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Original article

Impact of Soil Cadmium Contamination on Growth, Yield and Nutrient Concentration in Various Rice Varieties and Associated Health Risks

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Cadmium is primarily acquired through food, leading to severe health issues in humans. A pot experiment investigated the impacts of varying cadmium (Cd) levels (0, 10 and 20 mg/kg) on productivity and nutrient concentrations in six distinct rice varieties, including Binadhan-8, Binadhan-10, Binadhan-14, BRRI dhan50, BRRI dhan58, and a local variety. After harvesting, data on growth and yield parameters were recorded, and nutrient concentrations were analysed. Cadmium significantly declined plant height, tillering ability, grains/pot, 100-grain weight, and total yields. The grain production decreased by 6.58% in BRRI dhan50 to 26.73% in Binadhan-10 with 20 mg/kg Cd treatment. BRRI dhan58 yielded the highest, followed by BRRI dhan50 and Binadhan-8, with 20 mg/kg Cd application to the soil. Cadmium application increased the grain Cd level while reducing N, P, K, and S content. Binadhan-8 had the minimum (0.270 mg/kg) grain Cd level while Kheyali boro showed the maximum (0.480 mg/kg) with 20 mg/kg Cd. Rice varieties grown with 0 mg/kg Cd addition in soil had no cancer risk for adult Bangladeshis but those cultivated in Cd-contaminated soils (10 and 20 mg Cd/kg soil) exhibited carcinogenic risk. However, further field studies with different varieties and Cd levels are imperative for conclusive insights.

Key words: rice, cadmium, grain yield, grain cadmium, nutrient concentrations, cancer risk

Rice (*Oryza sativa* L.) is a primary dietary staple for a large portion of the global population, especially in Asian countries, where it accounts for nearly 90% of the daily caloric intake (Mu *et al.* 2019; Mukta *et al.* 2024). Nevertheless, the sustainability and safety of rice cultivation are increasingly challenged by the accumulation of heavy metals in agricultural soils. In areas where rice consumption is high, it can become a significant pathway for Cd entry into the human diet, thereby raising serious public health concerns (Shahriar *et al.* 2020). Cadmium is a class-1 non-threshold carcinogen (IARC 1993; Gianazza *et al.* 2007) which is known to accumulate in paddy soils primarily due to anthropogenic sources such as industrial emissions, the use of phosphate-based fertilisers and irrigation with contaminated wastewater (Horiguchi *et al.* 2012; Rizwan *et al.* 2016; Ali *et al.* 2021). Cadmium is a highly toxic element that disrupts key physiological functions in plants such as photosynthesis, enzyme activity, nutrient absorption, and grain formation, ultimately leading to stunted growth and lower grain yields in rice crops (Haider *et al.* 2021; Aslam *et al.* 2023; Li *et al.* 2023). Moreover, Cadmium presents a poten-

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tial threat to human physical health, as it frequently builds up in rice grains, creating a direct route into the human food chain (Mu *et al.* 2019; Shi *et al.* 2020; Meharg *et al.* 2022). Extended contact with Cd has been associated with bone fractures, lung cancer, pulmonary adenocarcinoma, and kidney failure (Afzal *et al.* 2019). The occurrence of Itai-itai disease in Japan is linked to Cd exposure from consuming Cd-contaminated rice (Kobayashi *et al.* 2009; Aoshima 2016). Under EU regulations, the highest accepted concentrations of cadmium in rice are defined at 40 µg/kg for children and 200 µg/kg for adults in the European Union (Commission Regulation (EC) 2006).

The harmful level of Cd is regarded as 5 − 10 mg/kg for plants and 3 mg/kg for soils (Das *et al.* 1997). The movement of Cd from soil to rice grains can significantly interfere with the absorption and internal allocation of mineral nutrients, including N, P, K, Mg, Fe, and Zn (Rochayati *et al.* 2011; Kinay *et al.* 2018; Zhang *et al.* 2014; Mukta *et al.* 2024). Such interferences adversely affect the nutritional composition and overall quality of the harvested rice. Cadmium levels in plants depend on the soil environment as well as the nature of plants, cultivars of crops and duration of Cd exposure (Hu *et al.* 2016; Zhao & Wang 2020). Choosing rice varieties with low Cd accumulation, managing water, crop rotation, and various microbial applications could be effective pathways to reduce Cd levels in paddy (Hu *et al.* 2015). Moderate levels of Cd in arable soils can result in a notable uptake and transfer of Cd in roots and other plant parts (Liu *et al.* 2010b).

Various studies have shown that different rice varieties absorb Cd from the soil at different rates, leading to varying levels of Cd accumulation in the grains (Arao & Ae 2003; Kibria *et al.* 2022). Researchers have likewise examined the detrimental impact of cadmium on rice growth and physiology. However, a thorough understanding of the interplay between cadmium-induced stress, nutrient dynamics and yield performance across diverse rice genotypes remains inadequate. There is also a lack of recent studies that consider local or high-yielding cultivars under environmentally relevant Cd levels. For food safety, the identification of low-Cd rice sources would be one of the effective ways to diminish Cd levels in paddy (Zhao & Wang 2020). Variation among different rice varieties in terms of Cd build-up helps in exploring the Cd defence mechanisms of crops. Therefore, this study was carried out to assess the influence of Cd pollution on the growth parameters, productivity, and mineral levels of rice varieties, aiming to identify rice varieties exhibiting lower grain Cd levels. This study supports the development of cadmium-resilient rice varieties by identifying genotypes with low cadmium accumulation and high nutrient efficiency. This addresses the global demand for safe and sustainable food systems by advancing environmentally responsible and food-secure rice cultivation, particularly in regions affected by cadmium contamination.

MATERIAL AND METHODS

The research was conducted within the net house located at the Department of Soil Science, Bangladesh Agricultural University (BAU), throughout the Boro season (January to May 2017), to investigate the impacts of Cd contamination on the physiological parameters, covering plant growth, yield, nutrient concentrations, and Cd accumulation levels across six important rice cultivars of Bangladesh. From a geographical standpoint, the net house is situated at a latitude of 24.75°N and a longitude of 90.50°E. The soil was taken from the Soil Science Field Laboratory at a depth of 0 − 15 cm and exhibited a silt loam texture with a pH of 6.5, as determined by the hydrometer method and glass electrode pH meter, respectively (Gee & Bauder 1979; Jackson 1973). It contained 0.08% total N, 13.7 mg/kg available S, 12.2 mg/kg available P, 0.11 me% exchangeable K, and 0.82 mg/kg total Cd. Total N was determined by the Micro-Kjeldahl method (Jackson 1973), available S by $CaCl_2$ extraction (Jackson 1973), available P by the Olsen method (Murphy & Riley 1962), exchangeable K by NH_4OAc extraction (Kundsen *et al.* 1982), and total Cd by atomic absorption spectrophotometry (AAS) following acid digestion. Afterward, nine kilograms of air-dried soil were placed in a pot with dimensions of 43 cm × 40 cm. Different levels of Cd, specifically 0, 10, and 20 mg/kg, were administered as cadmium chloride ($CdCl_2.H_2O$) based on the soil composition. This investigation was arranged using a Completely Randomized

Design (CRD), incorporating three replications. The five high-yielding rice cultivars, Binadhan-8, Binadhan-10, Binadhan-14, BRRI dhan50, BRRI dhan58, and one local rice variety were employed. Each container was supplied with an equivalent quantity of N, K, P, and S at the rate of 100 mg/kg N, 40 mg/kg K, 25 mg/kg P, and 25 mg/kg S from urea, muriate of potash, triple super phosphate, and gypsum, respectively. Seedlings aged 33 days were transplanted to pots, with a pair of seedlings/pot, and necessary intercultural operations were conducted. Various rice varieties were harvested at maturity on different dates, and their respective yields, along with yield-providing factors such as plant height, productive tillers/pot, filled grains, and 100-grain weight, were documented. The samples were dehydrated at 65ºC in an oven to get a constant mass. The grain production was assessed in t/ha at a 14% moisture basis, while the straw output was calculated on a sun-dry basis. Digestion of the grain specimens with the diacid mixture (HNO_3 : $HClO_4$ in the ratio of 3 : 1) provided the Cd concentration of the grain. The grain Cd content in the acid digest was determined through AAS (atomic absorption spectrophotometer). The samples were ground and analysed for N, P, K and S contents following standard methods (H_2SO_4 digestion for N and HNO_3-$HClO_4$ digestion for P, K & S) in the Department of Soil Science. Nitrogen was measured using the Micro-Kjeldahl method, which involved distillation with 40% NaOH, followed by titration with 0.01 N H_2SO_4 (Jackson 1973). Phosphorus was estimated using the Olsen method, measured with a spectrophotometer after colour development with Barton solution (Murphy & Riley 1962). Potassium was analysed using a flame photometer after extraction with NH_4OAc (Kundsen *et al.* 1982), while sulphur content was determined turbidimetrically using a spectrophotometer at 420 nm after extraction with $CaCl_2$ and the addition of acid seed and turbidimetric solutions (Jackson 1973). Two-way ANOVA was used to test for differences among treatments. When significant, the means were compared using the Least Significant Difference (*LSD*) test at $p \leq 0.05$, as shown in the table (Gomez & Gomez 1984). All analyses were done using R software.

Incremental Cancer Risk Calculation

The probable cancer risks due to exposure to Cd through rice intake were computed using the Incremental life cancer risk (ILCR) obtained from USEP (IRIS 2013). The following equation was used for the calculation of the lifetime cancer risk

$$ADI = \frac{RI \times FE \times EP}{HBW \times MT}$$

where:
ADI is an average daily intake of Cd, RI means regular intake of Cd [μg/day], HBW is human body weight [kg] = 65 kg, FE is frequency of exposure [d/yr] = 365, EP is the exposure period [yr] = 70, MT is the meantime [day] = 25,550; the Rice consumption rate for Bangladesh adults is 330 g/day (HIES 2022).

$$ILCR = ADI \times CdSF$$

where: CdSF is the Cd slope factor (15 μg/kg/d) derived from the (OEHHA 2014).

RESULTS

Effects on Growth Parameters

Application of varying levels of Cd to soil harmed the plant height of different rice varieties (Table 1). Rice plants reached a height of 88.9 cm when no cadmium (Cd) was applied whereas at 10 mg/kg and 20 mg/kg of Cd, the plant heights decreased to 85.2 cm and 82.2 cm, respectively. Different rice varieties also showed significant differences in terms of plant height (Table 1). The combined impact of varying cadmium (Cd) rates and different rice varieties was statistically significant. (Table 2). The height of six rice varieties varied between 68.3 cm for Binadhan-14 with a Cd rate of 20 mg/kg and 103.6 cm for Kheyali boro under the influence of control treatment. At all levels of Cd, Kheyali boro exhibited the highest plant, while Binadhan-14 displayed the smallest plant. The total number of productive tillers/pot was greatly decreased through Cd pollution (Table 1). Rice varieties exhibited notable variation in productive tillers/pot, with Kheyali boro having the greatest count at 9.8 per pot, and Binadhan-14 having the least at 3.7 per pot (Table 1). The combined impacts of three levels of Cd and rice varieties on productive tillers/pot were significantly notable (Table 2). The addition of 10 mg/kg Cd significantly reduced the effective tillers/pot in Binadhan-8, Binadhan-14, and BRRI dhan50 rice cultivars, with a further decrease observed at 20 mg/kg Cd. The count of filled grains/pot in rice varieties decreased significantly due to different levels of Cd contamination and the individual effect of varieties also significantly influenced filled grain numbers (Table 1). The combined impact of three Cd levels with various varieties demonstrated significant variability in the number of filled grains per pot (Table 2). BRRI dhan58 had the greatest number of filled grains/pot (1077), while Binadhan-14 had the fewest (341), with Binadhan-8 and Binadhan-14. The 100-grain weight was significantly affected by Cd pollution (Table 1). The 100-grain weight was found 1.85 g/pot with 20 mg/kg Cd application and 2.0 g/pot without Cd application. Binadhan-8 had the maximum 100-grain weight (2.38 g/pot) while Kheyali boro had the minimum (1.42 g/pot) (Table 1). But, the combined effect was non-significant for 100-grain weight (Table 2).

Effects on Grain Yield and Straw Yield

The exposure of 10 mg/kg and 20 mg/kg Cd resulted in a lower grain and straw yields compared to the control treatment (0 mg Cd/kg soil) (Table 1). Different rice varieties varied significantly in terms of productivity (Table 1). The combined impact displayed notable variation in the production of rice grain yield, but this effect was not significant for straw yield (Table 2). BRRI dhan58 yielded the maximum grain yield in the Cd control treatment, while Kheyali boro yielded the minimum. BRRI dhan58 produced the maximum yield at 20 mg/kg, suggesting it can be grown in Cd-contaminated soil.

Cadmium Levels in Rice Grain

Cadmium levels in rice grains were significantly

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Single effects of Cd and rice varieties on crop yield and factors contributing to yield

Factors	Effective tillers/pot [no.]	Plant height [cm]	Filled grains/pot [no.]	100-grain weight [g/pot]	Grain yield [g/pot]	Straw yield [g/pot]
Cd added [mg/kg]						
0	6.7[a]	88.9[a]	744[a]	2.00[a]	15.00[a]	20.39[a]
10	5.2[b]	85.2[b]	677[b]	1.92[b]	12.95[b]	18.19[b]
20	4.1[c]	82.2[c]	574[c]	1.85[b]	10.99[c]	15.98[c]
LSD	0.7	1.7	48.25	0.10	0.70	2.32
Level of significance	++	++	++	++	++	++
Varieties						
Binadhan-8	4.1[c]	84.2[c]	666[c]	2.38[a]	15.76[b]	17.97[b]
Binadhan-10	4.0[c]	93.4[b]	589[d]	2.19[b]	12.77[d]	22.03[a]
Binadhan-14	3.7[c]	74.7[d]	454[e]	1.98[c]	10.38[e]	17.90[b]
BRRI dhan50	5.1[b]	76.5[d]	831[b]	1.65[d]	14.59[c]	17.74[b]
BRRI dhan58	5.3[b]	84.5[c]	1046[a]	1.91[c]	19.46[a]	21.83[a]
Kheyali boro	9.8[a]	99.2[a]	404[e]	1.42[e]	4.93[f]	11.65[c]
LSD	1.0	2.4	68.24	0.13	0.99	3.28
Level of significance	++	++	++	++	++	++

Upper section shows the main effect of Cd treatment (averaged across all rice varieties). Lower section shows the main effect of rice variety (averaged across both control and Cd-treated conditions). The values sharing the same letters exhibit no significant variance at a 5% level of probability according to DMRT. *LSD* − least significant difference, and ++ denotes a significance level of $P < 0.01$.

influenced due to different Cd levels in the soil (Table 3). Grain Cd levels varied between 0.058 mg/kg in a control pot and 0.253 to 0.403 mg/kg in pots subjected to 10 and 20 mg/kg Cd. The Cd levels in various rice varieties varied between 0.168 mg/kg in Binadhan-8 to 0.287 mg/kg in BRRI dhan58. The combined impacts of Cd and variety were positively significant for Cd accumulation in grain (Table 4). Kheyali boro under Cd_{20} combination had the highest Cd level (0.480 mg/kg) which was identical to BRRI dhan50 and BRRI dhan58 with 20 mg/kg Cd application. While the minimum Cd level (0.010 mg/kg) was obtained for Binadhan-10 under the Cd_0 treatment.

Nutrient Concentrations in Rice Grain and Straw

Cadmium pollution in the soil led to a reduction in the levels of N, P, K, and S in both the grains and straw of rice (Table 3). The N level in the grains varied between 1.067% in the 20 mg/kg Cd addition and 1.172% in the control treatment. The maximum level was obtained for Binadhan-8, while the minimum was observed in Kheyali boro, and this was statistically identical to BRRI dhan58. Phosphorus content in grain varied from 0.228% in Binadhan-10 to 0.289% in Binadhan14. Potassium concentration in rice grain is also affected by Cd contamination, ranging from 0.248% in BRRI dhan50 to 0.313% in Binadhan-14. Binadhan-14

T a b l e 2

Combined impacts of Cd and rice varieties on crop yield and factors contributing to yield

Varieties	Cd level [mg/kg]	Effective tillers/pot [no.]	Plant height [cm]	Filled grains/ pot [no.]	100-grain weight [g/pot]	Grain yield [g/pot]	Straw yield [g/pot]
Binadhan-8	0	5.3^{cd}	87.3^{fg}	809^{c}	2.47	18.94^{b}	21.39
	10	4.0^{d-g}	83.8^{h}	669^{de}	2.36	15.48^{cd}	17.99
	20	3.0^{g}	81.6^{hi}	522^{fg}	2.32	12.85^{f}	14.53
Binadhan-10	0	5.0^{de}	96.6^{b}	679^{de}	2.23	16.15^{c}	23.35
	10	3.6^{efg}	92.6^{cd}	610^{ef}	2.20	12.81^{f}	22.27
	20	3.3^{fg}	91.0^{de}	478^{ghi}	2.16	9.34^{g}	20.49
Binadhan-14	0	4.6^{def}	80.3^{ij}	521^{fg}	2.04	13.19^{ef}	19.95
	10	3.6^{efg}	75.5^{k}	500^{gh}	1.99	10.40^{g}	17.54
	20	3.0^{g}	68.3^{l}	341^{j}	1.89	7.57^{h}	16.22
BRRI dhan50	0	7.0^{b}	78.0^{jk}	964^{b}	1.74	15.77^{cd}	21.62
	10	4.6^{def}	76.4^{k}	809^{c}	1.67	14.47^{de}	17.99
	20	3.6^{efg}	75.0^{k}	720^{cd}	1.53	13.52^{ef}	13.62
BRRI dhan58	0	6.6^{bc}	87.9^{ef}	$1,077^{a}$	1.95	20.51^{a}	23.70
	10	5.0^{de}	84.2^{gh}	$1,070^{a}$	1.90	19.59^{ab}	21.63
	20	4.3^{d-g}	81.4^{hi}	990^{ab}	1.87	18.27^{b}	20.17
Kheyali boro	0	11.6^{a}	103.6^{a}	416^{hij}	1.55	5.44^{i}	12.32
	10	10.6^{a}	98.5^{b}	403^{ij}	1.40	4.95^{i}	11.75
	20	7.3^{b}	95.6^{bc}	392^{ij}	1.31	4.41^{i}	10.87
LSD	−	2.65	1.81	118.19	0.23	1.71	5.68
Level of significance	−	+	+	++	NS	++	NS

The values sharing the same letters exhibit no significant variance at a 5% level of probability. *LSD* − Least significant difference, and +, ++, and NS denote a significance level of $P<0.1$, $P<0.01$, and non-significant.

displayed the maximum K content while BRRI dhan50 displayed the minimum. The S content in grains of various paddy varieties varied from 0.075% to 0.093%. The combined impacts of Cd and variety in grain were statistically non-significant in the case of N, K, P, and S concentrations. The correlations between grain Cd & grain N, grain Cd & grain S contents were significantly negatively correlated (Figure 1a and 1d) while it was non-significantly and negatively correlated between grain Cd & grain P, and grain Cd & grain K content (Figure 1b and 1c). Combined impacts of Cd and varieties were statistically non-significant in straw N, P, and S contents but significant for K (Table 6). The maximum straw K content (2.225%) was obtained for Binadhan-14 in the control treatment, while the minimum (1.060%) was for Kheyali boro at 20 mg/kg Cd treatment.

Incremental Lifetime Cancer Risk (ILCR)

The cancer risk was assessed through ILCR, which increased with the rates of Cd application to soil in all rice cultivars (Table 7). Rice cultivars grown without any Cd addition had an ILCR (Incremental Lifetime Cancer Risk) below 10×10^{-4} and are safe for human consumption. The consumption of the same amount of rice per day grown in this experiment under variable rates of Cd application to the rice cultivars showed the ICLR (Incremental Lifetime Cancer Risk) from 12.6×10^{-4} when Binadhan8 was grown with 10 mg/kg Cd to 36.36×10^{-4} when Kheyali boro was grown with 20 mg/kg. Therefore, rice grown in Cd-contaminated would be a risk to human health.

DISCUSSION

The growth and yield of all six rice varieties were significantly hampered by the soil exposure to Cd. Exposure to Cd distress resulted in a decline in the physiological development and total plant mass

Table 3

Single effects of Cd treatment and rice varieties on grain Cd concentration and nutrient content

Factors	Cd [mg/kg]	N [%]	P [%]	K [%]	S [%]
Cd levels					
0	0.058[c]	1.172[a]	0.286[a]	0.304[a]	0.105[a]
10	0.253[b]	1.097[b]	0.269[b]	0.272[b]	0.081[b]
20	0.403[a]	1.067[b]	0.248[c]	0.250[b]	0.064[c]
LSD	−	0.009	0.009	0.009	0.009
Level of significance	++	++	++	++	++
Varieties					
Binadhan-8	0.168	1.145[a]	0.250[c]	0.265[c]	0.083[bc]
Binadhan-10	0.221	1.127[b]	0.228[d]	0.257[cd]	0.075[c]
Binadhan-14	0.224	1.120[b]	0.289[a]	0.313[a]	0.087[ab]
BRRI dhan50	0.248	1.072[d]	0.283[a]	0.248[d]	0.093[a]
BRRI dhan58	0.287	1.100[c]	0.268[b]	0.267[c]	0.077[bc]
Kheyali boro	0.284	1.107[c]	0.287[a]	0.302[b]	0.085[abc]
LSD	0.005	0.013	0.013	0.013	0.013
Level of significance	NS	++	++	++	++

Upper section shows the main effect of Cd treatment (averaged across all rice varieties). Lower section shows the main effect of rice variety (averaged across both control and Cd-treated conditions). The values sharing the same letters exhibit no significant variance at a 5% level of probability. *LSD* − Least significant difference, and +, ++, and NS denote a significance level of $P < 0.1$, $P < 0.01$, and non-significant.

of rice (Wang *et al.* 2014; Mostofa *et al.* 2015; Rehman *et al.* 2015). The harmful impacts of Cd limited the growth of paddy, as evidenced by reduced shoot and root elongation, a decrease in the no. of leaves and roots/plant, and diminished root and leaf area (Song *et al.* 2015). Siddique *et al.* (2022) reported that exposure to 1 and 3 mg/kg cadmium stress led to a reduction in plant height in rice, with noticeable variation observed between the two cultivars studied. Kanu *et al.* (2017) and Herath *et al.* (2015) also found that Cd toxicity reduced tiller number and flag leaf area as well. As the soil Cd levels increased, the number of filled grains declined across many rice varieties (Cheng *et al.* 2005; Kibria *et al.* 2022). Cadmium has the potential to migrate into rice grains, leading to a decline in both grain quality and production, as well as a reduction in mineral content (Li *et al.* 2012). Nevertheless, how rice reacts to Cd stress varies depending on the genetic composition, dosage, and period of the applied Cd stress (Song *et al.* 2015). Siddique *et al.* (2022) reported that the total yields of rice plants decreased by 36% and 26%, respectively, in response to soil Cd. Cadmium toxicity lowers rice yield by affecting vital plant functions such as light energy conversion, mineral uptake, and metabolic activities, which collectively suppress growth and grain formation (Chen *et al.* 2018; Mitra *et al.* 2018). These variations in Cd levels could be attributed to differences in the variety type's ability to uptake and translocate Cd. The in-

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Combined impacts of Cd and rice varieties on Cd and nutrient content in grain

Varieties	Cd levels [mg/kg]	Cd [mg/kg]	N [%]	P [%]	K [%]	S [%]
Binadhan-8	0	0.070[gh]	1.220	0.280	0.285	0.115
	10	0.166[f]	1.120	0.245	0.260	0.077
	20	0.270[e]	1.095	0.225	0.250	0.057
Binadhan-10	0	0.010[h]	1.190	0.225	0.290	0.100
	10	0.260[e]	1.105	0.235	0.260	0.068
	20	0.393[bc]	1.085	0.225	0.220	0.058
Binadhan-14	0	0.050[gh]	1.180	0.306	0.340	0.110
	10	0.240[e]	1.100	0.295	0.305	0.086
	20	0.383[bc]	1.080	0.266	0.295	0.065
BRRI dhan50	0	0.083[g]	1.130	0.305	0.285	0.110
	10	0.236[ef]	1.060	0.270	0.240	0.095
	20	0.426[ab]	1.025	0.275	0.220	0.075
BRRI dhan58	0	0.050[gh]	1.140	0.265	0.295	0.100
	10	0.346[cd]	1.095	0.280	0.260	0.070
	20	0.466[a]	1.065	0.260	0.245	0.060
Kheyali boro	0	0.080[gh]	1.170	0.333	0.330	0.095
	10	0.293[de]	1.100	0.291	0.305	0.090
	20	0.480[a]	1.050	0.237	0.270	0.070
LSD	−	0.010	0.022	0.022	0.022	0.022
Level of significance	−	++	NS	NS	NS	NS

The values sharing the same letters exhibit no significant variance at a 5% level of probability. *LSD* − Least significant difference, and +, ++, and NS denote a significance level of $P<0.1$, $P<0.01$, and non-significant.

T a b l e 5

Single effects of Cd and rice varieties on Cd and nutrient content in straw

Factors	N [%]	P [%]	K [%]	S [%]
Cd levels [mg/kg]				
0	0.636[a]	0.104[a]	1.976[a]	0.091[a]
10	0.594[b]	0.092[ab]	1.761[b]	0.066[b]
20	0.578[c]	0.083[b]	1.506[c]	0.052[b]
LSD	0.009	0.009	0.19	0.009
Level of significance	++	++	++	++
Varieties				
Binadhan-8	0.626[a]	0.089	1.745[b]	0.067[bc]
Binadhan-10	0.615[b]	0.090	1.670[b]	0.063[c]
Binadhan-14	0.609[bc]	0.100	2.035[a]	0.078[a]
BRRI dhan50	0.579[d]	0.090	1.607[b]	0.070[abc]
BRRI dhan58	0.587[d]	0.098	1.717[b]	0.063[c]
Kheyali boro	0.600[c]	0.091	1.712[b]	0.075[ab]
LSD	0.013	0.013	0.27	0.013
Level of significance	++	NS	++	++

Upper section shows the main effect of Cd treatment (averaged across all rice varieties). Lower section shows the main effect of rice variety (averaged across both control and Cd-treated conditions). The values sharing the same letters exhibit no significant variance at a 5% level of probability. *LSD* − Least significant difference, and +, ++, and NS denote a significance level of $P<0.1$, $P<0.01$, and non-significant.

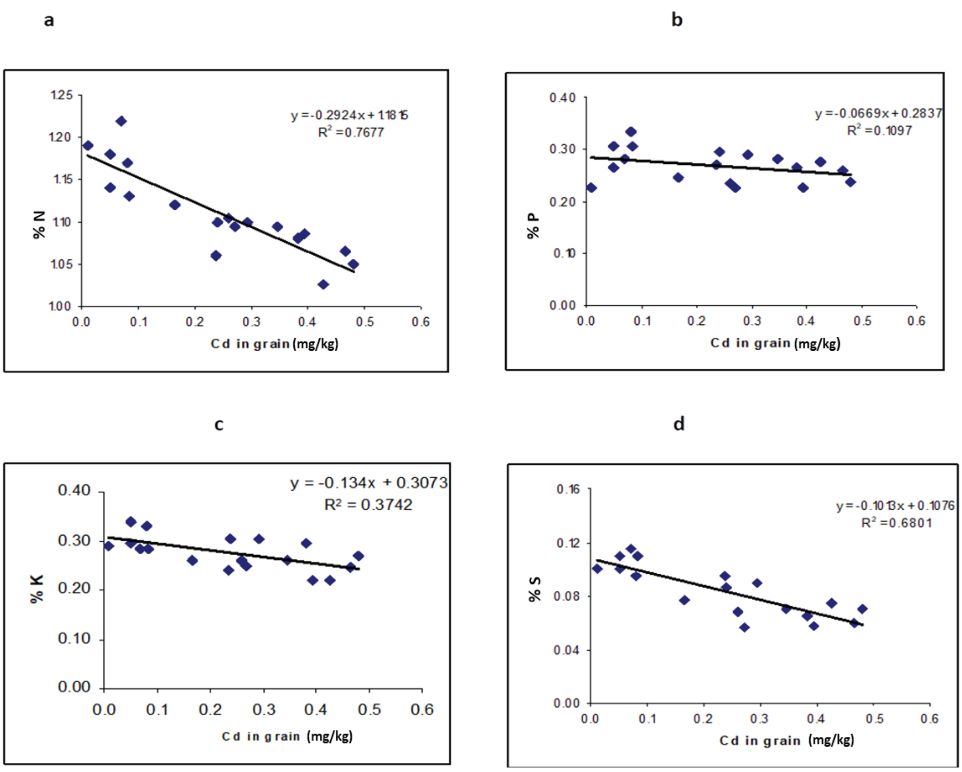

Figure 1. Relationship among Cd and N (a), P (b), K (c) and S (d) concentration in rice grain.

T a b l e 6

Combined impacts of Cd and rice varieties on nutrient content in straw

Varieties	Cd levels [mg/kg]	N [%]	P [%]	K [%]	S [%]
Binadhan-8	0	0.667	0.099	1.875[a-d]	0.093
	10	0.612	0.087	1.715[b-e]	0.063
	20	0.599	0.083	1.645[cde]	0.045
Binadhan-10	0	0.648	0.098	1.910[a-d]	0.083
	10	0.604	0.094	1.690[b-e]	0.058
	20	0.593	0.078	1.410[ef]	0.050
Binadhan-14	0	0.647	0.106	2.225[a]	0.090
	10	0.601	0.100	1.945[a-d]	0.080
	20	0.580	0.093	1.935[a-d]	0.065
BRRI dhan50	0	0.611	0.105	1.850[a-d]	0.100
	10	0.570	0.085	1.555[de]	0.065
	20	0.555	0.080	1.415[ef]	0.045
BRRI dhan 58	0	0.617	0.115	1.900[a-d]	0.085
	10	0.575	0.095	1.680[cde]	0.060
	20	0.570	0.085	1.570[cde]	0.045
Kheyali boro	0	0.630	0.100	2.095[ab]	0.095
	10	0.601	0.090	1.980[abc]	0.070
	20	0.570	0.082	1.060[f]	0.060
LSD	−	0.022	0.022	0.47	0.022
Level of significance	−	NS	NS	+	NS

The values sharing the same letters exhibit no significant variance at a 5% level of probability. *LSD* − Least significant difference, and +, ++, and NS denote a significance level of $P < 0.1$, $P < 0.01$, and non-significant.

troduction of 50 mg Cd/kg soil resulted in a decline in the weight of the aerial parts of two rice varieties (Liu *et al.* 2010a).

Cadmium can disturb plant nutrient absorption by modifying membrane permeability and contending with vital nutrients, potentially resulting in nutrient deficiencies in plants (Sarwar *et al.* 2010; Safarzadeh *et al.* 2013). Elevated Cd levels in soil have been associated with a reduction in essential mineral nutrients, such as N, K, P, Mg, Zn, Fe, and Mn in rice grains (Cheng *et al.* 2009; Zhang *et al.* 2019). Cadmium readily forms complexes with S in both plants and soils, leading to an inverse relationship between grain Cd and S. Cadmium diminishes the levels of both macro and micronutrients in both underground and above-ground parts (Gonçalves *et al.* 2009).

Liu *et al.* (2007) revealed that only a minimal proportion (0.73%) of the Cd taken up by rice plants was observed to move into the grain. Jing *et al.* (2009) revealed that the average Cd level in unpolished rice grains was 0.022 mg/kg, corresponding to a soil Cd level of 0.15 mg/kg. Some rice cultivars can accumulate more than five times the Cd concentration of others when grown in Cd-contaminated soils (Hongjiang *et al.* 2014). Kibria *et al.* (2022) found significant variations in grain Cd accumulating capacity among different rice varieties under control and stress conditions. The BINA-7 variety showed the highest Cd uptake, with levels of 0.45 mg/kg and 0.65 mg/kg at soil Cd concentrations of 5 mg/kg and 10 mg/kg, respectively. Conversely, the BR-52 variety had the lowest Cd uptake, with amounts of 0.15 mg/kg and 0.35 mg/kg under the same conditions.

T a b l e 7

Incremental Lifetime Cancer Risk (ILCR) of the population (per 10,000 population) due to dietary intake of Cd from rice

Varieties	Cd rate [mg/kg]	ICLR [per 10,000 population]
Binadhan-8	0	5.31
	10	12.60
	20	20.49
Binadhan-10	0	0.76
	10	19.73
	20	29.83
Binadhan-14	0	3.80
	10	18.22
	20	29.07
BRRI dhan50	0	6.30
	10	17.46
	20	32.33
BRRI dhan58	0	3.80
	10	26.26
	20	35.37
Kheyali boro	0	6.07
	10	22.24
	20	36.43

Cadmium can accumulate in rice grains through root absorption, followed by upward transport within the plant and subsequent transfer from shoot to grain during grain development (Wang *et al.* 2011; Liu *et al.* 2014). Cadmium uptake in rice roots is facilitated by transporters like OsIRT1 and OsNramp, with OsHMA3n sequestering Cd into vacuoles, while OsLCT1 redistributes it from leaf blades and participates in Cd transfer between vascular tissues (Uraguchi & Fujiwara 2012). The Incremental Lifetime Cancer Risk (ILCR) associated with the consumption of different cadmium (Cd)-contaminated rice varieties varied between 1.35×10^{-3} and 8.7×10^{-3} across various districts (Shahriar *et al.* 2020).

CONCLUSIONS

Rice plants exposed to high levels of Cd displayed significant detrimental effects on their growth characteristics like effective tillers, plant height, filled grains/pot, 100-grain weight, and finally total yield. Cadmium pollution led to maximization in the Cd levels in grains, subsequently minimizing the concentrations of N and S, and in a lesser extent affected also P and K. Hence, Cd pollution directly decreased both the grain yield and the mineral contents in rice grains. BRRI dhan50 and BRRI dhan58 demonstrated a certain level of resilience to Cd exposure (20 mg/kg) concerning growth and production parameters, which may be cultivated in Cd-contaminated soils but the risks for high Cd in rice still exist. Health risk assessment revealed that rice grown under Cd-contaminated conditions could contribute to elevated Incremental Lifetime Cancer Risk (ILCR) levels. The ILCR values ranged from 12.6×10^{-4} (Binadhan-8 at 10 mg/kg Cd) to 36.36×10^{-4} (Kheyali boro at 20 mg/kg Cd), exceeding the acceptable risk threshold and indicating a serious threat to human health through dietary intake. Overall, Cd pollution negatively affects both crop productivity and food safety. Although some varieties showed relative tolerance to Cd stress, their cultivation in contaminated soils requires caution, emphasizing the need for further studies on mitigation approaches and the development of safer rice cultivars.

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