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Risk Assessment of Potentially Toxic Metals and Metalloids in Soil, Water and Plant Continuum of Fragrant Rice

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Abstract: Globally, the demand for food is increasing day by day due to the rapid increase in the human population. Elevated levels of metals and metalloids in soils are biomagnified over time in crops cultivated in metal-contaminated soils, hence posing a risk of food chain contamination. The present investigation aimed to assess metal and metalloid concentrations in soil, water, and rice kernels which are widely cultivated in four districts of Punjab, Pakistan, and to determine the risk to human health. The results revealed that, of five rice varieties, super basmati was the most preferred by farmers due to its yield potential and consumer acceptance due to its taste and to its long kernel. A detailed analysis of metal and metalloid accumulation revealed that their mean concentration fluctuated in the soil, water, and rice samples in the study area. The decreasing trends of heavy metals and metalloids were observed to be Pb > Cu > As > Cr > Cd > Hg > Al in soil samples, Pb > Cr > Cu > Al > As > Hg > Cd in water samples, and Cu > Cr = Pb > Cd = Al > Hg > As in rice kernels. The bioconcentration factor for Cr was the highest in the Faisalabad area among all sampled sites. The pollution load index of As, Cd, and Hg registered the highest values, that were above the recommended safety threshold levels described by World Health Organization. The human health risk index was determined to be low at all sites except for As and Hg. These results point to potential health risks caused by the consumption of fragrant rice by humans. Regular monitoring is recommended to manage and control elevated concentrations and related health hazards as a result of the use of rice contaminated by the accumulation of metals and metalloids.

Keywords: kernels; soil; health risk; pollution load index; permissible limits; Pakistan

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1. Introduction

The world population is increasing, and it is expected to rise to 10 billion in 2050, which will be the biggest challenge to ensure the provision of nutritionally adequate food to humans [1]. It is estimated that about fifty percent of the world's population consumes rice daily as a dietary intake. Several industries also use many by-products of the rice crop as raw materials [2]. Rice is also one of the most important main crops in Pakistan that fulfills the nutritional needs (e.g., vitamins, fiber, etc.) of the population [3]. Rice has 20% protein, 3% nutritive fat, and 27% nutritive energy [4]. It is ranked as the second most consumed food by humans [5]. Pakistan produces a substantial amount of rice, especially in Punjab and Sindh, where 60–70% of the population consumes rice [6,7]. Pakistan produces around 6.0 million tonnes of rice yearly, exports around 4.0 million tonnes, and uses about 2.0 million tonnes of rice for domestic consumption [4,8].

Soil contamination by heavy metals (HMs) is a major environmental issue due to the global land use changes in agriculture and industry in the past few decades [9–11]. Soil is an essential source of minerals and serves as a vital source of nutrients for terrestrial ecosystems. Soils may be enriched with HMs and indicate the pollution status of the soil system [2]. The exposure pathways to HMs are not only restricted to the inhalation of polluted material but they also include the consumption of plants cultivated in the contaminated environment (e.g., soil, water, sediments) [8–11]. The presence of HMs in agricultural soils has increased mainly due to the excessive use of fertilizers, pesticides, contaminated water, waste material, and the atmospheric deposition of pollutants [12]. The cultivation of food crops on contaminated soils may cause higher levels of HM toxicity in plants [11,13] as elements in soils diffuse and root uptake occurs, with HMs ultimately becoming part of the food chain through bioaccumulation [14]. Upon the consumption of such plants, these metals enter the human body and may cause various health risks [15,16].

As these elements are found to move among various parts of the plant, such as between shoots and roots, and between shoots and grains, consuming these plants as food may cause serious diseases [17–21]. Studies have shown that high levels of heavy metals are carcinogenic, and many other diseases of the heart, kidneys, bones, and blood may also occur [22–25]. Biological and metabolic processes in the human body may become disrupted if the excessive intake of heavy metals occurs through food [26]. Heavy metals can interact with genetic make-up and metabolic functions, as well as influence embryonic development [27,28]. These metals are harmful in many ways; thus, the United States Environmental Protection Agency (US-EPA) and the Agency for Toxic Compounds and Disease Registry (ATSDR) have listed them among the top 20 most dangerous substances [29,30]. For example, a significant amount of arsenic (As) enters water bodies and agricultural soils through natural processes such as leaching from As-rich rocks and minerals, and the levels may be further aggravated by inputs related to anthropogenic activities [2]. The soil–plant transfer factor (TF) of metals and metalloids is a useful criterion to assess global human health concerns. Human health hazards are closely linked to the intake of metal-contaminated food crops [31].

The accumulation of potentially toxic metals and metalloids in soil, water, and rice kernels has the potential to cause adverse health effects through ingestion. Due to its outstanding cooking quality and excellent marketing potential on a national and international scale, basmati rice is very well known for its worth. Pakistan is the fourth-largest exporter and the eleventh-largest producer of rice [32]. Therefore, it is extremely important to evaluate elemental accumulation in the basmati rice cultivar, for doing so will help us to understand the implications and potential risks to public health. Hence, the aim of this study was to assess concentrations of HMs in soil, water, and locally cultivated fragrant rice and to evaluate the health risks to the local community associated with rice consumption. The objectives of this study were to: (1) determine the concentrations of selected heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), and lead (Pb) in soil, water, and rice kernels in the rice-cultured areas of Punjab; (2) to evaluate the toxicity of heavy metals by bioconcentration and pollution load index; and (3) to evaluate the human health risk from the consumption of rice.

2. Materials and Methods

2.1. Study Area

Punjab is known as the land of five rivers; it has fertile land and several food crops are grown in this region due to suitable climatic conditions, water availability, and market demand. Rapid urbanization and industrialization have impacted the soil and groundwater quality in vast areas of agricultural land in Punjab. Four rice-growing districts (Lahore, Narowal, Gujranwala, and Faisalabad) in the Punjab Province were selected for sampling in this study (Figure 1).

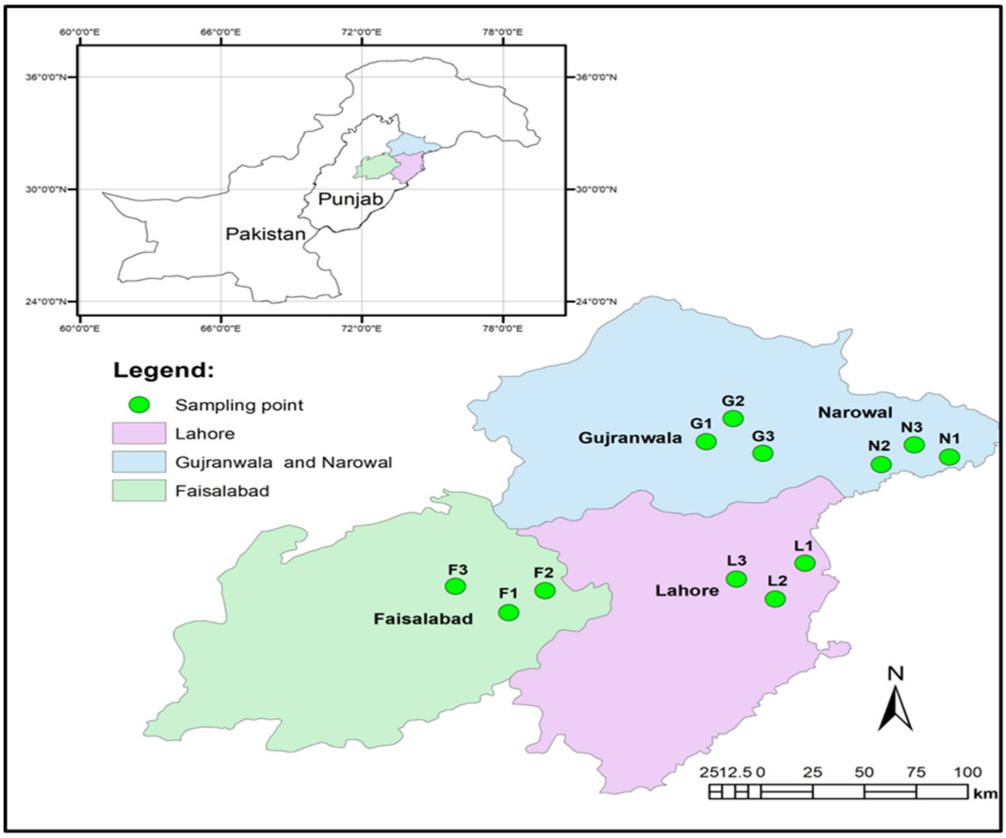

Figure 1. Study sites and sampling points in four rice-growing districts: Lahore, Narowal, Gujranwala, and Faisalabad in Punjab Province.

Three agriculture sites in each district were selected based on the area of rice cultivation (Table 1). Sampling sites from these districts were chosen to investigate the contamination levels in soil, water, and rice kernels.

Table 1. Site distribution of study area of various districts of Punjab, Pakistan.

District	Site Location	Site Number	ID
Faisalabad	Chak 25 GB	Site 1	F_1
Faisalabad	Chak 100 RB	Site 2	F_2
Faisalabad	Prokianwala	Site 3	F_3
Narowal	Noorkot	Site 1	N_1
Narowal	Manak	Site 2	N_2
Narowal	Jioke	Site 3	N_3
Gujranwala	Dogranwala	Site 1	G_1
Gujranwala	Rahwali	Site 2	G_2
Gujranwala	Jandiala Baghwala	Site 3	G_3
Lahore	Minhala	Site 1	L_1
Lahore	Kahna	Site 2	L_2
Lahore	Band Road	Site 3	L_3

2.2. Experimental Plan

An initial survey (n = 200) was conducted to determine the yield potential of the following five commonly planted fragrant rice cultivars grown in the study area: NIAB basmati, super basmati, Kissan basmati, Punjab basmati, and Kainat basmati. These five varieties are the most popular varieties of fragrant rice. Based on a short survey, the most cultivated, high yielding, and consumer-preferred fragrant rice cultivar was selected for the assessment of metal and metalloid accumulation in rice kernels.

2.3. Soil Sampling

From each district, 3 cultivation sites were selected and 4 samples (3 replicates of each sample) of soils were collected. Each surface soil sample (depth ~15 cm) was taken to represent the area of rice cultivation using a sterilized augur following the methods described by Tariq et al. [33]. Approximately 1.0 kg of soil was collected in clean zip lock bags and transported to the lab for further analysis. The soil samples were air dried, sieved (2 mm), and then stored in sealed plastic bags until further analysis [34].

2.4. Water Sampling

The same number of groundwater samples were collected from different places in the study area from tube wells and turbines. Before collecting samples, the turbine was allowed to run for at least 30 min, approximately, to access the fresh groundwater. Pre-cleaned plastic bottles (polypropylene) were used to collect the water samples. The water samples were labeled according to their sources, time, and the area from which they were obtained. Samples were stored at 15 °C until they were transported to the research laboratory for further analysis [35].

2.5. Rice Kernel Sampling

Rice kernel samples were collected from the same agricultural fields as the water and soil samples. Rice kernels were collected, dehulled, and stored in separate envelopes and transported to the laboratory for analysis. After sun-drying, the kernel samples were oven-dried at 105 °C for five days.

2.6. Digestion and Metal Analysis of Samples

Metal absorption in the soil and rice samples was measured on a dry weight basis. After drying, the soil and rice kernel samples were pulverized into powder using an electric grinder. By following the wet digestion method, approximately 2 g of sample was taken in a 10 mL aqua regia solution (1:3 ratio of acids as HNO_3:HCl) and allowed to digest at 100 °C until a clear solution was obtained [33]. The chemicals and salts used for digestion were of analytical grade and obtained from E. Merck (Darmstadt, Germany) with a certified purity of 99%. Standard preparation precautions were followed during the preparation and analysis of samples. The solution thus obtained was filtered (pore size ~42 µm) after cooling to room temperature. To bring the volume up to 50 mL for the analysis, purified distilled water was added to this solution. Water, soil, and rice kernel extract samples were analyzed to determine the concentration of metals and metalloids using ICP-MS (ELAN 9000, Perkin-Elmer SCIEX, Norwalk, CT, USA).

2.7. Bioconcentration Factor

Bioconcentration factor (*BCF*) was computed as per the protocols presented by Cui et al. [36] in the following equation.

$$Bioconcentration\ factor\ (BCF) = Element\ conc.\ in\ kernels / Element\ conc.\ in\ experimental\ soil$$

2.8. Pollution Load Index

The pollution load index (*PLI*) was measured using the following protocols described by Liu et al. [37] and is given below as an equation.

$$Pollution\ load\ index\ (PLI) = Element\ conc.\ in\ experimental\ soil / \ Element\ conc.\ in\ refrence\ soil$$

2.9. Health Risk Assessment

An assessment of the health risk index (*HRI*) for the measured metals and metalloids in all samples was carried out in this study. The HRI value was determined by calculating the daily intake of metal (*DIM*) first and then dividing this value by an oral reference dose (*RfD*) of elements (metals and metalloids) in rice kernels [38]. The daily intake of metals and metalloids was computed by multiplying the metal/metalloid concentration (C_{metal}) by daily food intake (mg/kg/person/day) ($C_{daily\ food\ intake}$) and correction factor (C_{factor}) then divided by an average weight of an individual ($B_{average\ weight}$).

$$(DIM) = C_{metal} \times C_{factor} \times C_{daily\ food\ intake} / B_{average\ weight}$$

$$HRI = DIM/RfD$$

The assumed daily intake of rice was 0.15 kg day^{-1}, 0.085 is the correction factor, and the average body weight of an adult person (age ~18 to 60 years) is considered to be 65 kg [38,39]. An HRI index value greater than one (>1) is assumed to be hazardous for humans [40,41].

2.10. Statistical Analysis

Data collected in this study were processed by employing the descriptive statistics technique. All data processing and statistical calculations were carried out using statistical software (Statistix, Version 10), principal component analysis (PCA) was carried out using XLSTAT software (Version 2021), and biplots were generated to compare the correlations among the observed data. Spatial distribution maps of various measured elemental concentrations in the soil, water, and rice kernels were developed using ArcGIS software (Version 10.3).

3. Results

3.1. Yield Potential of Fragrant Rice Cultivars

The survey results revealed that there was a yield gap in the yield capacity and the farmers' presented actual yield values of basmati rice cultivars. The actual yield potential of super basmati was higher than other cultivars in Lahore and Narowal; meanwhile, in Gujranwala, Kissan basmati showed maximum actual yield from the farmers' fields compared with the rest of the sampling areas. Similarly, in Faisalabad, Punjab basmati performed best compared with the rest of the cultivars (Figure 2). Furthermore, more than 80% of the local community in these four districts preferred super basmati as their favorite fragrant rice compared with the other cultivars.

3.2. Metal and Metalloid Concentrations in Irrigation Water Samples

Spatial variability in the levels of potentially toxic elements was noticed in the irrigation water. The average concentrations (mg/L) of metals and metalloids in the irrigation water samples of the Lahore and Gujranwala regions were As (1.88, 3.96), Cd (1.04, 1.77), Cr (25.01, 0.76), Cu (16.83, 5.78), Hg (4.2, 1.41) and Pb (40.17, 20.37). Meanwhile, in the Narowal region, the average concentrations of As, Cr, and Hg were higher in the agricultural water samples than the WHO standards for the respective metals. However, the Pb concentration in Narowal was within the permissible limit. The dark colors on the spatial maps (Figure 3) represent higher accumulation levels of As, Cr, and Pb in the irrigation water samples. The average concentrations of the studied metals and metalloids in the irrigation water in Faisalabad were below the permissible limits, except for Pb, which was higher than the WHO standards. The descending order for the metal and metalloid concentrations in the irrigation water was Pb > Cr > As > Cu > Hg > Cd (Figure 3).

3.3. Metal and Metalloid Concentrations in Soil Samples

The average metal and metalloid concentrations in the soil samples varied considerably among the sampling sites in the study area (Figure 4).

Figure 2. Maps showing the distribution of rice productivity (maund per acre; 40 kg = 1 maund) in the selected areas of Punjab, Pakistan. The yield capacity (potential) and actual yield of selected fragrant rice cultivars (Kissan basmati, NIAB basmati, Punjab basmati, Kainat basmati, and super basmati) investigated in this study are also shown as vertical bar graphs for comparison.

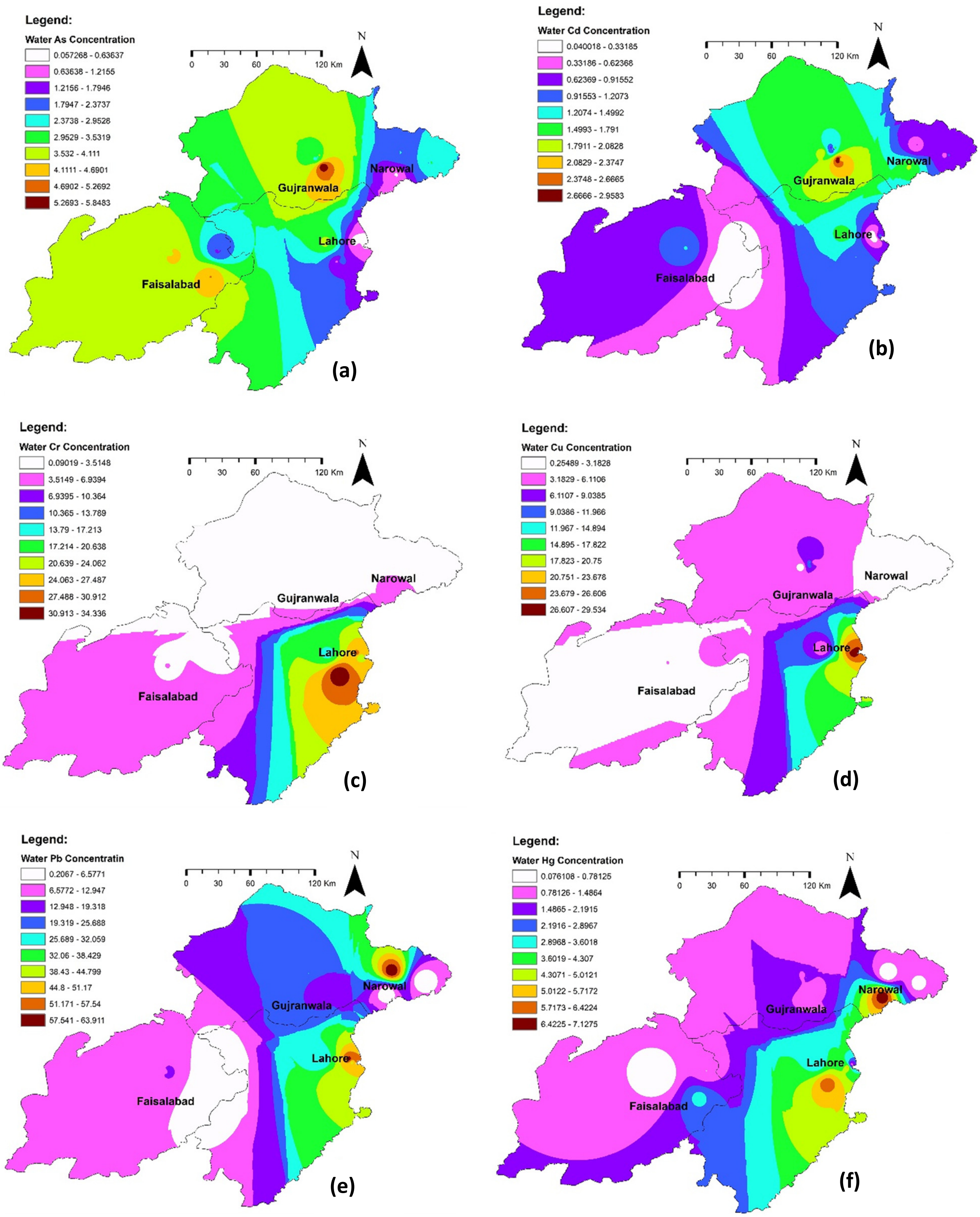

Figure 3. Spatial distribution maps of various metals and metalloids concentrations in irrigation water samples. Variation in color indicates the levels of metals and metalloid (mg L^{-1}) concentrations in water samples from sampling points; (**a**) arsenic contents; (**b**) cadmium contents; (**c**) chromium contents; (**d**) copper contents; (**e**) lead contents; (**f**) mercury contents.

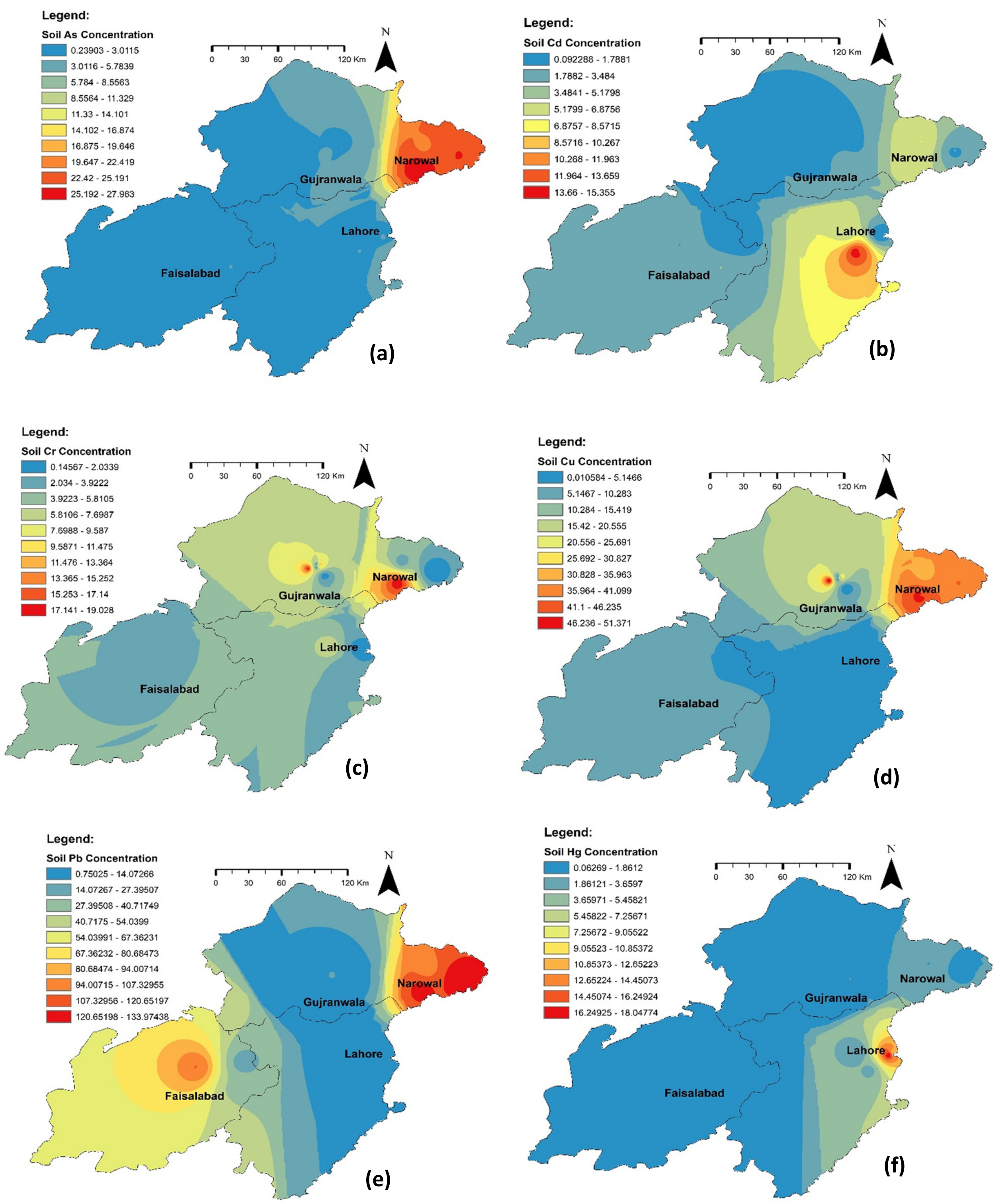

Figure 4. Spatial distribution maps of various metal and metalloid concentrations in surface soil samples. Variation in color indicates the levels of metals and metalloid (mg kg^{-1}) concentrations in soil samples from sampling points; (**a**) arsenic contents; (**b**) cadmium contents; (**c**) chromium contents; (**d**) copper contents; (**e**) lead contents; (**f**) mercury contents.

The average concentrations (mg kg^{-1}) of Pb (2.85) and Cu (1.71) in the soil samples of the Lahore region were found to be below the permissible limits described by the WHO; however, the As, Cd Cr, and Hg contents in the soil samples of Lahore were above the permissible limits. The dark colors on the spatial maps in the Narowal region represent the highest accumulation of As, Cu, and Pb that were above the permissible limits. Meanwhile, in Gujranwala, except for Al and Hg, the concentrations of all other potentially toxic metals and metalloids, i.e., As, Cd, Cr, Cu, and Pb, were found to be above the permissible limits. In the Narowal region, the concentrations of all the studied metals and metalloids were below the permissible limits, except for As and Pb. The average concentrations (mg kg^{-1}) of As (2.41), Cd (2.00), Cr (3.89), Cu (5.46), and Hg (0.74) in the soil samples of the Faisalabad region in which Pb, Cu and Cr were below the permissible limits are shown in Figure 4.

3.4. Metal and Metalloid Concentrations in Kernels of Super Basmati

Findings of the current study revealed that a considerable change in the accumulation of metals and metalloids was observed in kernels of super basmati from all the experimental sites. The results showed that the average concentration of Cu and Cr (14.03 and 2.98 mg kg^{-1}) was below the permissible limits as described by WHO guidelines in the Lahore region. Spatial distribution showed that As and Cd in Narowal and Gujranwala and Cu and Pb in the Gujranwala region had a much higher accumulation, as represented by darker colors on the maps. However, the As, Cd, Hg, and Pb levels (1.42, 4.43, 3.11, and 6.35 mg kg^{-1}, respectively) were found to be above the permissible limits in the same region. In Gujranwala, the average concentrations of As, Cd, and Hg were above the permissible limits. However, the average concentrations (mg kg^{-1}) of investigated metals and metalloids such as Pb (2.47), As (1.16), Cd (1.64), Cr (2.97), Cu (21.98), and Hg (2.04) were noticed in the kernels samples collected from Narowal region. In the Faisalabad region, the average concentrations of Pb, As, Cd, and Cr were found to be higher than the permissible limits of the WHO (Figure 5).

3.5. Bioconcentration Factor

At Lahore sites, the BAF of As, Cd, Cr, Cu, and Pb was higher than that of Hg. However, in the Gujranwala area, BAF values of As and Hg were lower than that of Cr, Pb, Cd, and Cu. Similarly, for Faisalabad, the BAF of Pb was lower than the rest of the investigated metals and metalloids. At the Narowal sites, the BAF of Pb, Hg, and Cr was higher than that of As, Cu, and Cd. Across the four studied locations, Cr in Faisalabad showed the highest BAF, while As in Gujranwala showed the lowest BAF value (Table 2).

Table 2. Bioconcentration factor and pollution load index of rice in selected areas.

Sites	**Metals**					
	As	**Cd**	**Cr**	**Cu**	**Hg**	**Pb**
			Bioconcentration Factor			
Lahore	0.5199	0.6533	0.8232	0.8801	0.4614	0.7716
Gujranwala	0.0664	0.7136	0.3517	0.8228	0.2735	0.6364
Faisalabad	0.8470	0.7282	0.9137	0.6467	0.8042	0.4219
Narowal	0.4471	0.3424	0.8297	0.4528	0.9673	0.8327
			Pollution Load Index			
Lahore	5.4622	8.4819	0.0362	0.0535	15.3055	0.0334
Gujranwala	5.8155	1.5861	0.0672	0.1184	3.1616	0.0212
Faisalabad	6.4355	2.5041	0.0415	0.1517	2.7348	0.0600
Narowal	5.1933	6.0027	0.0358	0.1482	4.7929	0.0349
Permissible Limit (mg/kg)	0.50	0.80	100	36	0.44	0.85

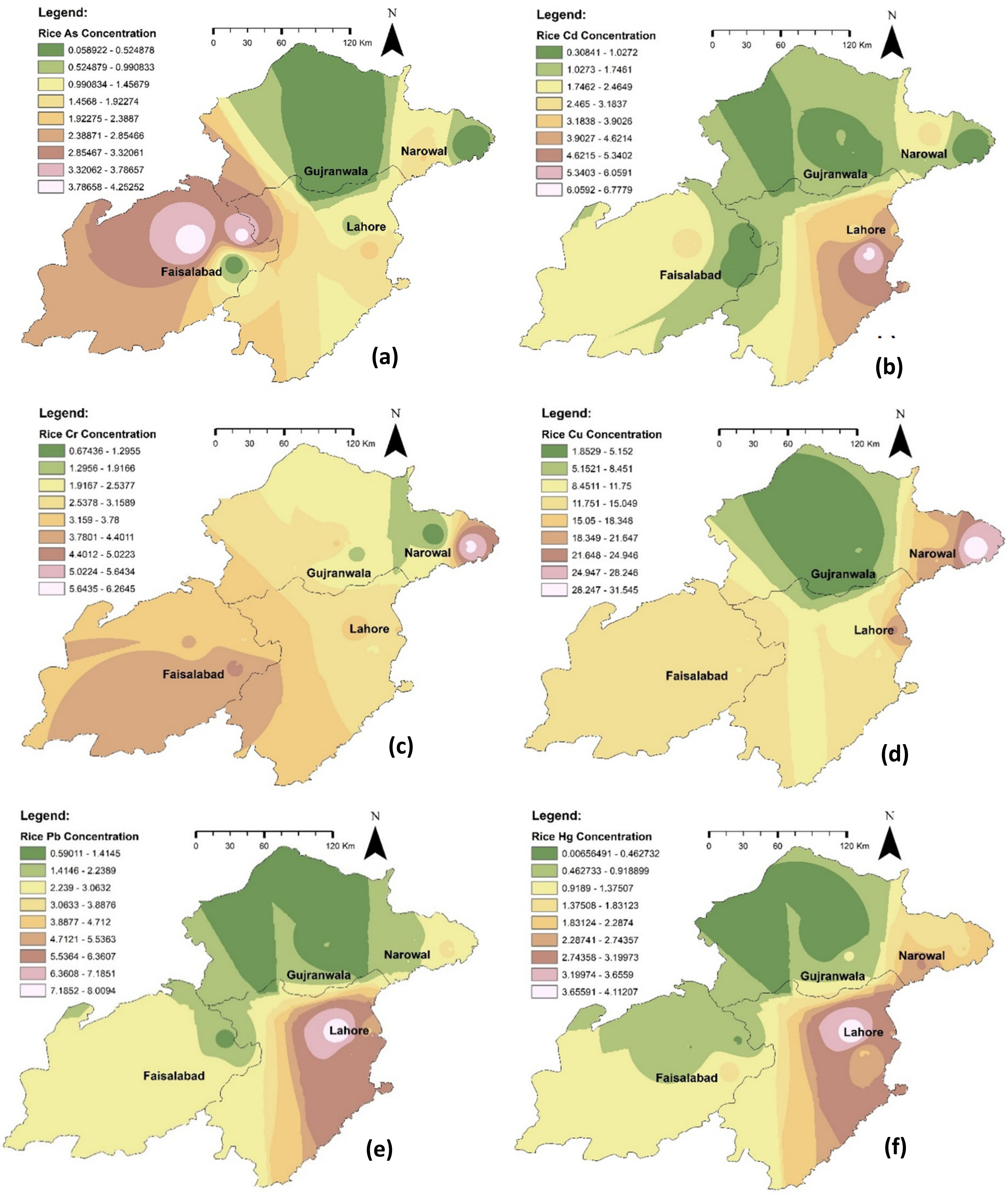

Figure 5. Spatial distribution maps of various metal and metalloid concentration in rice samples. Variation in color indicates the levels of metal and metalloid (mg kg^{-1}) concentrations in fragrant rice samples (super basmati) from sampling points; (**a**) arsenic contents; (**b**) cadmium contents; (**c**) chromium contents; (**d**) copper contents; (**e**) lead contents; (**f**) mercury contents.

3.6. Pollution Load Index

Variation in the degree of contamination was observed by using the values of the pollution load index (PLI). If the PLI values were greater than one, it was considered polluted, but PLI values below 1 were considered to be unpolluted. From the data, it was observed that PLI values of Cr, Cu, and Pb were below one in all the sampled sites and hence, were considered to be unpolluted. However, the values of As, Cu, and Hg were greater than one in all the studied areas and were found to be polluted (Table 2).

3.7. Principle Component Analysis (PCA)

Figure 6 shows the two-variable scatterplot overlaying a score plot with a loading plot. The biplot shows variations and relationships among the measured parameters at the sampled sites of Lahore (LHR), Faisalabad (FSD), Gujranwala (GRN), and Narowal (NRW). The Pb levels in water, soil, and rice samples showed the most variation among the metals, and Hg and As showed the least variation. Samples from Lahore were dominated by the Cr contamination and Pb was the most dominant metal at both Narowal and Faisalabad sampling sites. The Gujranwala area appears to be dominated by Cu metal contamination.

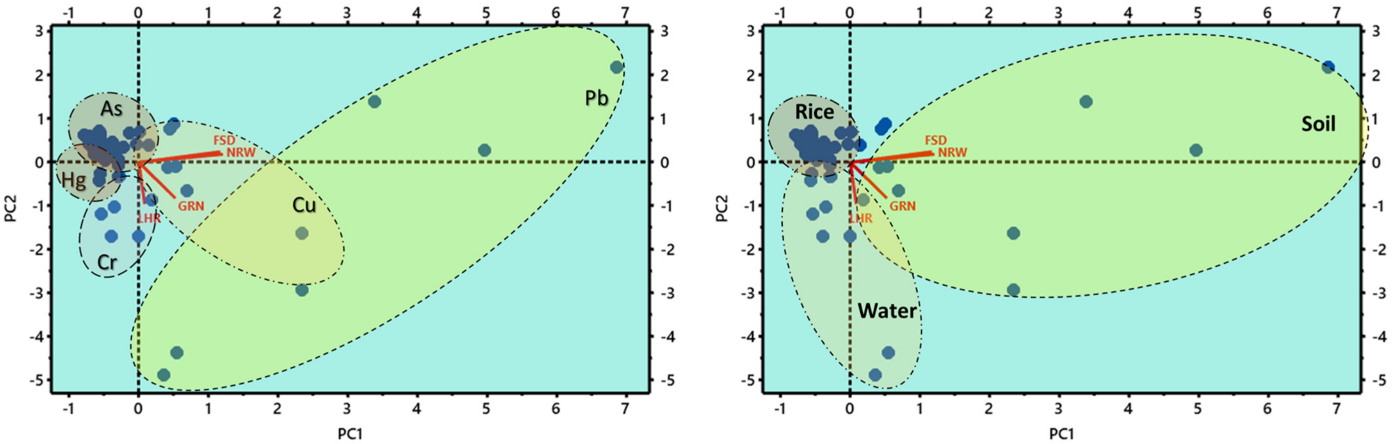

Figure 6. Principal component analysis (PCA) graph showing variables of metal and metalloid concentrations and clusters based on the similarity in chemical characteristics of sampling locations in the study area. It seems that Cu, Pb, and As originated from the same source and show similarities in chemical behaviors and enrichment. The possible sources of these metals and metalloids might be anthropogenic activities and contaminated irrigation water. It is interesting to note that a large number of sampled sites are clustered together in the quadrant of negative portions of PC1 and PC2. This reflects the general continuum of the soil–water–plant system.

3.8. Health Risk Index (HRI)

The values of the HRI determine the level of risk arising from the ingestion of metals and metalloids in contaminated food. The HRI values of metal- and metalloid-polluted rice from the various experimental areas ranged from 0.0115 to 11.74. This indicates that the health risk index was low, as no value exceeded one at any of the five sampled locations. The HRI values of Pb, Cu, Cr, and Cd were below one at all the experimental sites; however, As showed HRI values were above one except for Gujranwala, which represents a relatively minor risk. The Hg registered the maximum HRI values for all sampled sites in the study area (Table 3).

Table 3. Daily intake of metal and health risk index of rice in selected areas.

Sites	Metals					
	As	**Cd**	**Cr**	**Cu**	**Hg**	**Pb**
	Daily Intake of Metal					
Lahore	0.0005	0.0002	0.0008	0.0005	0.0003	0.0006
Gujranwala	0.0001	0.00003	0.0001	0.0004	0.0007	0.00007
Faisalabad	0.0005	0.0005	0.0002	0.0007	0.0006	0.0001
Narowal	0.0004	0.0002	0.0003	0.0005	0.0004	0.0004

Table 3. *Cont.*

Sites	Metals					
	As	Cd	Cr	Cu	Hg	Pb
	Health Risk Index					
Lahore	1.7559	0.2785	0.2898	0.0146	5.5467	0.3048
Gujranwala	0.4162	0.0379	0.0592	0.0115	11.7474	0.0373
Faisalabad	1.9208	0.5346	0.0953	0.0186	11.5512	0.0949
Narowal	1.4028	0.2277	0.1075	0.0145	7.9006	0.2000
RfD (mg/kg/day)	3×10^{-4}	1×10^{-3}	3×10^{-3}	4×10^{-2}	6×10^{-5}	2×10^{-3}

4. Discussion

Industrialization and the agriculture sector are the backbones of the economy of a country [42]. However, these sectors are a major contributor to the environmental pollution of an area. Moreover, anthropogenic activities are also the main reason for soil and groundwater pollution [43]. The food that is produced on these polluted soils using metal-contaminated irrigation water leads to the bioaccumulation of metals and metalloids in foods, which creates severe health complications in the local community [38,44].

Crops are also becoming increasingly polluted as a result of soil pollution [45]. Because the areas in the current study are dominantly industrial in terms of land use, significant amounts of heavy metals and metalloids are discharged into the soil, where they are eventually accessible to crop roots and accumulate in rice grains [46]. In similar studies, heavy metals have been detected at high concentrations in crops grown in industrial areas of Bangladesh [47,48]. In this study, the elemental concentration of soils flooded with contaminated water and the levels of all the metals and metalloids were higher than the findings reported by Jaishree et al. [49]. The concentrations in most of the soil samples were below the allowable limits set by the WHO and European Union [50], except for the concentration of a few potentially toxic metals and metalloids, i.e., As, Cd, Cr, Cu, and Pb. The lower levels of metals and metalloids in the irrigation water indicated a better quality of water, which is most likely due to the better control and management of the irrigation water distribution system [51].

Similar observations have been made by Othman et al. [52], who reported that the average content of metals and metalloids in soil and rice samples depends upon the genetic makeup of the plant and the presence of metal-binder transporter proteins. A greater absorption of metals indicates that rice plants hyper-accumulate these metals from the soils [10,53]. The average concentration of metals and metalloids in rice samples was lower than the permissible limits described by the WHO. The concentration of metals and metalloids in rice kernels varies according to the location and presence of industrialized areas near the rice fields [53]. Although our study showed that Cd and Cr levels in rice were low, several researchers have reported higher metal and metalloid concentrations in rice [54,55].

The main reason behind the accumulation of metals and metalloids in eatable commodities is rapid industrialization, and soil, air, and water pollution because of the inadequate disposal of waste materials [3,38]. Thus, the main sources for the accumulation of metals and metalloids in soil and water are both natural and man-made [56]. These sources cause metal and metalloid buildup in the groundwater and soil rhizosphere, and affect the level of crops [57–59]. The accumulation of metals and metalloids in the soil–plant continuum is mainly due to anthropogenic sources such as pesticides, fertilizer residues [60], and domestic wastewater [61]. Human activities are the principal sources of metals and metalloids in paddy fields. The contents of these potentially toxic metals and metalloids in industrialized areas are generally higher than in non-industrialized areas [62], which results in enrichment in the soil and grain samples [63,64].

The concentration and type of metal behave differently in the soil–plant system. The values of BAF and PLI higher than permissible limits might be due to deteriorated water quality, excessive use of fertilizers (phosphatic fertilizers), and the contamination of groundwater with industrial effluents. The likely reason for the lower pollution load index values in the studied region may be the low density of industrial units [65]. Similarly, Cr showed maximum BAF in Faisalabad, which might be due to the maximum accumulation of metals and metalloids in the soil rhizosphere, as this region is heavily industrialized. The variation in the BAF values might be due to crop type, rooting behaviors, the movement of metals and metalloids in the soil–plant continuum, and several edaphic factors [66]. Metals and metalloids of higher values of BAF seem to have a greater accumulation ability of these elements from soil to rice kernels [10,65]. Variations in the HRI values were observed at all the experimental sites. The health risk of single-metal exposure was found to be low, and safe for the consumption of food items, but the combination of several heavy metals may cause significant risks [66–69]. Exposure to two or more contaminants (i.e., heavy metals) may result in additive or synergistic effects [70–72] on life, including human life.

Heavy metal and metalloid exposure pathways include consuming food in both fresh and processed forms [73,74]. However, more studies on other pathways should be carried out to assess human health risks. Based on the results obtained in this study, it can be suggested that measures must be taken to ensure the safety of local food in terms of contaminant levels and reduce the risks from all possible exposure pathways. Considering the limited number of soil and rice samples analyzed in this investigation, future research with a larger number of samples and larger areas is required to advance our understanding of human dietary exposure and potential health dangers from heavy metals.

5. Conclusions

This study showed that super basmati was the most cultivated and consumer-preferred rice type in the study area. Most of the metals and metalloid contents in all samples from the study area were found to be above the allowable limits set by FAO/WHO. A higher value of the pollution load index was observed for As and Hg, hence putting the local communities in Lahore, Faisalabad, and Narowal at risk. Furthermore, several additional factors such as the excessive use of fertilizers, the input of industrial waste, herbicide sprays, and the application of toxic agricultural chemicals contaminating the irrigation water are the possible causes of elevated metals in edible basmati rice types. This study highlighted the importance of assessing the heavy metal pollution situation and encouraging routine monitoring programs to meet the criteria of the Sustainable Development Goals (SDGs) of "Zero hunger" and "Good health and well-being". The results of this study could be used to create new monitoring programs and encourage people to take preventive steps to lower the risks associated with rice consumption.

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