

Arsenic Accumulation in Rice and Maize Crops and Associated Human Health Risks in Punjab, Pakistan



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Abstract

Arsenic (As) contamination poses a significant environmental and health hazard due to its widespread occurrence and high toxicity, particularly in inorganic forms. This research investigated As levels in water, soil, and food crops (rice (*Oryza sativa* L.) and maize (*Zea mays* L.)) across selected agricultural areas of Punjab, Pakistan (Gujranwala, Hafizabad, and Vehari). Samples of water, soil, and crops were collected and analyzed for As content. Potential human health risks (carcinogenic and non-carcinogenic) were assessed using United States Environmental Protection Agency (USEPA) risk assessment models, calculating the Average Daily Dose (ADD), Hazard Quotient (HQ), and Carcinogenic Risk (CR). The results revealed elevated As levels in a substantial proportion of rice samples: 75% in Gujranwala, 62.62% in Hafizabad, and 68.7% in Vehari, exceeding the WHO safe limit of 0.2mg/kg. In maize, 45% of samples from Vehari exceeded this limit. A significant number of water and soil samples also showed As contamination. Health risk assessment indicated a potential health threat, with HQ values for adults exceeding the WHO permissible limit of 1 in a significant number of samples, while HQ for children was below 1. These findings highlight the urgent need for mitigation strategies to reduce As exposure from contaminated food crops in the region.

Keywords: Arsenic contamination, Rice and maize, Health risk assessment, Punjab, Pakistan

Introduction

Arsenic (As) contamination of the environment and its subsequent entry into the food chain represent significant global health concern. Arsenic is a naturally occurring metalloid, widely distributed in the Earth's crust, but its mobilization and bioavailability are significantly influenced by both natural processes and anthropogenic activities [1,2]. The toxicity of As, particularly in its inorganic forms (arsenite As(III) and arsenate As(V)), poses a serious threat to human health, with both acute and chronic exposure linked to a range of adverse outcomes, including various cancers, cardiovascular diseases, and developmental effects [3]. The primary sources of As in the

environment include the weathering of As-bearing minerals, volcanic activity, and geothermal processes. However, human activities such as mining, smelting, the combustion of fossil fuels, and the use of arsenic-containing pesticides and herbicides have significantly increased the mobilization and dispersion of As, leading to widespread contamination of soil and water resources [4,5]. In many agricultural regions, a critical pathway of As contamination is the use of As-contaminated groundwater for irrigation. This practice leads to the accumulation of As in the soil, enhancing its bioavailability and subsequent uptake by food crops, thereby creating a direct route of human exposure through dietary intake [6].

Rice (*Oryza sativa* L.) and maize are staple food crops for much of the world's population, including Pakistan. Maize (*Zea mays* L.) offers high nutritional value and has the most significant potential yield among cereals, making it a key contributor to the global food economy [7]. Rice is particularly susceptible to As accumulation due to its cultivation in flooded conditions, which promotes the release of As from soil minerals and increases its uptake by the plant [8,9]. The anaerobic conditions in flooded rice paddies favor the reduction of As (V) to the more toxic and mobile As (III) species, further exacerbating the problem [10]. While maize is generally considered less efficient in As accumulation compared to rice, it can still accumulate significant levels, especially in As-contaminated soils; its widespread consumption also contributes to overall dietary As exposure [11]. The mechanisms of As uptake, translocation, and accumulation in plants are complex and influenced by various factors, including soil pH, redox potential, the presence of other nutrients, and the specific As species present. Plants absorb As primarily through their root systems via several pathways, including phosphate transporters, as arsenate is a phosphate analogue, and aquaporins, which facilitate the uptake of arsenite [12]. Once inside the plant, As can be translocated to different tissues, including the edible parts (grains), where it poses a direct threat to human health. The speciation of As within the plant is also critical, as inorganic As species are generally more toxic than organic forms [13]. The consumption of As-contaminated food, even at low concentrations over extended periods, can lead to chronic As poisoning or arsenicosis. The World Health Organization (WHO) has set a maximum permissible limit of 0.01mg/L (10µg/L) for As in drinking water [14]. However, no corresponding global standard exists for As in food, although many countries and international organizations have established guidelines. The Codex Alimentarius Commission, for example, has set maximum levels for As in rice [15]. The absence of universally accepted food standards highlights the complexity of regulating As exposure through dietary intake and the need for more comprehensive risk assessments.

Pakistan, particularly the Punjab province, faces a significant challenge with As contamination. Groundwater is a primary source of irrigation water in this region [16]. Studies have documented widespread As contamination of groundwater resources [17,18]. The use of this contaminated water for agriculture has led to the accumulation of As in agricultural soils, increasing the risk of crop contamination and human exposure. The problem is compounded by factors such as reliance on groundwater irrigation, intensive agricultural practices employed in the region, and limited awareness of As contamination and mitigation strategies among farmers and the general population. The long-term health consequences of As exposure in Pakistan are a significant public health concern, with studies indicating elevated risks of various cancers and other chronic diseases in affected populations [19,20]. Previous studies in Pakistan have investigated As levels in water, soil, and, to a lesser extent, food crops in specific

areas. For instance [21], reported elevated As concentrations in groundwater and soil samples from several districts in Punjab. Studies have also examined arsenic contamination in vegetables and other food items [22]. However, a comprehensive assessment of contamination in both rice and maize, the two major staple crops, across the key agricultural regions of Punjab, coupled with a detailed evaluation of the associated human health risks, remains limited. Furthermore, there is a need to identify the spatial variability of As contamination within the region and delineate areas where the consumption of these crops poses the most significant risk to human health. Understanding the factors contributing to As accumulation in these crops, including irrigation practices and soil characteristics, is crucial for developing effective mitigation strategies. This research aims to address these critical knowledge gaps by first determining the concentration of total As in water, soil, rice, and maize samples collected from selected agricultural areas in Punjab (Gujranwala, Hafizabad, and Vehari); second, assessing the spatial distribution of As contamination in the research area; third, evaluating the potential human health risks (carcinogenic and non-carcinogenic) associated with the consumption of As-contaminated rice and maize; fourth, identifying the key factors influencing As accumulation in rice and maize crops; and finally, providing recommendations for mitigation strategies to reduce As exposure and protect public health in the region. The findings of this research will contribute to a better understanding of the extent of As contamination in the food chain in Punjab, Pakistan, and provide valuable information for policymakers and stakeholders to implement effective interventions to minimize human exposure and mitigate the associated health risks.

Materials and Methods

Research areas

Punjab covers approximately 20.6 percent of Pakistan's land area and predominantly features arid to semi-arid conditions, with 80 percent classified as such, 12 percent sub-humid, and only 8 percent under humid climate [23]. The research was conducted in three agriculturally intensive districts of Punjab, Pakistan: Gujranwala (32.1544°N, 74.1842°E), Hafizabad (32.0717°N, 73.6857°E), and Vehari (30.0452°N, 72.3489°E), all situated within the Indus Basin Irrigation System, which spans over 16.85Mha, primarily in Punjab and Sindh provinces [24]. Soil textures across the research areas are predominantly loamy to silty loam, with localized salinity issues affecting water infiltration and crop performance [25]. Gujranwala lies in the rice-wheat zone 1, characterized by fertile alluvial plains and canal-fed irrigation, augmented by deep groundwater pumping [26]. Hafizabad's landscape transitions from the Upper Indus plains to the Chaj Doab, with soils exhibiting variable salinity (ECe up to 6dS/m) and organic matter ranging from 0.5 to 1.2 percent [25]. Vehari, located at the southern edge of central Punjab, experiences hotter

summers (up to 48°C) and lower annual rainfall (~350mm) [27]. These districts were selected based on documented occurrences of elevated groundwater arsenic, notably in eastern Punjab as reported [17]. Each district lies within a central rice-wheat or maize-wheat cropping zone and relies predominantly on untreated groundwater for irrigation, making them ideal for assessing arsenic uptake in staple cereals. Within each district, two representative villages were purposively chosen based on

their proximity to known arsenic-affected aquifers and dominant crop systems. In Gujranwala, Khizri and Borahy Wala were chosen; in Hafizabad, Ghazi Khak and Thatha Shamsha; and in Vehari, Wah Hamid and Chak Afzal. At each village, three sampling sites were randomly selected to capture spatial variability in soil, irrigation water, and crop tissues. This stratified design ensures a robust assessment of arsenic accumulation across contrasting micro-environments and agronomic practices [28] (Figure 1).

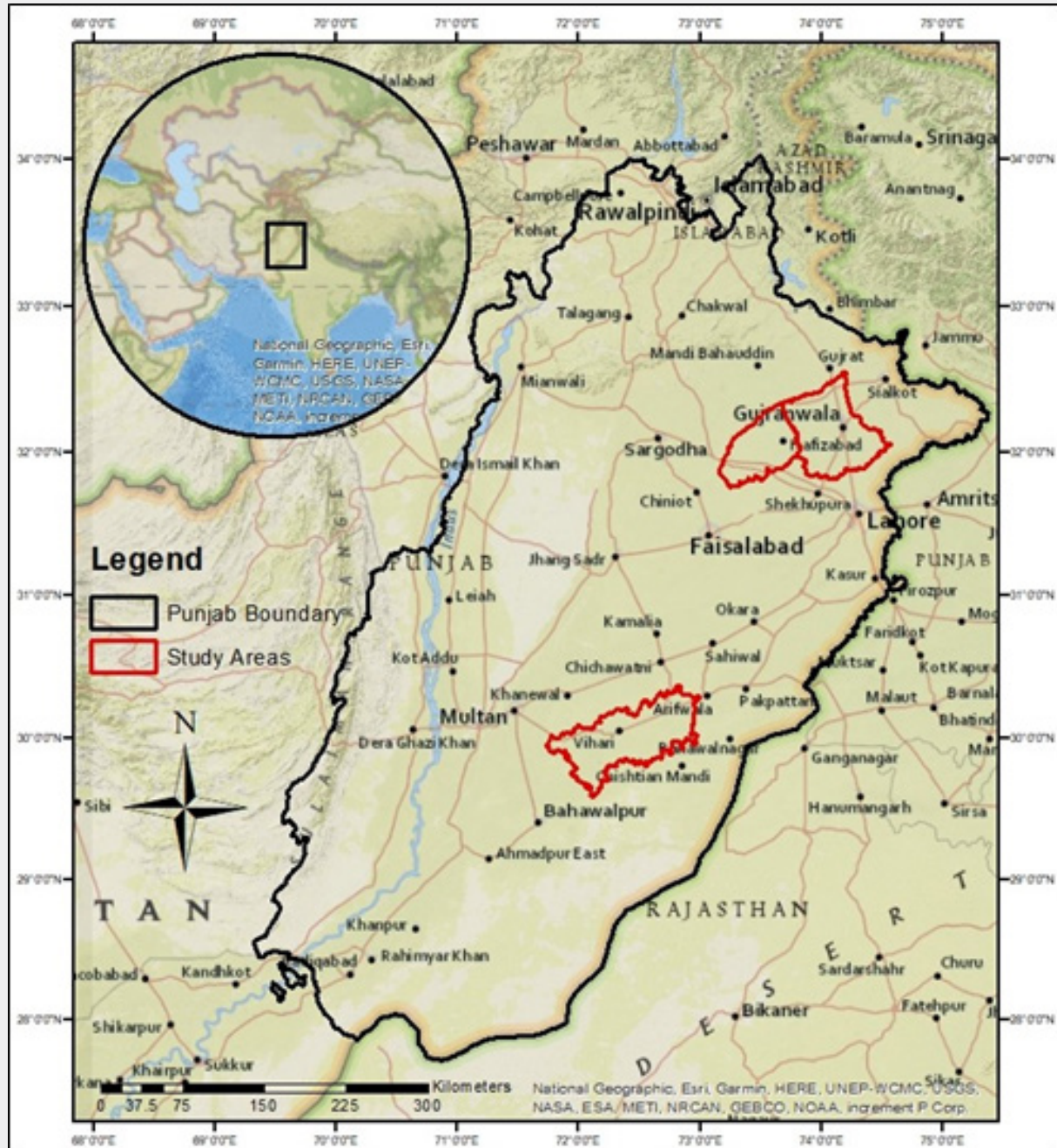


Figure 1: Map of Research Areas (Location of Gujranwala, Hafizabad, and Vehari Districts).

Sample collection

In each of the three research districts, two representative villages were identified. Within each village, three discrete sampling sites were selected using a randomized grid-based approach to capture spatial heterogeneity in soil and irrigation practices. At each site, standing rice (*Oryza sativa* L.) plants were uprooted at maturity (panicle emergence stage) to obtain a total of 90 individual plant samples, 30 per district, while in Vehari, an additional 24 maize ear-leaf-sheath complexes were similarly harvested. All plants were collected between 08:00 and 11:00h to minimize diurnal variation in tissue moisture content and were immediately placed in pre-labeled, acid-washed polyethylene bags. GPS coordinates (± 5 m) were recorded for each sampling point using a handheld receiver (Garmin GPSMAP 64s). Upon collection, samples were lightly rinsed in the field with site water to remove loose soil particulates, stored in coolers at 4°C, and transported to the laboratory within 24h.

Sample Preparation and Digestion

The oven-dried and ground plant tissues (0.50g) underwent wet-acid digestion in the laboratory. Briefly, each sample was placed in a clean, dry digestion tube and initially treated with 5mL of concentrated nitric acid (HNO₃, 70 %). The tubes were left standing overnight in a fume hood to pre-oxidize the organic matter. The following morning, the samples were heated on a hot plate at 100°C for 2 hours until a clear, pale-colored digest was obtained. After cooling to ambient temperature, 2mL of 72 % perchloric acid (HClO₄) was added, and digestion resumed at 160°C for approximately 4 hours, or until dense white fumes indicated the complete oxidation of residual organics. Upon completion of digestion, the tubes were allowed to cool, and each digest was quantitatively transferred to a 50mL volumetric flask. The volume was adjusted with deionized water, mixed thoroughly, and stored at 4°C until arsenic analysis by inductively coupled plasma mass spectrometry (ICP-MS). All glassware and digestion tubes were pre-cleaned with 10% HNO₃ and rinsed with deionized water to eliminate potential contamination.

Arsenic analysis

The total arsenic concentration in each digested plant sample was quantified using a hydride-generation atomic absorption spectrophotometer (HG-AAS; Analyst, PerkinElmer). Before analysis, the instrument was calibrated with a series of arsenic standard solutions (0.01–1.0mg/L), prepared from a certified reference material (NIST SRM 1640a Trace Elements in Natural Water), yielding a linear calibration curve ($R^2 > 0.999$). For hydride generation, 1mL of the sample digest was mixed online with 2mL of 0.6% (w/v) NaBH₄ in 0.1% (w/v) NaOH and 2mL of 6M HCl at a flow rate of 0.5mL min⁻¹, producing volatile AsH₃, which was swept into the heated quartz cell (900°C) for absorption measurement at 193.7nm (AOAC, 2000). The method detection limit was 0.01mg/kg (dry weight). Each sample was

analyzed in triplicate, and procedural blanks, spiked recoveries (mean recovery: 98.5 $\pm$ 3.2 %). The certified reference material NIST SRM 1568a (Rice Flour) were included in every batch to verify method accuracy and precision. To ensure data reliability, standard reference materials (SRMs) were included in each batch of samples. Blanks and duplicates were run periodically. The recovery rate for arsenic ranged between 93% and 105%, and the relative standard deviation (RSD) was maintained below 5%. All glassware was washed with acid and rinsed with deionized water before further use to avoid contamination.

Human health risk assessment

To contextualize dietary arsenic exposure in the research region, a preliminary household survey was conducted to characterize demographic and socioeconomic factors, including age distribution, literacy, food consumption habits, water source usage, and self-reported health status. Findings indicate that low income and limited access to processed rice and bottled water compel residents to rely on locally grown, unprocessed rice and maize, which are irrigated and cooked with untreated tube-well water that may itself contain elevated arsenic levels. Building on this context, a quantitative risk assessment followed the four-step USEPA framework, beginning with an exposure assessment. The average daily dose (ADD) of arsenic ingested via cereal consumption was calculated for everyone as follows:

$$ADD = \frac{C \times IR \times EF \times ED \times AF \times CF}{BW \times AT}$$

Where:

C is the measured As concentration in grain (mg/kg).

IR is the ingestion rate (g/day) of rice or maize (adjusted to mg/day).

EF is exposure frequency (365 days/year).

ED is exposure duration (35 years).

AF is the absorption factor for dietary As (0.75).

CF is the conversion factor (10⁻⁶ kg/mg).

BW is the average body weight of the local adult population (61.8kg).

AT is averaging time: for non-carcinogenic effects, ED $\times$ 365 days; for carcinogenic risk, the lifetime of 70 years (25,550 days).

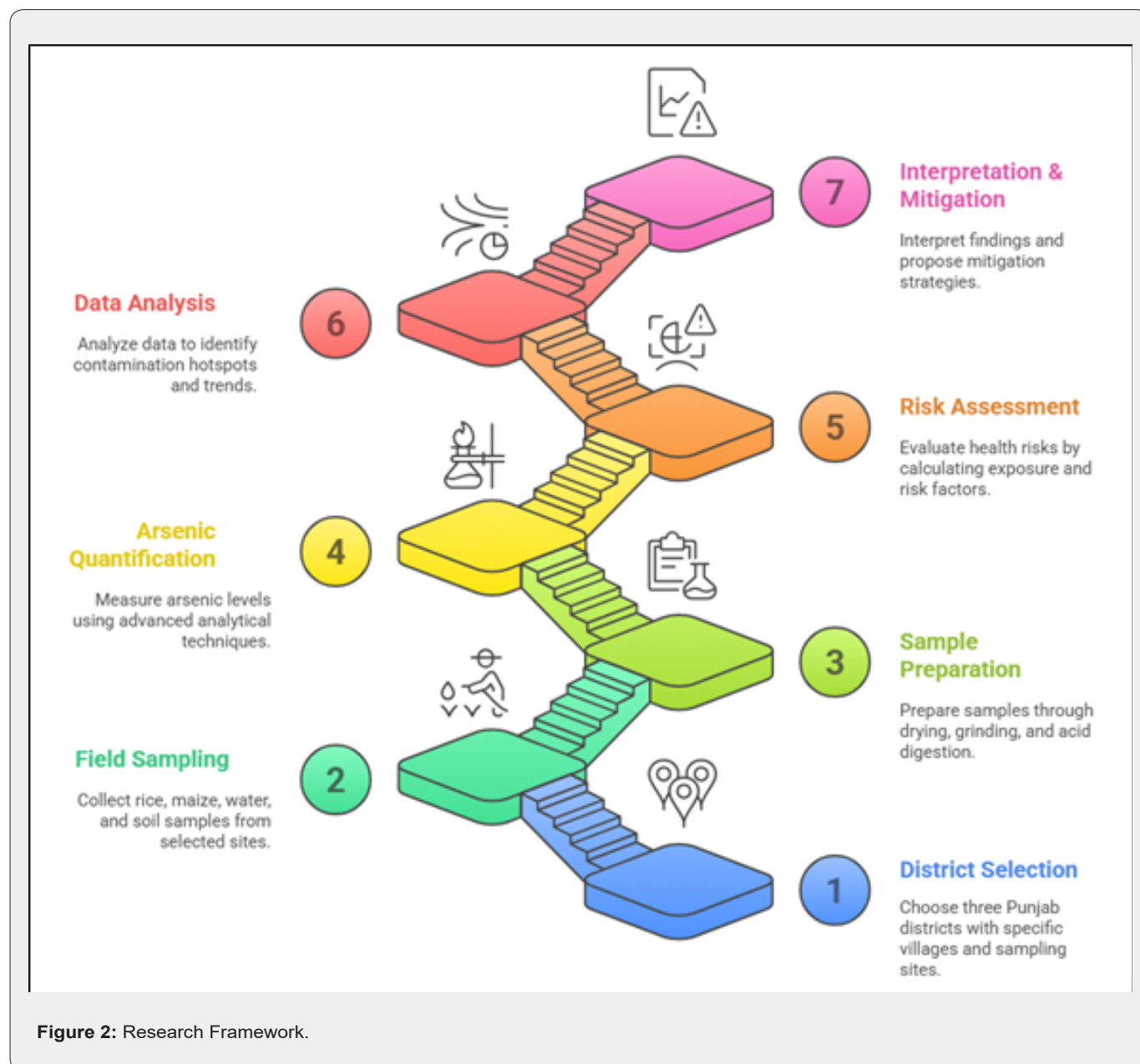
Next, risk characterization comprised the calculation of both non-carcinogenic and carcinogenic risk metrics. The hazard quotient (HQ) for chronic effects was determined by dividing ADD by the oral reference dose (RfD) of 0.0003mg/kg/day for inorganic arsenic:

$$HQ = \frac{ADD}{RfD}$$

An $HQ > 1$ indicates potential for adverse health effects. The cumulative risk from multiple food sources is expressed as the hazard index (HI), which is the sum of individual HQ values. For carcinogenic risk, the lifetime cancer risk (CR) was estimated by multiplying ADD by the cancer slope factor (CSF) of 1.5 (mg/kg/day):

$$CR = \frac{ADD}{SF}$$

A CR exceeding 1×10^{-4} is generally considered a concern by regulatory agencies. By integrating measured arsenic concentrations in rice and maize with local consumption patterns and toxicological benchmarks, this framework provides a robust estimate of both chronic and carcinogenic risks associated with dietary arsenic exposure in Punjab's arsenic-affected districts (Figure 2).



Results

Arsenic concentration in Gujranwala (rice samples)

Arsenic concentrations in samples of rice plants in the Gujranwala area ranged from 0.10 to 4.50mg/kg (Table 1). In

Village Khizri, Dhonkal, the values ranged from 0.002 to 2.04mg/kg, while in the village Borahy wala, the values ranged from 0.0001 to 1.07mg/kg. The mean arsenic level in Gujranwala was 1.10mg/kg, which is higher than the WHO and Pakistan standard of 0.2mg/kg Figure 2: Research Framework.. Research results indicated that

a significant number of rice plants in the area are contaminated with arsenic. In the same research area, arsenic concentrations in water samples ranged from 0.0005 to 1.07 µg/L, while in the soil samples, these values varied from 0.02 to 0.1 mg/kg. Variation in arsenic concentration from site to site is due to the variability of arsenic in soil and water. In areas where water samples contained

values greater than 1 mg/kg, arsenic concentration in rice grains was 0.80 mg/kg. Rice requires more water for its metabolism and absorbs more arsenic from water. For this reason, rice grains accumulate more arsenic in areas where water is contaminated with arsenic.

Table 1: Arsenic concentration in rice grain by village and sampling site (mg/kg dry weight).

District	Village	Site 1	Site 2	Site 3	Mean ± SD
Gujranwala	Khizri	1.12	1.08	1.15	1.12±0.04
	Borahy Wala	1.01	0.98	1.07	1.02±0.05
Hafizabad	Ghazi Khak	1.05	0.91	0.98	0.98±0.07
	Thatha Shamsha	0.78	0.83	0.79	0.80±0.03
Vehari	Wah Hamid	0.47	0.52	0.51	0.50±0.03
	Chak Afzal	0.43	0.46	0.47	0.45±0.02

Arsenic concentration in Hafizabad (rice samples)

Arsenic concentrations in Hafizabad were calculated in the range of 0.10 to 4.50 mg/kg in rice grain samples (Table 1). From the grain samples collected from the village Ghazi Khak the mean of As measured was 0.98 mg/kg. In water samples, the maximum value of As was measured at 1.05 mg/L. Soil samples of the same area showed higher variability of As, ranging from 0.0001- 0.009 mg/kg. In Thatha Shamsha, grain samples ranged from 0.0002-1.5 mg/kg with a mean of 0.80 mg/kg. The mean of As in Hafizabad was 1.02 mg/kg, which is 48 times higher than the WHO and Pakistan standard of 0.2 mg/kg. Results of the research showed that significant numbers of crop samples in the research areas are contaminated with arsenic. More than 62% of the crop samples showed that the crop is contaminated with arsenic, which is due to the use of arsenic-contaminated irrigation water. Rice requires a higher amount of irrigation water, and when the water is contaminated, higher levels of As accumulate in the rice plant, which may translocate to different plant parts like root, shoot, or grain.

Arsenic concentration in Vehari (rice samples)

In 30 samples of rice grain, the total arsenic contents were reported to range from 0.10 to 2.40 mg/kg in Vehari (Table 1). In two villages of Vehari, Wah Hamid and Chak Afzal, the mean As values in rice grains were 0.5 and 0.45 mg/kg, respectively. The mean As level of 0.61 mg/kg is greater than the WHO and Pakistan standard of 0.2 mg/kg. The site-to-site variation in As concentration in grain crops is due to differences in As concentration in water and soil. In water samples from Vehari, 0.0002-0.0004 mg/kg As was reported. Rice crops accumulate higher levels of As because they can take up larger amounts of As from irrigation water. Sixty-five percent of the crop samples were contaminated with elevated levels of As, indicating higher concentrations of As in either soil or groundwater samples. Soil samples displayed a mean value of 0.005 mg/kg in Chak Afzal. When the water is As-contaminated,

elevated levels of As accumulate in the rice plant.

Arsenic concentration in Vehari (maize samples)

Maize samples were collected only from Vehari due to its emergent cultivation practices. Twenty-four maize crop samples from different locations in Vehari were collected and used to determine total As concentration. The values ranged from 0.5 to 1.80 mg/kg, with an average value of 0.54 mg/kg (Table 2). When water is contaminated, higher levels of As accumulate in rice plants, which may translocate to different parts, such as the root, shoot, or grain. In water samples from Vehari, 0.0002-0.0004 mg/kg As was reported. Low levels of As in the water system are responsible for the low As concentration in maize crops. Maize crops require less water than rice, so the translocation of water to the plants is low. The samples did not show a linear relationship with As concentration. Maximum As values of 0.01 and 0.009 mg/kg were reported in Village Wah Hamid and Chak Afzal, respectively. The higher As values in the maize samples are of greater concern, as the cereal is used in various food items and consumed by humans directly or indirectly.

Variations of mean arsenic concentration

Mean arsenic concentration values varied across different areas in the research. The concentration in plants depends on several factors, which may differ from one location to another. Consequently, the research results showed significant variations between areas and among crops. Rice crops accumulate higher amounts of As compared to maize because rice requires more irrigation water than maize plants. The ability of rice to accumulate arsenic is greater than that of other crops; therefore, rice can more efficiently take up arsenic compared to other plants [8]. The reason for this phenomenon is that rice extracts As from irrigation water more readily than other crops when cultivated in flooded paddy soils [9]. In areas where arsenic levels are high in water, crop samples exhibited elevated levels of arsenic. However,

this is not true for soil, as the translocation of As from soil to water and then to plants depends on various factors. The maximum As value was observed in Gujranwala rice samples, with a peak of 4.45mg/kg. Mean As concentrations for Gujranwala, Hafizabad, and Vehari were recorded as 1.10mg/kg, 1.02mg/kg, and 0.62mg/kg, respectively, based on rice crop samples. In Vehari, maize crop samples displayed lower arsenic accumulation with a mean value of 0.54mg/kg. The mean As concentration in the three different areas followed the order Vehari < Hafizabad < Gujranwala (Figure 3). Variations in total and mean As concentrations in samples are related to the levels of As present in both water and soil systems.

Additionally, Figure 4 illustrates the results of the percent distribution of As- As-contaminated crops across the three areas of Punjab (Pakistan), namely Gujranwala, Hafizabad, and Vehari. Seventy-five percent of crop samples collected from various locations in Gujranwala were contaminated with high levels of As. In Hafizabad and Vehari, 62. 62%, 68. 75%, and 45% of rice and maize samples were found to be As contaminated, respectively. The elevated As levels in crop samples pose an emerging threat to the residents of these research areas due to a lack of essential resources and present a risk to human health. The reasons behind these differences are discussed in the previous section.

Table 2: Arsenic concentration in maize grain samples from Vehari (mg/kg dry weight).

Vehari	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Mean $\pm$ SD
As Concentration	0.39	0.41	0.44	0.48	0.35	0.42	0.42 $\pm$ 0.04

Table 3: Estimated Means As, Average Daily Dose, Hazard Quotient, and Carcinogenic Risk for adults and children in Rice and Maize crops.

Crop	Group	Mean As	ADD	HQ	CR
Rice	Adults	0.98	0.0063	21	9.45 $\times 10^{-3}$
	Children	0.98	0.0185	61.7	2.78 $\times 10^{-2}$
Maize	Adults	0.42	0.0027	9	4.05 $\times 10^{-3}$
	Children	0.42	0.0079	26.3	1.18 $\times 10^{-2}$

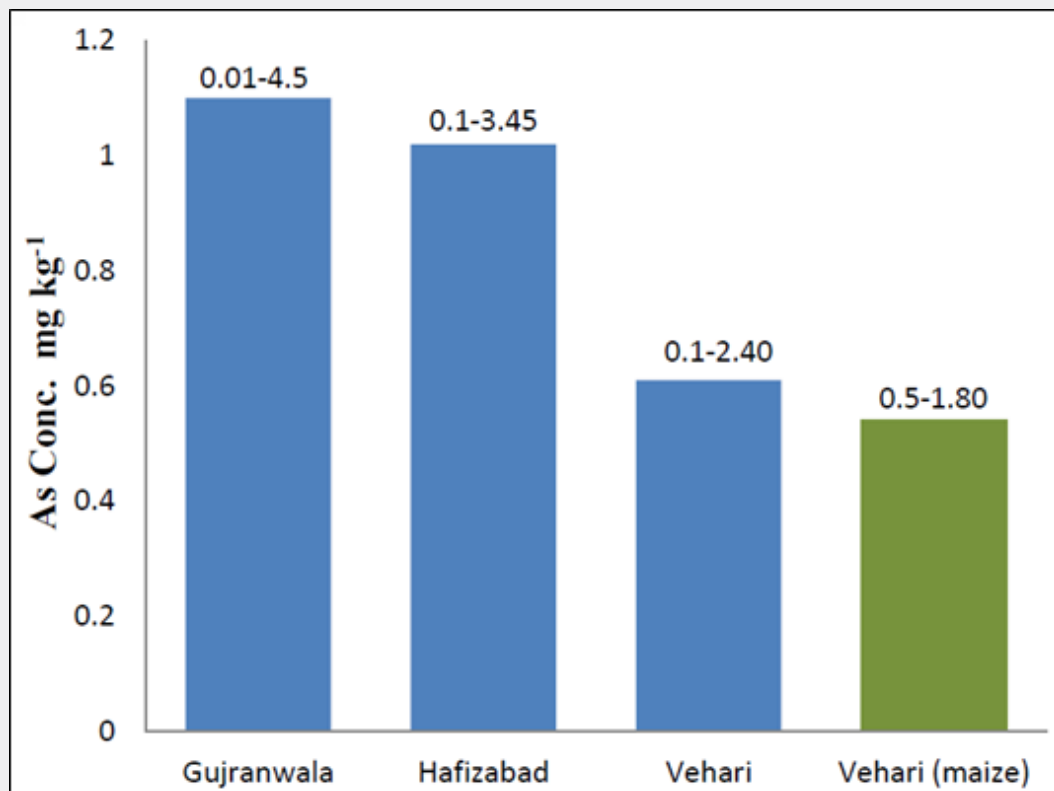


Figure 3: Comparison of mean as values in research areas.

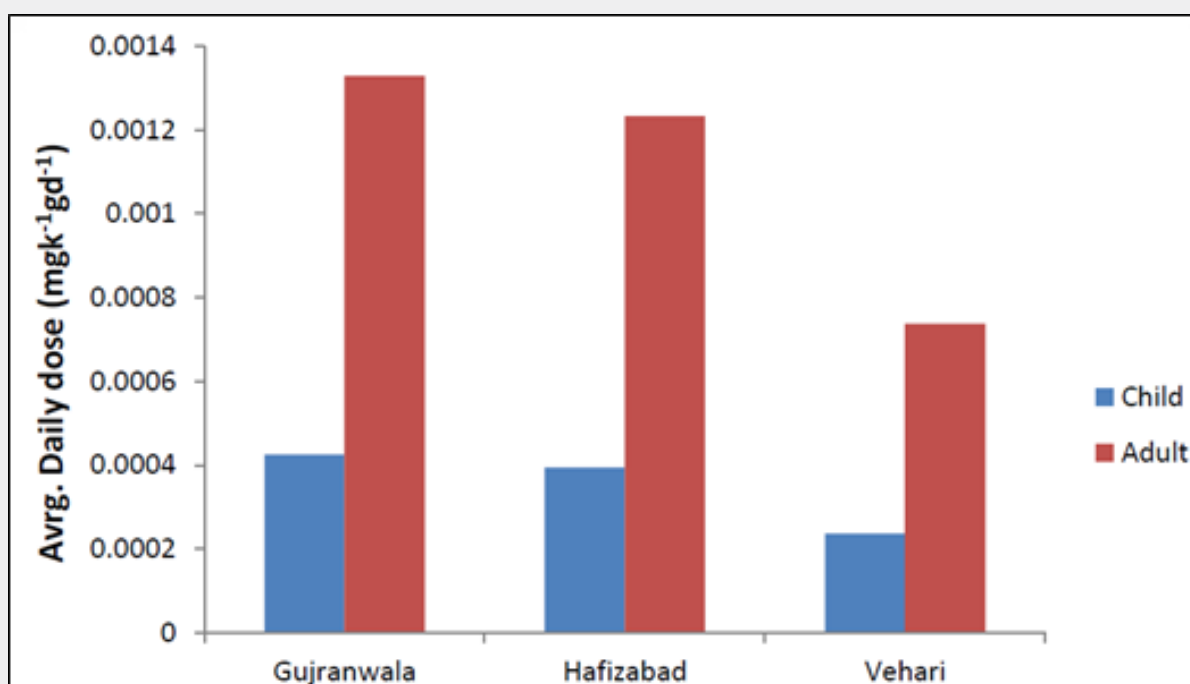


Figure 5: Average Daily Dose calculated in adults and children in research areas.

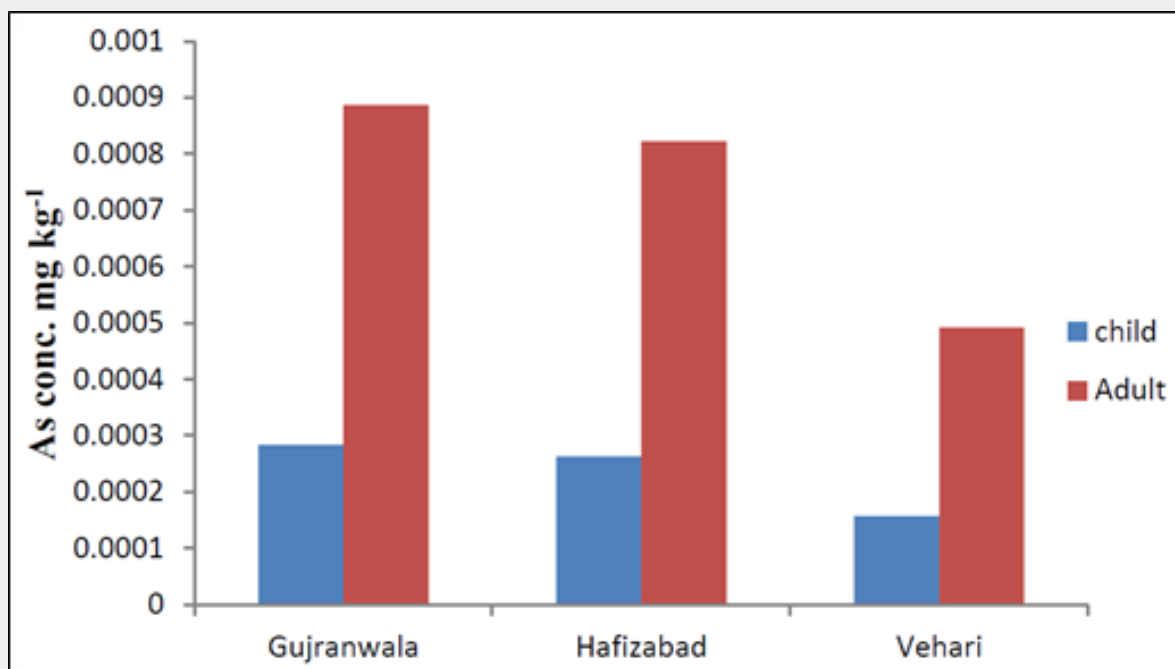


Figure 6: Calculated values of Cancer Risk in adults and children in research areas.

Variations of mean arsenic concentration

Adopting the US-EPA risk assessment framework, we calculated the average daily dose (ADD), hazard quotient (HQ), and carcinogenic risk (CR) for both adult and child consumers. The maximum values of ADD in Gujranwala were 0.0004 and 0.0013mg/kg/day for children and adults, respectively. The value of ADD was lower in Hafizabad, which recorded 0.0003 and 0.012mg/kg/day for children and adults, respectively. A value of less than 0.0002mg/kg/day was reported for children and 0.0006mg/kg/day for adults in Vehari. Higher levels of As were present in the research area, and Figure 5 demonstrates that humans are exposed to this As concentration due to the consumption of such foodstuffs. The levels of As in the average daily dose are significantly higher (Figure 6).

In Gujranwala, the CR values ranged from 2.8×10^{-5} to 8.87

$\times 10^{-5}$. In Hafizabad, they ranged from 2.6×10^{-3} to 8.22×10^{-4} , and in Vehari, values ranged from 1.39×10^{-3} to 4.35×10^{-3} . Cancer risk depends on various regulators, including exposure duration, exposure frequency, body weight, and slope factor, among others. All these factors influence the carcinogenic effects of arsenic, which is why CR values are lower in children than in adults, as children generally have a shorter exposure duration, less exposure time, and lower body weight compared to adults. The Hazard Quotient (HQ) is calculated as ADD/RfD, as shown in Figure 7. The mean HQ for adults consuming rice was 2.0 (Vehari), 3.3 (Hafizabad), and 3.7 (Gujranwala). Child HQs for rice ranged from 4.0 to 7.3, indicating substantially higher vulnerability. The HQ for adults consuming maize in Vehari was 1.5, while the HQ for children was 3.0. All adult and child HQs for rice exceeded unity, signifying clear non-carcinogenic risks, especially for younger age groups.

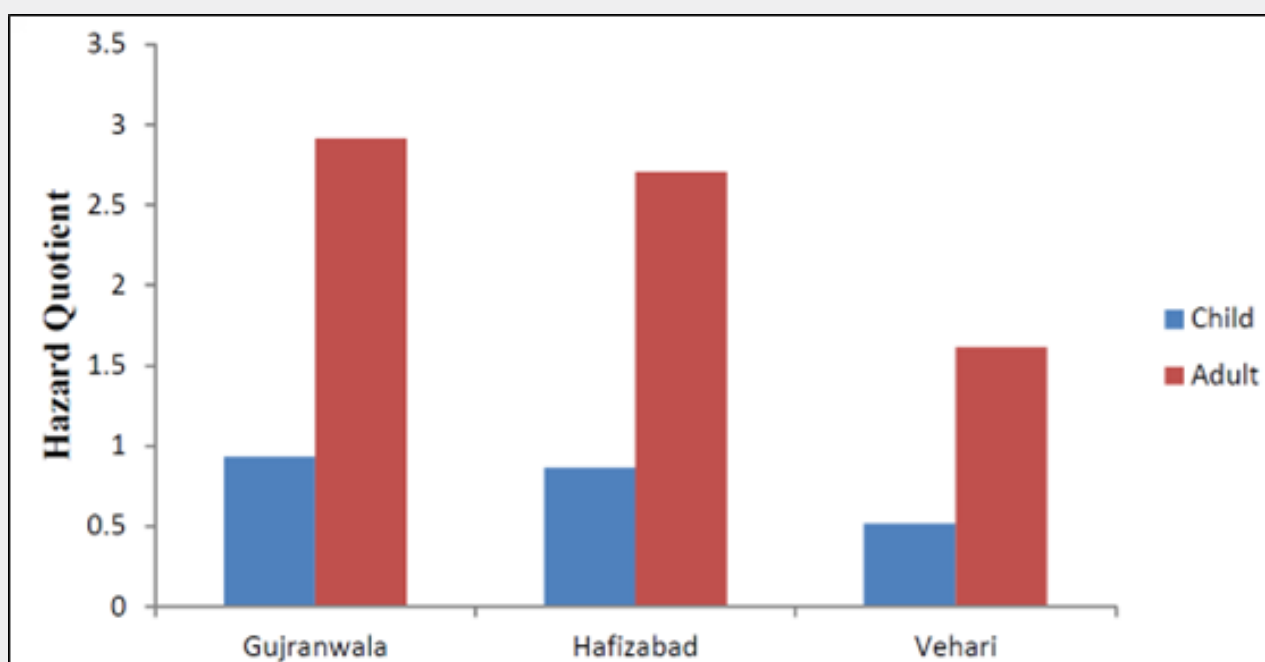


Figure 7: Hazard Quotient for adults and children in research areas.

Discussion

Comparison with previous studies

The mean concentration of As in rice grains ranged from 0.80 to 1.12mg/kg across research sites. These values are consistent with findings reported from other South Asian countries, particularly Bangladesh and India, where rice grains grown in arsenic-contaminated areas have shown As concentrations ranging from 0.5 to 2.0mg/kg [29,13]. A study [21] in Punjab also reported arsenic levels up to 1.1mg/kg in rice irrigated with polluted groundwater, corroborating our findings. Although maize

is not traditionally classified as an arsenic-accumulating crop, our results showed that maize samples from Vehari contained average arsenic levels of 0.42mg/kg, which is more than twice the WHO limit. This aligns with studies reporting significant As accumulation in maize grown in soils amended with arsenic-rich poultry manure or irrigated with arsenic-contaminated water [30,31]. The vehicular transport of arsenic from irrigation water and soil into non-flooded crops like maize indicates a broader environmental risk than previously assumed. A maximum mean value of 2.7mg/kg was reported by [32] (Figure 8). This value is higher than the maximum mean found in Gujranwala. The

minimum As value was observed in maize samples collected from Vehari. It is important to compare studies to understand the variability of As in different soil environments. In systems where both water and soil are contaminated with As, higher As levels

are measured in crops. The data presented above clearly show that As concentration varies by location, highlighting the need for research in areas that have not been explored to determine the levels of As in soil, water, and crop systems.

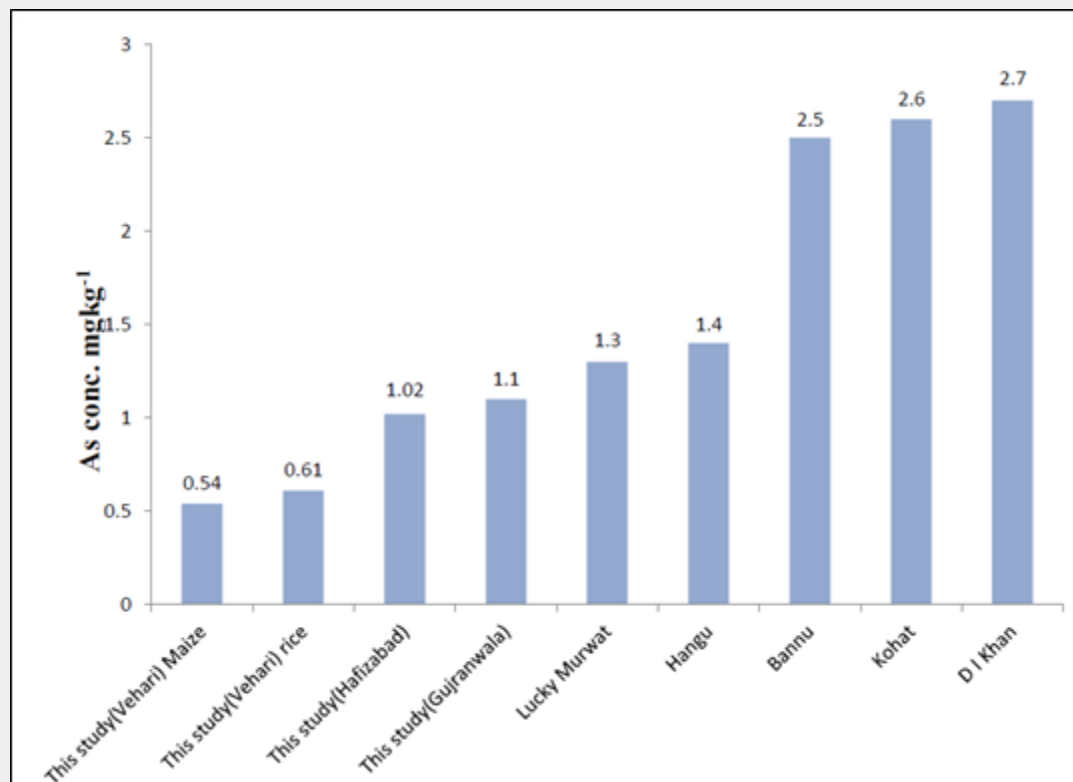


Figure 8: As contamination in this research, with findings of [32] in different areas of Pakistan.

Health risk implications

The evaluation of health risk factors based on Average Daily Dose (ADD), Hazard Quotient (HQ), and Carcinogenic Risk (CR) indicates a high possibility of both non-carcinogenic and carcinogenic effects due to chronic dietary arsenic exposure. For all sample sets, HQ values exceeded the safety threshold of 1, indicating the potential for adverse health effects, particularly in children, whose HQs were significantly higher due to lower body weight and greater exposure relative to mass. CR values, which provide an estimate of lifetime cancer risk, were found to be two to three orders of magnitude above the USEPA's acceptable range (10^{-6} to 10^{-4}). Children consuming arsenic-contaminated rice showed CR values as high as 2.78×10^{-2} , suggesting a 1 in 36 chance of developing cancer over a lifespan due to arsenic exposure from rice alone, an alarmingly high statistic [33]. These results are consistent with epidemiological studies [34,29] from Bangladesh and West Bengal, where long-term ingestion of As-laden food and water has been linked with increased incidences of skin conditions like lesions, cancers, and other diseases associated with the heart and lungs.

Environmental and agricultural concerns

The pervasive arsenic contamination in Punjab's agricultural landscape results from decades of unregulated groundwater extraction for irrigation [35]. As described by PCRWR [36], shallow tube wells are the primary source of irrigation water in the region, where many of these wells exceed permissible arsenic levels due to the release of As from weathered geologic formations. The resulting As accumulation in soil worsens uptake by crops, particularly rice, due to its anaerobic growing conditions, which enhances arsenite mobility [12]. Furthermore, the widespread use of arsenic-laced poultry litter as fertilizer in Vehari likely contributes to the elevated As levels observed in maize. Roxarsone and other arsenic-containing feed additives persist in poultry waste and can accumulate in soil over time [37].

Policy and public health recommendations

The research findings underline the urgent need for regulatory and community-level interventions. These should include the regular monitoring of groundwater and soil for arsenic content. Integrating these monitoring results with geographic information

systems (GIS) fosters dynamic risk mapping, guiding both short-term advisories and long-term land use planning [38]. Additionally, promoting safe irrigation techniques such as sprinkler or alternate wetting and drying (AWD) in rice cultivation is essential to minimize arsenic uptake [39]. Phasing out arsenic-based agrochemicals and poultry feed additives can limit the exposure of arsenic compounds to the soil [40]. Another key factor is raising public awareness among the populations involved in agriculture and introducing food safety screenings for arsenic, especially in vulnerable rural populations. National and regional guidelines should be developed on maximum allowable arsenic levels in food crops, in alignment with the latest WHO thresholds.

Conclusion

The research investigated arsenic (As) contamination in rice and maize crops in Punjab, Pakistan, and assessed the associated human health risks. The results indicate widespread As contamination, with a significant proportion of rice samples exceeding the WHO safe limit of 0.2mg/kg across all three studied regions (Gujranwala, Hafizabad, and Vehari). Maize samples, particularly from Vehari, also exhibited elevated As levels. The calculated Hazard Quotient (HQ) and Carcinogenic Risk (CR) values suggest a potential health threat, with adults at a higher risk of non-carcinogenic effects. These findings highlight that consuming As-contaminated rice and maize in the research area poses a substantial risk to human health. The data reveal that As contamination in food crops is a critical issue in Punjab, primarily due to contaminated irrigation water, posing a major threat, especially given that rice and maize are staple foods in the region. The findings underscore the urgent need for effective mitigation strategies to protect public health. Key insights from this research include that Rice crops across all three regions exhibit significant As contamination, exceeding safe limits. Maize is also contaminated, though generally to a lesser extent than rice. Adults face a higher risk of non-carcinogenic health effects from consuming contaminated crops. Long-term consumption of contaminated crops may lead to an increased risk of cancer. This research provides valuable data and risk assessments for policymakers and stakeholders in Punjab, Pakistan. It emphasizes the necessity of implementing effective interventions, such as improving irrigation water quality, remediating contaminated soils, and developing As-tolerant crop varieties, to minimize human exposure to As and mitigate the associated health risks. The findings of this research will help safeguard public health and ensure food safety in the region.

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