

CADMIUM CONTAMINATION IN RICE AND ASSOCIATED HUMAN HEALTH RISK

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Rice (*Oryza sativa* L.), the traditional food for the Bangladeshi population, serves as a significant disclosure pathway of cadmium for humans. A few studies have explored cadmium levels in different rice varieties in Bangladesh. The study examined the impacts of cadmium pollution on growth, and productivity and evaluated the varietal resistance. Cadmium was added to the soil at 15 mg/kg. A pot experiment involving nine T-aman rice varieties was conducted at 0 (control) and 15 mg Cd/kg soil. Cadmium toxicity led to reduced quantity and quality of rice production. Cadmium pollution enhanced the grain cadmium levels while depleting the amounts of nitrogen, phosphorus, potassium, and sulphur. Local varieties and BRRI dhan72 exhibited the lowest grain cadmium concentration when grown with 0 mg/kg cadmium in the soil, while BRRI dhan52 (2.94 mg/kg) showed the highest with 15 mg/kg cadmium in the soil. The average daily intake of cadmium from rice grain was higher with 15 mg/kg cadmium addition. All rice varieties showed high HQ (Hazard Quotient) and ILCR (Incremental Lifetime Cancer Risk) values under 15 mg/kg cadmium in soil. The HQ and ILCR values ranged from 2.39 to 16.09, and 0.36×10^{-4} to 2.41×10^{-4} , respectively, for a Bangladeshi adult due to the application of 15 mg/kg cadmium. The highest HQ (16.09) and ILCR (2.41×10^{-4}) values were obtained for BRRI dhan52 at 15 mg/kg cadmium for adults. The susceptibility of the varieties due to 15 mg/kg cadmium may be ranked as BRRI dhan52>Binadhan-23>BRRI dhan79>Binadhan-12>BRRI dhan62>BRRI dhan71>Zeeramala>BRRI dhan72>Local HYV.

Key words: Cd-contamination, rice yield, variety, hazard quotient, cancer risk

Heavy metal contamination is a burning issue due to severe harmfulness, widespread dispersion, long-lasting nature, and bioavailability of these metals in comparison to other pollutants (Fan *et al.* 2017). These pollutants in soil threaten soil quality and compromise the safety of the food supply (Sodango *et al.* 2018). The contamination of paddy by heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb) in Bangladesh has been extensively documented (Jahiruddin *et al.* 2017; Begum *et al.* 2023; Meharg *et al.* 2023; Shahriar *et al.* 2023). Cadmium pollution is a major concern nowadays, particularly in emerging nations

with a high population density (Cai *et al.* 2019a). Both human and natural sources can contaminate soil with cadmium, a major environmental and health problem (Pan *et al.* 2016). Anthropogenic sources such as agricultural activities like phosphorous fertilisation, irrigation with Cd-contaminated water, pesticide application, and industrial activities are the major reasons for Cd enhancement in soil (Bolan *et al.* 2013; Liu *et al.* 2020). Many people worldwide rely on rice as their main food, especially in Asia, where it constitutes approximately 90% of their dietary intake (Kosolsaksakul *et al.* 2014; Mu *et al.* 2019). Rice (*Oryza sativa* L.) is a prima-

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ry contributor to Cd intake, where it is consumed twice or three times daily (Herath *et al.* 2014). The consumption of rice with high levels of cadmium was highest in Bangladesh and Sri Lanka, among 12 countries (Meharg *et al.* 2013). Rice (*Oryza sativa* L.) plants can readily absorb bioavailable Cd from soil and then transfer it to other parts (Song *et al.* 2015). Cadmium stress affects both plant biomass and nutritional status in crops, which ultimately reduces the quality and quantity of crops (Wang *et al.* 2014). Furthermore, it induces genotoxicity and free radical damage in rice (Kanu *et al.* 2017). Cadmium disrupts the translocation and absorption of essential nutrients (Ca, Mg, P, K, and Mn) (Nazar *et al.* 2012). By altering N metabolism, Cd bioaccumulation alters several physiological processes (Chaffei *et al.* 2004). Cadmium consumption is linked to heart failure, anaemia, cancer, hypotension, emphysema, proteinuria, skeletal deformities, lung cancer, renal malfunction in the eyes, and osteoporosis (Ali *et al.* 2013; Ashraf *et al.* 2015). Consuming rice contaminated with Cd causes itai-itai disease, which was first discovered in Japan in 1970 (Kobayashi 1978). Cadmium availability in soil depends on pH, redox conditions, submergence, and the existence of micronutrients such as manganese and zinc (Ferraz *et al.* 2011). Water management during the grain-filling period in flooded rice fields significantly influences Cd concentration, as Cd becomes less soluble in these conditions (Arao *et al.* 2009). To minimize the danger of human exposure from consuming rice, mitigation methods are required to lessen the movement of Cd from root to grain. The most important one is to reduce the anthropogenic sources of cadmium accumulation. Soil dressing, water management, selecting rice cultivars with low Cd accumulation, bioremediation, and soil organic matter management are possible mitigation strategies (Bolan *et al.* 2013; Sebastian & Prasad 2014). Cadmium immobilization through amendments such as biochar, lime, silicon, and sulphur compounds reduces the bioavailability of Cd (Rizwan *et al.* 2016). Rice varieties show significant variation in Cd bioaccumulation. Cadmium accumulation varies in terms of rice genotypes, and it is more concentrated in roots than straw and grain (Liao *et al.* 2016). Understanding these varietal differences is crucial for selecting and breeding rice varieties that are less susceptible

to Cd contamination. Therefore, the selection of suitable rice varieties is important because it can be used for plant breeding to develop a variety with desirable characteristics. In countries with a rice-based diet, it is essential to lower the level of Cd in rice to minimize human health hazards. The present study aimed to evaluate the varietal resistance against Cd toxicity, select the best rice varieties capable of growing well in Cd-contaminated soils but accumulating less Cd in grains, and assess the human health risks of Cd intake through rice consumption.

MATERIAL AND METHODS

Location and initial properties of soil

A pot experiment was conducted in the roadside corner of the Soil Science Field Laboratory of Bangladesh Agricultural University, Mymensingh, throughout the transplanted (T.) aman season (June to November) of 2022. The experimental location maintained an average minimum temperature of 24.71°C, a maximum temperature of 32.06°C, and a consistent relative humidity (RH) of 84.33% throughout the study. It was located at 24° 71.59' N latitude and 90° 42.50' E longitude and had a soil pH of 7.14. It is part of the Sonatala series under agroecological zone (AEZ) 9, recognized as the Old Brahmaputra Floodplain. The soil sample was collected at 0–15 cm from the Soil Science Field. After collection, the sample was processed, and standard methods were employed to assess the properties (Table 1). The soil displayed a silt loam texture and contained a total Cd of 0.56 mg per kg soil.

This experiment involved 18 treatments, which consisted of two levels of Cd viz. 0 (control) and 15 mg Cd/kg soil and nine T-aman rice varieties. The varieties BRRI dhan52, BRRI dhan62, BRRI dhan71, BRRI dhan72, BRRI dhan79, Binadhan-12, Binadhan-23, Zeeramala, Local HYV were used considering yield and other special characteristics. This trial was arranged using a completely randomized design (CRD), comprising three replications. An amount of 18 kg of soil was taken in a single pot and there were altogether 54 pots used for this experiment. The source of Cd was cadmium nitrate tetrahydrate, which was applied once during soil preparation for the pot experiment. The pots expe-

rienced field conditions for 2 weeks, succeeded by saturated conditions for the later 1 week. To cultivate healthy seedlings, the seeds were first subjected to optimal conditions including sufficient water, oxygen, and the right temperature for germination. Once germinated, these seeds were sown in the field for the subsequent pot experiment. Healthy 30-day-aged seedlings were placed in pots with three hills, and a trio of seedlings were set in each hill. All pots received 3.2 g urea, 2.3 g MoP (muriate of potash), 0.98 g TSP (triple super phosphate), and 0.9 g gypsum, respectively as a source of N, K, P, and S. Complete doses of P, K, and S were introduced during the final pot set up, with nitrogen added in equal splits at 7, 30, and 45 days after transplanting (DAT).

Plant analysis

After harvesting, data on plant growth and yield parameters were taken. The yields were estimated on a g/pot basis. Plant samples collected from the pot experiment were analysed for N, K, P, S, Zn, and Cd contents. Grain samples were dehydrated at about 65°C in an oven for 48 hours. The grains were dehusked using a dehusker. Finally, the grain samples were ground in the Ball Mill.

Determination of N, K, P, and S

The samples were ground and examined for N, K, P, and S contents following standard methods (H₂SO₄ digestion for N and HNO₃-HClO₄ process-

ing for P, K & S) in the Soil Science Laboratory, Bangladesh Agricultural University.

Cadmium determination

The cadmium concentration of digested samples was determined through Shimadzu Atomic Absorption Spectrophotometer AA-7000 (SHIMADZU AA-7000). For digestion, a 0.2 g subsample was placed in a digestion tube, adding 5 ml of HNO₃, and allowing it to rest overnight. The next day, 2 ml of H₂O₂ was added, and the tubes were heated on a digestion block, gradually reaching 120°C about 4–5 hours until transparent solutions were obtained. After cooling, the processed sample was diluted to 50 ml with deionized water and filtered.

Cadmium exposure assessment and its health risk

The ADI (Average Daily Intake) of Cd due to rice consumption was determined using this formula (Islam *et al.* 2017; Kibria *et al.* 2022):

$$ADI_{Cd} = \frac{C_{Cd} \times RC \times EF_r \times EP}{ABW \times AET}$$

where: ADI_{Cd} – daily average Cd intake (mg Cd/kg BW/day) (BW – body weight); C_{Cd} – Cd concentration in rice (mg Cd/kg rice grain) (obtained from the present study); RC – rice consumption rate for adults or kids (kg rice/day) [Each adult individual in Bangladesh consumes 0.329 kilograms of rice daily (HIES, 2023)]; EFr – exposure frequency (365 days exposure/year); EP – exposure period [Lifespan for Bangladeshi people is 72.3 years (BBS, 2022)];

T a b l e 1

Different physical and chemical properties of soil from the BAU farm under study

Properties	Method followed	Value	Reference
Textural class	Hydrometer method	Silt loam	Gee and Bauder 1979
pH (Soil: water =1: 2.5)	Glass electrode pH meter	7.14	Jackson 1973
Organic matter [%]	Wet oxidation	1.45	Walkley and Black 1934
CEC [me/100 g soil]	Flame photometric	12.56	Jackson 1967
Total N [%]	Micro-Kjeldahl	0.13	Jackson 1973
Available P [ppm]	Olsen	12.76	Murphy and Riley 1962
Exchangeable K [meq/100 g soil]	NH ₄ OAc extraction	0.11	Kundsen <i>et al.</i> 1982
Available S [mg/Kg]	CaCl ₂ extraction	11.50	Jackson 1973

Note: CEC – Cation Exchange Capacity, BAU – Bangladesh Agricultural University.

ABW – average body weight (kg) [ABW for Bangladeshi adults is 60 kg (Islam *et al.* 2017)] and AET – average exposure time (days) ($365 \text{ days} \times 72.3 \text{ years} = 26389.5 \text{ days}$).

Chronic health hazards of Cd were estimated through HQ_{Cd} :

$$HQ_{Cd} = ADI_{Cd} / RfD_{Cd}$$

where: RfD_{Cd} is the reference dose (mg Cd/kg BW/day). Here, RfD_{Cd} is about $1 \times 10^{-3} \text{ mg/kg BW/day}$. For children, RC – rice consumption 0.15 kg/person/day (Islam *et al.* 2019); EP – 6 years (Cui *et al.* 2018); ABW – 16 kg for Bangladeshi children (Islam *et al.* 2019; AET – ($365 \text{ days} \times 6 \text{ years} = 2190 \text{ days}$)).

The potential cancer hazards linked to the ingestion of Cd exposure were assessed utilizing the subsequent formula (Islam *et al.* 2017):

$$ILCR_{Cd} = ADI_{Cd} \times SF_{Cd}$$

Here, SF_{Cd} – slope factor for Cd ($15 \times 10^{-3} \text{ mg/kg/day}$) (IRIS, 2013).

Statistical analysis

Data collected for each parameter were subjected to Two-way ANOVA, followed by mean separation tests for various treatments that showed significant differences at $p \leq 0.05$, using Tukey's Honest Significant Difference (HSD) test, and correlation coefficients were conducted using R software and graphs were generated using Microsoft Excel.

RESULTS

Effects of cadmium on yield components

Total tillers (TT) and productive tillers (ET) per hill

The combined effect of varieties and 15 mg/kg Cd application led to statistically significant variations over productive tillers per hill but had no significant variations over total tillers per hill (Table 2). The maximum total tillers per hill (14.56) and productive tillers per hill (11.33) were found in Zeeramala and Binadhan-23, respectively, with 0 mg/kg Cd treatment. Local HYV and BRR1 dhan52 with 15 mg/kg Cd treatment produced minimum total tillers per hill (6.74) and productive tillers per hill (5.73),

respectively. Mueez *et al.* (2019) found that varying doses of Cd adversely affected the number of effective tillers, and plant height in different rice varieties including BRR1 dhan29, BRR1 dhan60, and BRR1 dhan61. Cadmium, absorbed by plants from polluted soil, causes physiological and biochemical changes that ultimately affect the rate of plant growth and physical structure (Haider *et al.* 2021).

Plant height (PH) and panicle length (PL)

Soil application of Cd in combination with different rice varieties showed a distinct negative effect on both plant height and panicle length (Table 2). Zeeramala and the Local HYV exhibited the tallest plant height (104.75 cm) and longest panicle length (26.22 cm) with 0 mg/kg Cd treatment. BRR1 dhan62, subjected to 15 mg/kg Cd treatment, displayed the lowest plant height (54.25 cm) and panicle length (12.99 cm). Kibria *et al.* (2022) found that Rani Salut, a local variety, produced the highest no. of tillers and plant height under Cd exposure conditions (5 and 10 mg/kg on a soil basis). Herath *et al.* (2014) also found that rice variety, soil Cd level (50 and 100 mg/kg), and its interaction significantly affected the shoot height, root dry weight, flag leaf area, and Cd accumulation.

Filled grains (FG) and unfilled grains (UnFG) per panicle

The interaction effect for Cd \times variety increased the count of filled grains per panicle and decreased the occurrence of unfilled grains per panicle ($p < 0.05$). The greatest number of filled grains per panicle (152.24) was found in Local HYV with 0 mg/kg Cd treatment, while filled grains per panicle (27.59) was minimum in BRR1 dhan62 which was statistically identical to BRR1 dhan52 with Cd treatment. The local HYV showed maximum unfilled grains per panicle (83.49) in combination with Cd_{15} treatment while Binadhan-23 produced minimum unfilled grains per panicle (13.04) with Cd_0 treatment. The number of grains per panicle (118) of BRR1 dhan93 decreased by 7.81%, under Cd stress (25 mg/kg soil) compared to the control treatment (Sobahan *et al.* 2023).

1,000-grain weight (TGW)

The combination of Cd \times variety resulted in significant variations in terms of 1,000-grain weight

T a b l e 2

Combined impacts of variety and added cadmium on the total tiller (TT), productive tiller (PT), plant height (PH), panicle length (PL), filled and unfilled grains (FG and UnFG), and 1,000-grain weight (TGW)

Variety	Cadmium [mg/kg]	TT [no./hill]	ET [no./hill]	PH [cm]	PL [cm]	FG [no./hill]	UnFG [no./hill]	TGW [g/pot]
BRR1 dhan52	Cd ₀	11.52±0.55	7.91±0.24 ^{def}	83.34±0.97 ^{efgh}	22.14±1.22 ^{bcde}	54.78±1.79 ^g	45.43±1.31 ^{cd}	22.48±0.62 ^{bed}
	Cd ₁₅	7.33±0.88	5.73±0.22 ^j	73.40±3.00 ^{hi}	18.10±0.72 ^f	36.67±0.98 ^{hi}	55.75±1.44 ^b	17.41±1.57 ^f
BRR1 dhan62	Cd ₀	12.33±0.51	8.35±0.33 ^{cde}	78.90±0.97 ^{ghi}	19.16±0.88 ^{ef}	45.48±1.72 ^{gh}	14.15±1.65 ⁱ	22.9±0.10 ^{bed}
	Cd ₁₅	11.68±0.87	6.80±0.18 ^{ghij}	54.25±1.35 ^j	12.99±0.78 ^g	27.59±1.42 ⁱ	21.12±1.55 ^{ij}	18.82±0.61 ^{ef}
BRR1 dhan71	Cd ₀	12.41±0.30	10.82±0.18 ^{ab}	92.19±1.67 ^{cde}	22.47±0.56 ^{bed}	86.40±1.30 ^e	32.00±1.22 ^{fg}	23.05±0.48 ^{bed}
	Cd ₁₅	9.56±0.29	8.30±0.20 ^{cde}	87.31±1.8 ^{def}	22.31±0.21 ^{bcde}	84.59±1.34 ^{cd}	43.53±1.76 ^{cde}	22.68±0.58 ^{bed}
BRR1 dhan72	Cd ₀	11.75±0.49	9.48±0.29 ^{bc}	87.13±2.66 ^{cdef}	25.12±0.42 ^{ab}	72.33±1.03 ^{de}	41.55±0.97 ^{cde}	26.82±0.87 ^a
	Cd ₁₅	9.33±0.51	7.39±0.25 ^{efgh}	85.34±2.53 ^{defg}	24.58±0.74 ^{ab}	57.48±1.07 ^g	48.53±2.05 ^{bc}	27.45±0.47 ^a
BRR1 dhan79	Cd ₀	11.56±0.89	8.44±0.29 ^{cde}	87.39±1.69 ^{cdef}	21.24±0.16 ^{cdef}	65.91±2.29 ^{ef}	37.15±2.70 ^{def}	25.04±0.93 ^{abc}
	Cd ₁₅	9.61±0.49	6.04±0.43 ^{ij}	84.87±2.81 ^{defg}	20.74±0.28 ^{defg}	62.45±0.83 ^{ef}	22.90±0.86 ^{hi}	25.83±0.99 ^{ab}
Binadhan-12	Cd ₀	12.22±0.29	9.22±0.11 ^{cd}	75.57±1.22 ^{ghi}	19.71±0.11 ^{def}	106.80±4.92 ^b	23.8±1.88 ^{ghi}	12.86±0.23 ^g
	Cd ₁₅	9.67±0.69	7.26±0.13 ^{efghi}	72.54±0.69 ^j	19.52±0.3 ^{def}	104.32±4.90 ^b	18.970±2.89 ^{ij}	12.36±0.28 ^g
Binadhan-23	Cd ₀	11.78±0.48	11.33±0.19 ^a	95.71±2.37 ^{abc}	24.88±0.81 ^{ab}	85.53±3.88 ^{cd}	13.04±0.73 ^j	23.16±0.43 ^{bed}
	Cd ₁₅	10.89±1.28	7.89±0.23 ^{defg}	91.67±2.59 ^{cde}	23.8±0.62 ^{bc}	66.08±2.97 ^{ef}	13.37±0.65 ⁱ	24.35±0.27 ^{abc}
Zeeramala	Cd ₀	14.56±0.62	7.51±0.29 ^{efg}	104.75±2.04 ^a	21.31±0.28 ^{cde}	66.25±3.00 ^{ef}	36.04±0.68 ^{ef}	20.19±0.68 ^{def}
	Cd ₁₅	10.78±0.48	6.09±0.09 ^{hij}	102.69±1.46 ^{ab}	21.2±0.52 ^{cdef}	55.57±2.32 ^g	31.06±1.89 ^{fgh}	22.16±0.34 ^{cde}
Local HYV	Cd ₀	7.44±0.29	6.56±0.29 ^{ghij}	94.53±1.33 ^{bcd}	27.25±0.11 ^a	152.24±3.08 ^a	76.58±0.93 ^a	22.68±0.12 ^{bed}
	Cd ₁₅	6.74±0.38	5.89±0.36 ⁱ	92.53±1.18 ^{bcde}	25.18±0.69 ^{ab}	144.17±0.52 ^a	83.49±1.46 ^a	22.47±0.13 ^{bed}
Level of Significance for Variety × Cd		NS	***	***	***	**	***	***

The mean ± SE values sharing a common letter(s) in each column exhibit no significant differences at a 5% probability level. Standard error means are denoted by SE (±). Statistical significance is represented as *** for P<0.001, ** for P<0.01, * for P<0.05, and NS for non-significant.

(Table 2). The maximum 1,000-grain weight was 27.45 g/pot found in BRRi dhan72 with 0 mg/kg Cd treatment, and the minimum weight (12.36 g/pot) was found in Binadhan-12 with 15 mg/kg Cd treatment. Kibria *et al.* (2022) also investigated that as the amount of cadmium in the soil went up, the 1,000-grain weight decreased in every rice variety they studied.

Effects of cadmium on grain yield (GY) and straw yield (SY) [g/pot]

Evaluating grain yield and straw yield under Cd stress helps identify plants with higher tolerance and those that are more susceptible. Both grain yield and straw yield of different rice varieties were significantly ($p < 0.05$) impacted by the combination of Cd \times variety (Figure 1). Local HYV with 0 mg/kg Cd treatment produced the highest amount of grain yield (53.66 g/pot) and grain yield (60.10 g/pot).

The lowest grain yield (25.34 g/pot) and straw yield (29.14 g/pot) were observed in BRRi dhan52 with 15 mg/kg Cd treatment. Cadmium stress significantly reduced both grain yield and straw yield. Cadmium stress alters gene expression, which in turn inhibits or induces (peroxidase, superoxide dismutase, catalase) enzymes, increases highly reactive chemical formation, and ultimately affects metabolism and biological yield (Shanying *et al.* 2017). Crop yield was lowest at high concentrations of Cd in the soil (Rizk *et al.* 2014). Cadmium stress affects both plant biomass and nutritional status in crops, which ultimately reduces the quality and quantity of crops (Wang *et al.* 2014).

BRRi dhan52 showed the highest level of Cd susceptibility in terms of grain yield (32% yield decrease) (Figure 2). The second susceptible variety was BRRi dhan62. BRRi dhan71, BRRi dhan72, and local HYV were the more tolerant varieties to

T a b l e 3

Combined effects of variety \times Cd on N, P and K concentration in grains of different varieties of T-aman rice

Variety	Cd dose [mg/kg]	Nitrogen [%]	Phosphorus [%]	Potassium [%]
BRRi dhan52	Cd ₀	1.24±0.01 ^{ab}	0.26±0.00 ^{cd}	0.31±0.00 ^{gh}
	Cd ₁₅	1.09±0.01 ^{fgh}	0.22±0.00 ^{fg}	0.26±0.00 ^j
BRRi dhan62	Cd ₀	1.23±0.01 ^b	0.27±0.00 ^{bc}	0.32±0.00 ^g
	Cd ₁₅	1.18±0.01 ^{cd}	0.24±0.00 ^{defg}	0.29±0.00 ^{hi}
BRRi dhan71	Cd ₀	1.23±0.01 ^b	0.27±0.00 ^{bc}	0.43±0.00 ^c
	Cd ₁₅	1.17±0.00 ^{de}	0.24±0.01 ^{def}	0.39±0.00 ^d
BRRi dhan72	Cd ₀	1.01±0.01 ^{ij}	0.31±0.01 ^a	0.37±0.01 ^{de}
	Cd ₁₅	0.98±0.02 ^j	0.24±0.01 ^{defg}	0.34±0.01 ^f
BRRi dhan79	Cd ₀	1.22±0.00 ^{bc}	0.25±0.00 ^{cde}	0.48±0.00 ^a
	Cd ₁₅	1.13±0.00 ^{def}	0.22±0.01 ^{fg}	0.46±0.00 ^b
Binadhan-12	Cd ₀	1.28±0.00 ^a	0.26±0.01 ^{cd}	0.31±0.00 ^{gh}
	Cd ₁₅	1.18±0.01 ^{cd}	0.23±0.01 ^{efg}	0.27±0.00 ^{ij}
Binadhan-23	Cd ₀	1.17±0.01 ^{de}	0.30±0.00 ^a	0.36±0.00 ^c
	Cd ₁₅	1.04±0.02 ^{hi}	0.26±0.01 ^{cd}	0.32±0.00 ^g
Zeeramala	Cd ₀	1.12±0.00 ^{efg}	0.29±0.00 ^{ab}	0.36±0.01 ^{cf}
	Cd ₁₅	1.01±0.01 ^{ij}	0.27±0.00 ^{bc}	0.32±0.00 ^g
Local HYV	Cd ₀	1.08±0.01 ^{gh}	0.23±0.00 ^{efg}	0.26±0.00 ^j
	Cd ₁₅	1.04±0.01 ^{hi}	0.21±0.00 ^g	0.23±0.00 ^k
Significant level for variety \times Cd	–	***	***	*

The mean±SE values sharing a common letter(s) in each column exhibit no significant differences at a 5% probability level. Standard error means are denoted by SE (±). Statistical significance is represented as *** for $P < 0.001$, ** for $P < 0.01$, * for $P < 0.05$, and NS for non-significant.

Cd contamination in terms of grain yield compared to other rice varieties. According to Kanu *et al.* (2017), Basmati rice yields a reduction over control of 12.43, 22.66, and 31.33% at three Cd levels (50, 100 and 150 mg/kg soil).

Effects of cadmium on N, P, K, S, and Zn concentration

The combination of Cd × variety had a significant effect on N, P, K, S, and Zn amounts in grain (Table 3). Binadhan-12×Cd₀ gave the highest N concentration (1.28%) in grain and was statistical-

ly equivalent to BRR1 dhan52×Cd₀. The minimum N concentration (0.98%) was obtained in BRR1 dhan72×Cd₁₅. The variety × Cd combination was negatively significant on P levels (Table 3). The highest P level (0.31%) was found in BRR1 dhan72 with 0 mg/kg Cd treatment which was statistically similar to Binadhan23 and Zeeramala with 0 mg/kg Cd treatment whereas the lowest P concentration (0.21%) was found in Local HYV with 15 mg/kg Cd treatment. There was a significant impact of Cd × variety on grain-K concentration and the effect was negative (Table 3). The highest K quantity (0.48%)

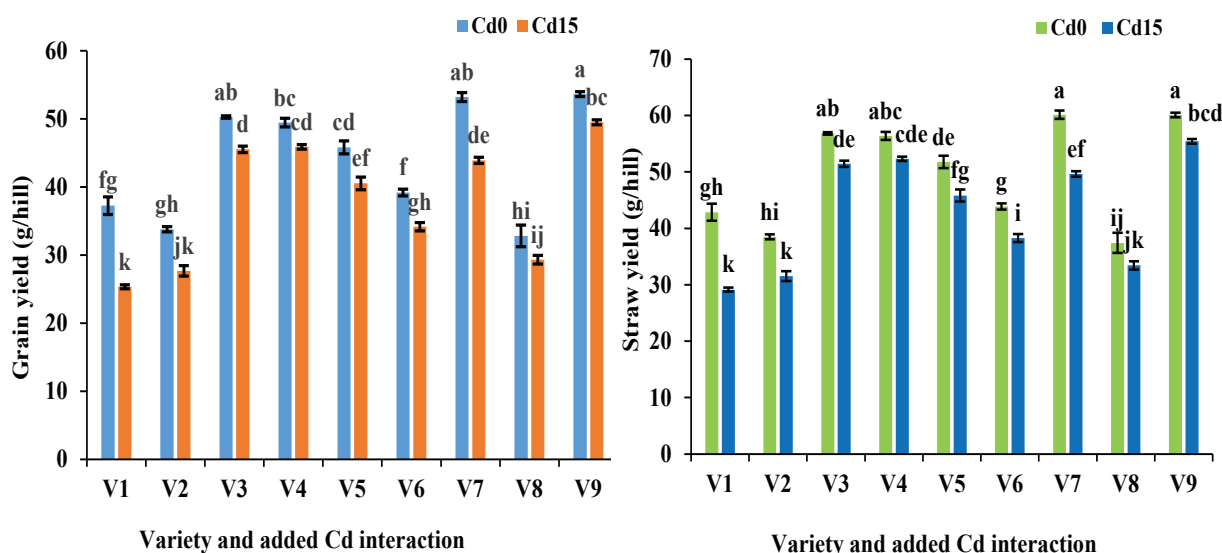


Figure 1. Combined impacts of Variety × Cd on grain yield and straw yield [g/pot]; (V1 – BRR1 dhan52, V2 – BRR1 dhan62, V3 – BRR1 dhan71, V4 – BRR1 dhan72, V5 – BRR1 dhan79, V6 – Binadhan-12, V7 – Binadhan-23, V8 – Zeeramala, V9 – Local HYV).

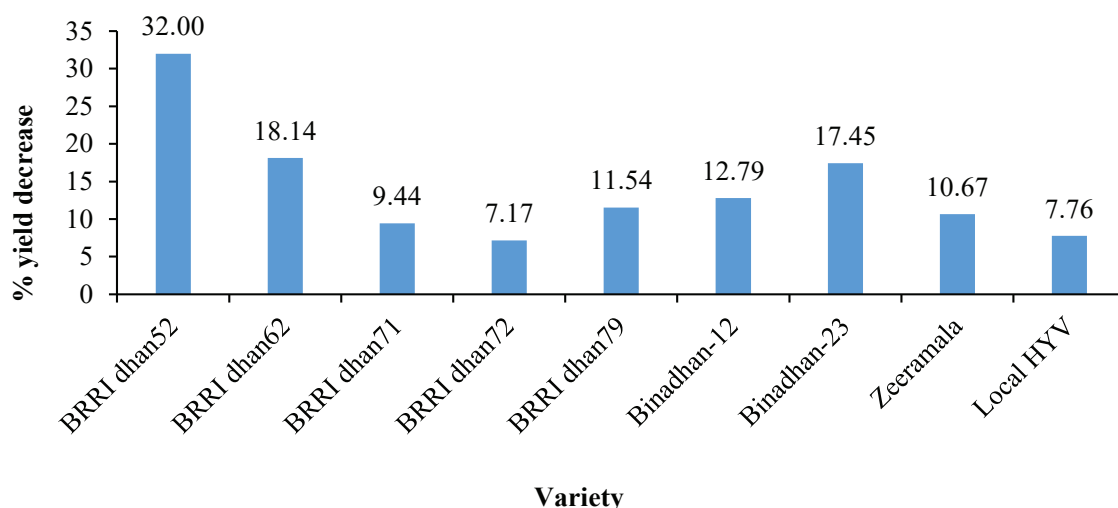


Figure 2. Grain yield decrease [%] over cadmium control due to 15 mg/kg cadmium treatment in different varieties.

was found in the BRR1 dhan79×Cd₀ combination while the lowest (0.23%) was obtained in the local HYV×Cd₁₅ combination. The interaction effect of varieties and 15 mg/kg Cd application showed remarkable variations in S and Zn concentration in rice grain, however, this variation was not statistically significant (Table 4). The highest S concentration (0.22%) was found in Binadhan-12 with Cd₀ whereas the Zn concentration was highest (24.03 mg/kg) obtained for Zeeramala×Cd₀. Both S and Zn concentrations were lowest in Local HYV with 15 mg/kg Cd treatment. Cadmium toxicity decreases plant mineral absorption and photosynthetic activity, thereby reducing crop yield and quality (Rizwan *et al.* 2016). By altering N metabolism, Cd bioaccumulation alters several physiological processes

(Chaffei *et al.* 2004). Similarly, an abundance of N in plants could play a role in diminishing the levels of Cd within plant tissues (Majeed *et al.* 2021). High Cd concentrations in the growth medium, roots, panicle, and lastly grains drastically declined N, K and micronutrient content (Rizk *et al.* 2014). Cadmium hinders the absorption of Zn and Fe in plants, leading to a decrease in the leaf chlorophyll content (Xu *et al.* 2017).

Cadmium concentration in rice grain

The interaction impacts of variety × Cd to the soil had a significant impact on the cadmium build-up in grain (Table 4). The highest Cd concentration (2.94 mg/kg) was obtained for BRR1 dhan52×Cd₁₅ followed by Binadhan-23×Cd₁₅ and

T a b l e 4

Interaction effects of variety × Cd on S and Zn, and cadmium concentration in grains of different varieties of T-aman rice

Variety	Treatments	Sulphur [%]	Zinc [mg/kg]	Cadmium [mg/kg]
BRR1 dhan52	Cd ₀	0.18±0.00	22.14±0.09	0.43±0.02 ^{fe}
	Cd ₁₅	0.14±0.00	17.44±0.31	2.94±0.12 ^a
BRR1 dhan62	Cd ₀	0.21±0.01	23.54±0.84	0.04±0.01 ^{gh}
	Cd ₁₅	0.19±0.01	20.76±0.34	1.36±0.15 ^{dc}
BRR1 dhan71	Cd ₀	0.21±0.01	22.35±0.31	0.04±0.01 ^{gh}
	Cd ₁₅	0.19±0.00	20.74±0.27	1.06±0.07 ^c
BRR1 dhan72	Cd ₀	0.22±0.00	22.21±0.43	0.00±0.00 ^h
	Cd ₁₅	0.20±0.00	20.92±1.00	0.49±0.01 ^f
BRR1 dhan79	Cd ₀	0.19±0.00	19.00±0.90	0.00±0.00 ^h
	Cd ₁₅	0.16±0.00	18.57±1.35	1.82±0.12 ^{bc}
Binadhan-12	Cd ₀	0.22±0.00	20.70±0.85	0.03±0.01 ^{gh}
	Cd ₁₅	0.19±0.00	18.20±0.83	1.48±0.02 ^{cd}
Binadhan-23	Cd ₀	0.20±0.00	21.00±0.68	0.05±0.01 ^{gh}
	Cd ₁₅	0.17±0.00	17.41±0.02	2.07±0.23 ^b
Zeeramala	Cd ₀	0.21±0.00	24.03±0.47	0.00±0.00 ^h
	Cd ₁₅	0.19±0.00	21.60±0.44	0.53±0.03 ^f
Local HYV	Cd ₀	0.16±0.00	17.08±1.15	0.00±0.00 ^h
	Cd ₁₅	0.14±0.00	16.41±0.77	0.44±0.04 ^{fe}
Significant level for Variety × Cd		NS	NS	***

The mean±SE values sharing a common letter(s) in each column exhibit no significant differences at a 5% probability level. Standard error means are denoted by SE (±). Statistical significance is represented as *** for P<0.001, ** for P<0.01, * for P<0.05, and NS for non-significant.

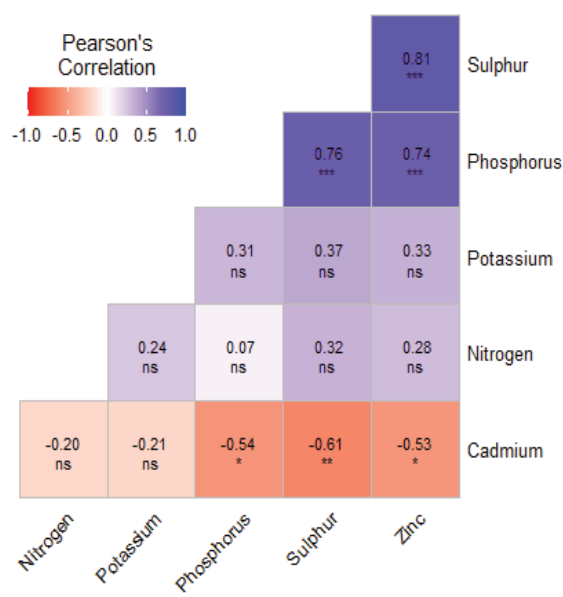
BRR1 dhan72* Cd_{15} . Cadmium concentration (0 mg/kg) was minimum in BRR1 dhan71* Cd_0 , BRR1 dhan72* Cd_{15} , Binadhan-23* Cd_{15} , and Local HYV. The rice plant tends to accumulate Cd more quickly than other cereals, and in some nations, like China, and those in the subcontinent, such as Sri Lanka, India, and Bangladesh, rice is the main food source for Cd consumption (Chen *et al.* 2021). The higher assimilation of Cd by plants likely resulted in its translocation to roots and above-ground sections. Ye *et al.* (2012) investigated the impact of rice variety on Cd accumulation and found that hybrid and japonica grain assimilated less Cd than indica polished grain. Plant Cd accumulation is genotype-dependent (Li *et al.* 2018). Cadmium pollution decreased the levels of K, Ca and Na within the rice plants, concomitantly elevated the level of Cd (Mueez *et al.* 2019). Binadhan-7 was the highest Cd accumulator (0.45 and 0.65 mg/kg) at 5 and 10 mg/kg Cd stress soil (Kibria

et al. 2022). It also examined that BR-52 contained 0.15 and 0.35 mg/kg Cd at 5 and 10 g/pot Cd stress soil. Cd absorption in plants increased proportionally with higher soil Cd toxicity levels (Kanu *et al.* 2017). Cadmium can easily move through the roots and then be transported into the vascular bundles of plants through the ascent of sap or carriers in shoots (Dong *et al.* 2019). OsNramp5 and HvNramp5 are the key transporters facilitating the assimilation of Cd through plant roots (Wu *et al.* 2016). Then Cd is translocated into the stem by OsHMA2 in rice. Ultimately, during the reproductive stage, Cd accumulation in grains is governed by OsHMA2, OsZIP7, OsLCT1, and OsCCX2 (Yamaji *et al.* 2013; Tan *et al.* 2019; Feng *et al.* 2021). Recent studies have highlighted the search for crop varieties with low Cd uptake and high tolerance, aiming to cultivate safe rice in contaminated soils (Rizwan *et al.* 2016; Xu *et al.* 2022).

T a b l e 5

ADI (Average Daily Intake), HQ (Hazard Quotient), and ILCR (Incremental Lifetime Cancer Risk) values for combined effects of different cadmium doses and varieties of T-aman rice (for adults)

Variety	Cd dose [mg/kg]	ADI [mg/kg BW]	HQ	ILCR
BRR1 dhan52	Cd_0	2.37×10^{-3}	2.37	0.36×10^{-4}
	Cd_{15}	16.09×10^{-3}	16.09	2.41×10^{-4}
BRR1 dhan62	Cd_0	0.20×10^{-3}	0.20	0.03×10^{-4}
	Cd_{15}	7.45×10^{-3}	7.45	1.12×10^{-4}
BRR1 dhan71	Cd_0	0.22×10^{-3}	0.22	0.03×10^{-4}
	Cd_{15}	5.81×10^{-3}	5.81	0.87×10^{-4}
BRR1 dhan72	Cd_0	0.00×10^{-3}	0.00	0.00×10^{-4}
	Cd_{15}	2.70×10^{-3}	2.70	0.41×10^{-4}
BRR1 dhan79	Cd_0	0.00×10^{-3}	0.00	0.00×10^{-4}
	Cd_{15}	9.96×10^{-3}	9.96	1.49×10^{-4}
Binadhan-12	Cd_0	0.15×10^{-3}	0.15	0.02×10^{-4}
	Cd_{15}	8.11×10^{-3}	8.11	1.22×10^{-4}
Binadhan-23	Cd_0	0.27×10^{-3}	0.27	0.04×10^{-4}
	Cd_{15}	11.34×10^{-3}	11.34	1.70×10^{-4}
Zeeramala	Cd_0	0.00×10^{-3}	0.00	0.00×10^{-4}
	Cd_{15}	2.92×10^{-3}	2.92	0.44×10^{-4}
Local HYV	Cd_0	0.00×10^{-3}	0.00	0.00×10^{-4}
	Cd_{15}	2.39×10^{-3}	2.39	0.36×10^{-4}



ns $p \geq 0.05$; * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$

Figure 3. Estimation of Pearson's correlation coefficients among different nutrient contents in rice grain. Statistical significance is represented as *** for $P < 0.001$, ** for $P < 0.01$, * for $P < 0.05$, and NS for non-significant.

Correlation among N, K, P, S, and Cd

The provided correlation coefficient value (r) showed the relationship among different nutrient elements (N, P, K, S) and Cd (Figure 3). A significant positive relationship was found between zinc and phosphorus as well as sulphur. Phosphorus and sulphur were also positively correlated. Cadmium had a negatively significant relationship with phosphorus, sulphur, and zinc. Nitrogen and potassium were also negatively correlated with Cd, but the relationship was non-significant. A substantial relationship was observed between Cd and Zn concentrations in rice grains (Ishikawa *et al.* 2005; Majeed *et al.* 2022).

Adverse effects on health from rice consumption daily average intake (ADI) of cadmium

In Cd-exposed conditions, the ADI value was higher than in Cd-controlled conditions (0 mg/kg Cd treatments). For adults, ADI of Cd from rice

T a b l e 6

ADI (Average Daily Intake), HQ (Hazard Quotient), and ILCR (Incremental Lifetime Cancer Risk) values for combined effects of different cadmium doses and varieties of T-aman rice (for children)

Variety	Cd dose [mg/kg]	ADI [mg/kg BW]	HQ	ILCR
BRR1 dhan52	Cd ₀	4.06×10 ⁻³	4.06	0.61×10 ⁻⁴
	Cd ₁₅	27.55×10 ⁻³	27.55	4.13×10 ⁻⁴
BRR1 dhan62	Cd ₀	0.34×10 ⁻³	0.34	0.05×10 ⁻⁴
	Cd ₁₅	12.76×10 ⁻³	12.76	1.91×10 ⁻⁴
BRR1 dhan71	Cd ₀	0.38×10 ⁻³	0.38	0.06×10 ⁻⁴
	Cd ₁₅	9.94×10 ⁻³	9.94	1.49×10 ⁻⁴
BRR1 dhan72	Cd ₀	0.00×10 ⁻³	0.00	0.00×10 ⁻⁴
	Cd ₁₅	4.63×10 ⁻³	4.63	0.69×10 ⁻⁴
BRR1 dhan79	Cd ₀	0.00×10 ⁻³	0.00	0.00×10 ⁻⁴
	Cd ₁₅	17.04×10 ⁻³	17.04	2.56×10 ⁻⁴
Binadhan-12	Cd ₀	0.25×10 ⁻³	0.25	0.04×10 ⁻⁴
	Cd ₁₅	13.88×10 ⁻³	13.88	2.08×10 ⁻⁴
Binadhan-23	Cd ₀	0.47×10 ⁻³	0.47	0.07×10 ⁻⁴
	Cd ₁₅	19.42×10 ⁻³	19.42	2.91×10 ⁻⁴
Zeeramala	Cd ₀	0.00×10 ⁻³	0.00	0.00×10 ⁻⁴
	Cd ₁₅	5.00×10 ⁻³	5.00	0.75×10 ⁻⁴
Local HYV	Cd ₀	0.00×10 ⁻³	0.00	0.00×10 ⁻⁴
	Cd ₁₅	4.10×10 ⁻³	4.10	0.61×10 ⁻⁴

grain ranged from 0 to 16.09×10^{-3} mg/kg BW (Table 5). The highest ADI value was obtained for BRR1 dhan52* Cd_{15} , and the lowest ADI value for BRR1 dhan72* Cd_0 , BRR1 dhan79* Cd_0 , Zeeramala* Cd_0 , and finally Local HYV* Cd_0 . For children, the ADI value ranged from 0 to 27.55×10^{-3} mg/kg BW (Table 6). The ADI of cadmium for kids is comparatively greater than the ADI value for adults. All rice varieties showed a higher ADI value at Cd-exposed treatments that exceeded the safe limit. Even BRR1 dhan52 showed a four-fold higher value than the tolerable limit at Cd-controlled treatments. The daily consumption of arsenic (As), lead (Pb), and cadmium (Cd) through rice intake (199 g/day) were observed to constitute 50%, 80%, and 30% of the recommended ADI established by FAO/WHO (Kwon *et al.* 2017).

Non-carcinogenic and cancer health hazards for adult

The HQ (Hazard Quotient) value indicates the non-carcinogenic health hazards, while the ILCR (Incremental Lifetime Cancer Risk) value indicates cancer health hazards (Table 5). All rice varieties showed safe HQ (Hazard Quotient) value in the Cd-controlled environment except BRR1 dhan52. But when these varieties were exposed to a contaminated environment, they possessed a higher HQ (Hazard Quotient) value which exceeded the safe

limit (HQ=1) (Figure 4). BRR1 dhan52* Cd_{15} had the highest HQ (Hazard Quotient) value (16.09) and HQ (Hazard Quotient) value was the lowest in local HYV while considering Cd exposed environment. The comprehensive sequence considering variety was BRR1 dhan52>Binadhan-23>BRR1 dhan79>Binadhan-12>BRR1 dhan62>BRR1 dhan71>Zeeramala>BRR1 dhan72>Local HYV.

Cadmium-exposed varieties had a higher cancer risk than Cd-controlled varieties. The highest ILCR (Incremental Lifetime Cancer Risk) value was obtained in BRR1 dhan52* Cd_{15} (2.41×10^{-4}) followed by Binadhan-23* Cd_{15} and BRR1 dhan79* Cd_{15} . The highest value of 2.41×10^{-4} indicates an average of 2.41 people will show carcinogenic effects when consuming BRR1 dhan52 exposed to 15 mg/kg Cd-containing soil. At Cd-controlled treatments, the highest value was obtained in BRR1 dhan52 (0.36×10^{-4}). Kibria *et al.* (2022) also found the same result. At controlled conditions, all varieties showed the HQ (Hazard Quotient) safe limit except BRR1 dhan87, but while exposed to 5 and 10 mg Cd/kg soil, they exhibited maximum HQ (Hazard Quotient) values, indicating potential adverse effects on human health. The mean HQ (Hazard Quotient) for sticky rice consumption in Thailand was 2.263, while the mean HQ (Hazard Quotient) for white rice consumption was 0.630 (Suwatvitayakorn *et al.* 2020). In rural Bajestan and Gonabad, 16–38% of

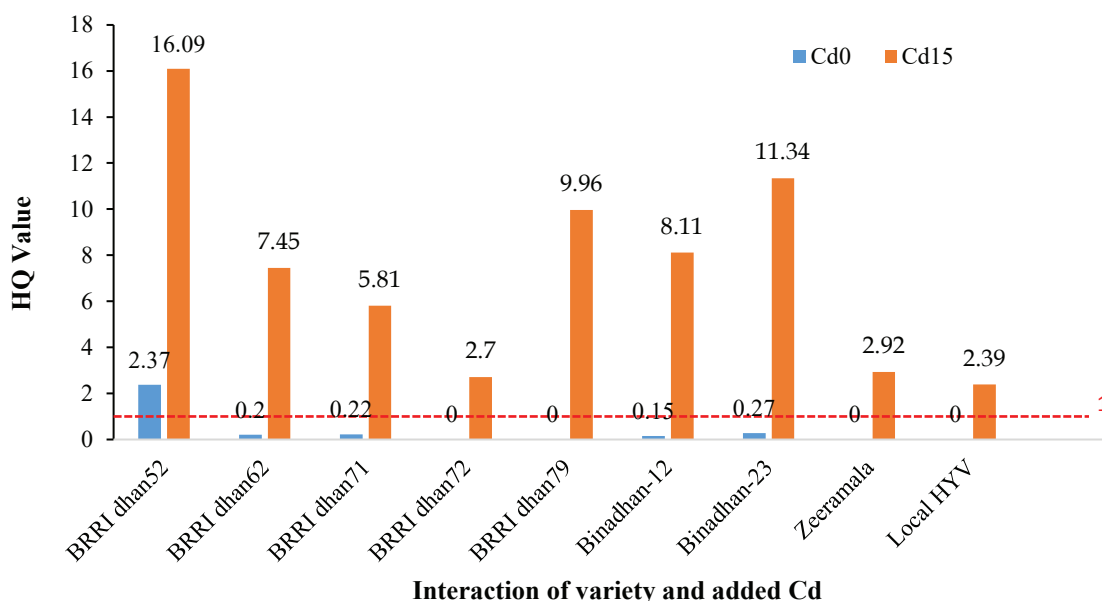
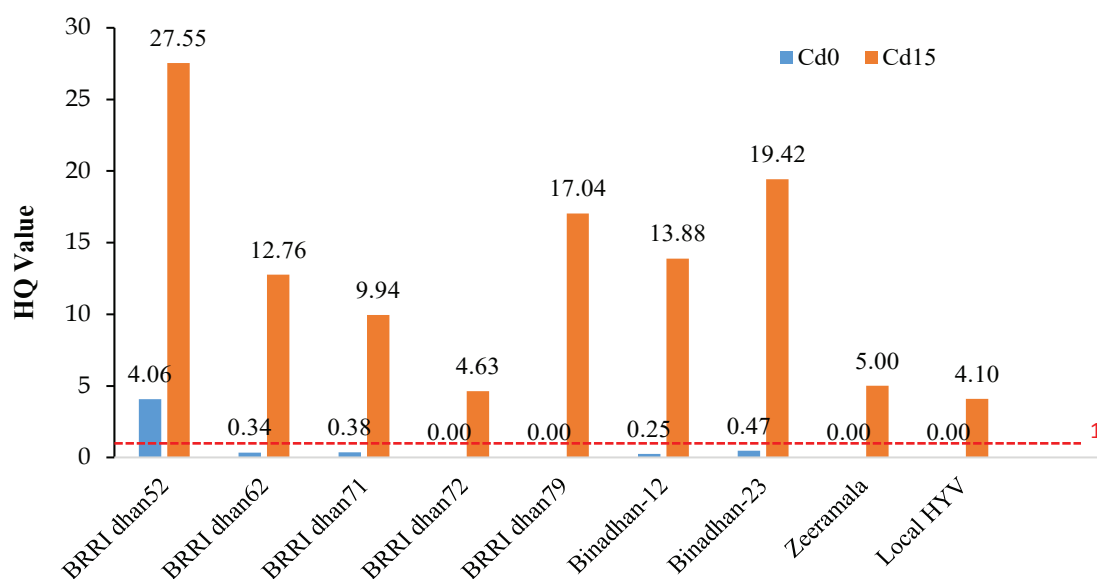


Figure 4. HQ (Hazard Quotient) values (adult) at combined impacts of added Cd and variety. The stippled line indicates the acceptable threshold of HQ (Hazard Quotient).



Interaction of variety and added Cd

Figure 5. HQ (Hazard Quotient) values (children) at combined impacts of added Cd and variety. The stippled line indicates the acceptable threshold of HQ (Hazard Quotient).

children and infants faced Cd contamination with HQ (Hazard Quotient) values surpassing 1, while adults in Bajestan had a 42% cancer risk from Cd, exceeding the EPA's safe limit of 1.0×10^{-4} (Qasemi *et al.* 2019).

Non-carcinogenic and carcinogenic risk for children

The result showed that non-carcinogenic health risks are more prominent for children than adults under Cd-exposed conditions. All the varieties showed a safe HQ (Hazard Quotient) value in the Cd-controlled environment except BRR1 dhan52 (4.42). But when these varieties were exposed to a Cd-contaminated environment, they possessed a higher HQ (Hazard Quotient) value, exceeding the safe limit (HQ (Hazard Quotient) = 1) (Figure 5). BRR1 dhan52* Cd_{15} had the highest HQ (Hazard Quotient) value (27.55), and BRR1 dhan72, BRR1 dhan79, Zeeramala, and Local HYV at no Cd conditions had the lowest (0.00) HQ (Hazard Quotient) value.

Children are more susceptible to carcinogenic effects than adults. The ILCR (Incremental Lifetime Cancer Risk) value for children was highest (4.13×10^{-4}) in the case of BRR1 dhan52* Cd_{15} whereas it was lowest in BRR1 dhan72, BRR1 dhan79, Zeeramala and Local HYV at no Cd conditions.

Cai *et al.* (2019b) found that while the HQ (Hazard Quotient) values of Cd, As, and Cr in soil, groundwater, and atmospheric precipitates were within the safe limit, the cancer risk surpassed it. Kids in the industrial-polluted area were exposed to health risks 30.25 folds higher than the safe limit from water, soil, crops, and fish. The majority of hazards were caused by consuming crops contaminated by As (27%), Cd (46%), and Pb (20%) (Cai *et al.* 2019c).

CONCLUSIONS

The findings of this experiment revealed that soil contamination with cadmium had a considerable impact on rice yield and its contributing factors. Notably, BRR1 dhan71, BRR1 dhan72, Binadhan-23, and local varieties exhibit a degree of tolerance to 15 mg/kg Cd contamination concerning vitality, and yield showcasing their potential for cultivation in cadmium-affected soils. However, BRR1 dhan52 and BRR1 dhan62 emerge as more susceptible varieties, indicating the need for careful selection of cultivars in contaminated environments. The Local HYV, Zeeramala, and BRR1 dhan71 had the lowest grain Cd concentration with 15 mg/kg Cd than the other rice varieties. Cadmium concentration in rice grain was found to negatively correlate with phosphorus,

sulphur, and zinc. Additionally, cadmium-exposed varieties possessed higher health hazards where HQ (Hazard Quotient) and ILCR (Incremental Lifetime Cancer Risk) values exceeded the safe limit (HQ= 1; ILCR= 10^{-4}). Rice varieties exposed to high levels of cadmium pose a cancer risk and children are more susceptible than adults. The ILCR value for children was highest (4.13×10^{-4}) in the case of BRRI dhan52* Cd_{15} . The ILCR value indicates some varieties are unsafe for human consumption and pose a significant health risk to humans. These results provide valuable insights for sustainable rice cultivation, leading future research and informing practical interventions to deal with the challenges triggered by Cd contamination in agricultural ecosystems.

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