side), suggesting an inverse relationship between juiciness and soluble solids/metal content.

Whereas, Dim2 distinguishes morphological traits such as peel, aril, and fruit dimensions (positive side) from metal-related variables like Cr and Ni (negative side). Variables with similar directions are positively correlated, while those in opposite directions show negative relationships. The distribution of samples across the plot reflects the patterns, some samples associated with higher juice content and others linked to higher soluble solids or metal concentrations, indicating clear variability among the studied samples.

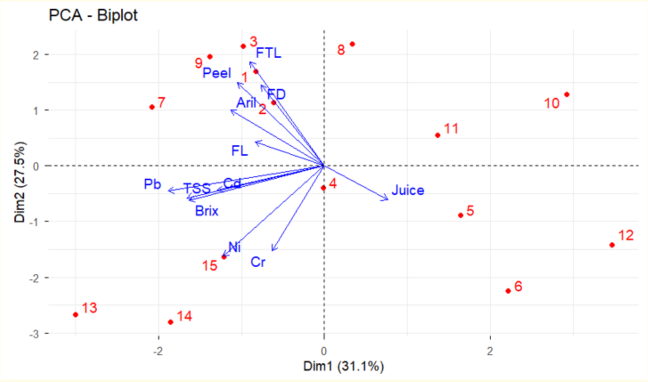

Figure 1: PCA – Biplot explaining % variance among the heavy metal and fruit traits.

Comprehensive risk characterization of heavy metal contamination

Health risk assessment helps to quantify the level of exposure and determines whether the consumption of such fruits poses non-carcinogenic or carcinogenic risks. Simple comparison of concentrations with permissible limits provides an initial warning. Hence, risk assessment tools—such as Target Hazard Quotient (THQ), hazard quotient (HQ), and hazard index (HI)—offer a more comprehensive understanding of actual risk to different population groups.

Health risk evaluation (Table 5) indicates that Cd and Pb are the primary contributors to non-carcinogenic risk. Cadmium recorded the highest THQ values, particularly at BSSK (1.800), while Pb also contributed substantially, especially at BSSK (1.200) and SSSK (0.650). The cumulative risk, expressed as the Hazard Index (HI), exceeded the safety threshold (HI > 1) in all locations except STSSK, with BSSK showing the highest value (3.000), indicating considerable health concern. The Pollution Load Index (PLI) further identified BSSK as heavily contaminated (PLI = 1.200), whereas other sites reflected moderate pollution levels. Comparable trends of elevated THQ and HI values have been documented in contaminated food systems [3,23,24,29]. Overall, Cd and Pb emerge as the dominant risk-driving elements due to their persistence, tendency to accumulate in biological systems, and toxic effects within the food chain [9,7,15].

Factory	Cr (THQ)	Cd (THQ)	Pb (THQ)	Ni (THQ)	HI	PLI
VSSSK1	0.320	0.450	0.480	0.010	1.300 •	0.650
VSSSK2	0.350	0.500	0.400	0.020	1.250 •	0.600
SSSK	0.300	0.600	0.650	0.020	1.450 •	0.700
STSSK	0.280	0.300	0.250	0.010	0.950	0.550
BSSK	0.900	1.800	1.200	0.050	3.000 •	1.200 •

Table 5: Comprehensive risk characterization of heavy metal contamination using THQ, HI, PLI, and Carcinogenic risk models.

***• :** Exceeds risk threshold.

Discussion

The combined evaluation of results indicates that cadmium (Cd) and lead (Pb) are the primary contaminants governing both the distribution patterns and associated health risks in pomegranate fruits. The observed decline in Cd and Pb concentrations with increasing distance, supported by statistical analysis and regression outcomes, points toward their origin predominantly from industrial emissions and atmospheric transport processes [19,33]. In contrast, chromium (Cr) and nickel (Ni) displayed minimal spatial variability, suggesting that their presence is largely controlled by natural soil composition rather than anthropogenic inputs [2].

The frequent exceedance of WHO/FAO guideline values, along with Hazard Index (HI) values greater than unity in most locations, indicates a potential non-carcinogenic health concern, particularly pronounced at BSSK. Variability observed across certain sites further implies that additional factors, such as soil characteristics and agricultural practices, may also influence metal accumulation. Overall, Cd and Pb represent the most critical elements from a risk perspective due to their persistence in the environment, high bioavailability, and toxicological significance within the food chain [26,31].

Conclusion

This study reveals that heavy metal accumulation in pomegranate fruits is governed by a complex interaction of industrial emissions, spatial dispersion, and environmental factors. Cadmium (Cd) and lead (Pb) emerged as the most critical contaminants, exhibiting clear distance-dependent trends and significantly contributing to elevated health risks (HI > 1) in most factories, particularly BSSK. The strong statistical and regression relationships confirm their predominantly anthropogenic origin, while chromium (Cr) and nickel (Ni) reflect background geogenic contributions. The persistence and bioavailability of Cd and Pb amplify their risk potential, underscoring the need for integrated management strategies, stricter regulation, and continuous monitoring to mitigate long-term public health impacts.

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Conflict of Interest

Hereby authors declare there is no conflict of interest exists.

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