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Evaluation of Cadmium Accumulation of Pak Choi *(Brassica rapa* sub. *Chinesis)* at Different Cadmium Concentrations and pH Levels and Health Risk Analysis

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Abstract

Cadmium is one of the most toxic heavy metals found in food and poses a substantial danger to human health, including carcinogenic consequences. This might be utilized as a bio-indicator for cadmium bioaccumulation in plants. Using cadmium-contaminated water for vegetable growing has been linked to increased health risks. Also, pH affects cadmium solubility and plant absorption. It is unknown about risk of cadmium concentrations in agricultural water resources (e.g., rivers, lakes, effluents, etc.) and the health risk of eating vegetables produced in cadmium polluted water affected by pH levels. In this study, hydroponically grown pak choi was utilized to assess cadmium bioaccumulation and health risks. The experiment used four initial cadmium doses (0 mg/L, 1 mg/L, 2 mg/L, and 3 mg/L) over four weeks. The original pH levels for experiments I, II, and III were 7.5, 6.5, and 5.5. For the investigation, low nitrogen and phosphorus concentrations were used (ammonium = 0.91 ± 0.36 mgN/L, nitrate = 0.50 ± 1.40 mgN/L, phosphate = 0.23 ± 0.10 mgP/L). Using an ICP-OES, cadmium concentrations of 1 – 3 mg/L substantially decreased pak choi growth ($p < 0.05$). Due to cadmium solubility at acidic pH levels, the greatest concentration (2.67 ± 0.1 mg/L) was reported at pH of 5.5. According to USEPA method, an average daily intake of 1 – 3 mg/L cadmium-contaminated pak choi cultivated will not cause chronic non-carcinogenic (hazard quotient < 1) but can induce carcinogenic impact (cancer risk > 10^{-6}) after 30-year consumption. Thus, thorough monitoring of cadmium in irrigation water is recommended.

Keywords: Bioaccumulation; Cadmium; Health risk assessment; Hydroponics; Pak Choi

1. Introduction

Cadmium is one of the most harmful heavy metals found to contaminate both natural soil and water resources from commercial fertilizers, manure, sludge, and industrial effluents (López-Millán *et al.,* 2009). Cadmium is the main contaminated pollutant that affects environments, agricultural lands, and human health, causing chronic adverse effects on kidneys, liver, bone, and blood from long-term exposure (Genchi *et al.,* 2020). Soils contaminated with cadmium and heavy metals have become a worldwide problem and serious disaster of the environment, leading to losses in agricultural yield and hazardous health effects as they enter the food chain (Anwar *et al.,* 2009).

Hydroponics is known as the innovation of growing plants without soil and has been developed for urban farming and smart agriculture. Natural water resources and wastewater containing nutrients were reported to be effective for growing plants in hydroponics due to available nutrient concentrations (e.g., ammonium, nitrate, and phosphate) (Woraharn *et al.,* 2021). However, integration of hydroponics with water resource reuse has met limitations due to human perception and lack of information in health risk assessment from the resource recovery. Cadmium contaminated water resources and resulted in bioaccumulation in plants at high levels (Woraharn *et al.,* 2021). Moreover, pH level is a key factor to control ions dissociation; thus, affecting nutrient and cadmium dissolution, availability, uptake, plant growth, and toxic responses (Alexopoulos *et al.,* 2021). Thus, there is a need to evaluate the toxicity level of cadmium on plant growth and health risk assessment for human consumption.

The objectives of this study are to (1) evaluate the bioaccumulation of cadmium and its effects on plant growth at different cadmium concentrations and pH levels and (2) to conduct health risk analyses of consuming pak choi grown by different levels of cadmium concentrations in hydroponics.

2. Materials and method

2.1 Hydroponic set up and operation

Hydroponics Nutrient film technique (NFT) systems were constructed, consisting of a channel allowing a thin layer of recirculating water to flow through the root zone in grow bed and a recirculating tank with a water pump for water circulation (Figure 1). Pak choi (*Brassica rapa* sub. *Chinesis*) was used for the bioaccumulation test of cadmium. After the seeding, plants were transferred to the hydroponic growing bed for 28 days in the NFT systems. Before starting each experiment, commercial hydroponic nutrient solutions were added to the hydroponic systems to adjust ammonium and phosphorus concentration in the range of wastewater for agricultural reuse (~1 ± 0.5 mgN/L, ~ 0.3 ± 0.1 mgP/L).

2.2 Experimental design, sampling, and chemical analyses

The hydroponic experiments were conducted in a 28-day operation and conducted in duplicate. Three experiments were designed using pH levels of 7.5, 6.5, and 5.5 in experiment no. 1, 2, and 3, respectively. In each experiment, four Cd supplemented conditions were used: control (no Cd added), 1 mg/L, 2 mg/L, and 3 mg/L. Different pH was adjusted by sulfuric acid. Water samples were taken every week for ammonium, nitrate, phosphate using the Standard Methods (APHA, 2005), and pH levels using portable pH probes (HACH, Loveland, CO, USA). Pak choi were harvested at the end of each experiment for wet weight and dry weight (70^{o}C for 48 hours) for cadmium analysis and moisture content. Cadmium in the whole edible part of pak choi and root was measured separately using inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES).

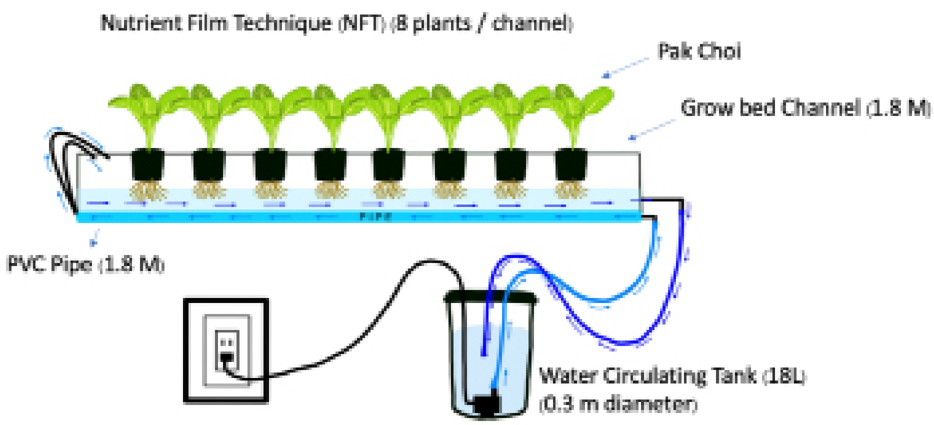

Figure 1. Hydroponic setup used in this study

2.3 Calculations

2.3.1 Bioaccumulation

Bioconcentration factors (BCF) were used to evaluate the levels of cadmium concentrations in plant tissues relative to concentration in water.

$$BCF_{plant\text{-}water} = C_{plant}\ (mg/kg)/C_{water}\ (mg/L) \quad (1)$$
$$BCF_{root\text{-}water} = C_{root}\ (mg/kg)/C_{water}\ (mg/L) \quad (2)$$

Where, $BCF_{plant\text{-}water}$ and $BC_{Froot\text{-}water}$ are bioconcentration factors in pak choi (edible part) and root, respectively; C_{plant} and C_{root} are concentrations of cadmium in pak choi (edible part) and root, respectively (mg/kg); C_{water} is cadmium concentration in hydroponic recirculating water (mg/L). BCF was determined using slope of cadmium concentrations in plant by water.

2.3.2 Exposure assessment and risk characterization

The average daily dose (ADD) was used to evaluate cadmium intake per day from vegetables during the lifetime of consumption.

$$ADD = C_{medium} \times IngR \times EF \times ED / BW \times AT \quad (3)$$

Where ADD is an average daily dose (mg/kg-day); C_{medium} is cadmium concentration in pak choi (mg/g wet wt.); IngR is ingestion rate of pak choi (2.86 g wet/day of the whole population) (U.S.EPA., 2018); EF is exposure frequency (365 days/years); ED is exposure duration (30 years for non-carcinogenic and carcinogenic risk assessment) (U.S. EPA, 2018). AT is averaging time (days, AT = ED × 365). AT for non-carcinogenic risk is 10,950 days (30 years) and, AT for carcinogenic risk is 25,550 days (70 years). Cadmium content in wet weight basis was calculated based cadmium content in dry weight basis and moisture content.

$$HQ = ADD/RfD \quad (5)$$
$$R_c = ADD \times CSF \quad (6)$$

Where, RfD is the reference dose of the non-carcinogenic risk of cadmium via ingestion route (0.001 mg/kg-day) and CSF is the cancer slope factor for carcinogenic risk of cadmium via ingestion route (15 kg-day/mg) (Quispe *et al.,* 2021). Cadmium intake in a person was considered not to cause a human health risk when HQ was below 1.0 for non-carcinogenic risk and R_c below 10^{-6} for carcinogenic risk (Quispe *et al.,* 2021).

2.4 Statistical analyses

The plant weight, cadmium contents in plants, cadmium contents in roots, pH level, and EC among the four groups were compared using a one-way analysis of variance (one-way ANOVA) and analysis of covariance (ANCOVA) to identify significant differences ($p < 0.05$). Tukey post-test was used to identify significant differences ($p < 0.05$) within each experiment, which are indicated by letters A to D in each Table.

3. Results and discussion

3.1 Nutrient availability and cadmium solubility at varying pH levels

Ammonium, nitrate, and phosphate concentrations were in ranges of 3.9 – 12.6 mgN/L, 3.2 – 7.5 mN/L, and 0.22 – 0.43 mgP/L, respectively (Table 1), which were in ranges of domestic waste/wastewater used in agricultural systems (Rana *et al.,* 2011). For example, municipal wastewater with ammonium, nitrate, and phosphate concentrations of 0.72 mgN/L, 0.842 mgN/L, and 0.209 mgP/L was found to be successful for growing tomatoes from domestic wastewater (Rana *et al.,* 2011). Results showed that cadmium doses supplemented into hydroponic systems did not affect ammonium, nitrate, and phosphate concentrations ($p > 0.05$).

Different pH levels affected the cadmium dissolution and were available in water (Table 2). At low pH, there were high soluble cadmium concentrations more than that at higher pH levels (e.g., 6.5 and 7.5), as shown in Table 2. Particularly, at 3 mg/L cadmium added, the % cadmium availability was found to increase toward low pH levels.

For example, at a cadmium dose of 3 mg/L, the pH level of 5.5 showed the highest cadmium available in water (89.0%) compared to pH levels of 6.5 (42.3%) and 7.5 (32.0%). The result could be because other ions in hydroponics such as bicarbonate and other nutrient minerals (e.g., nitrate, sulfate, chloride, ionic strength, etc.) contributed to the precipitation of some cadmium ions and resulted in a loss of calcium soluble in water (Kubier *et al.,* 2019). Another reason could be due to cadmium uptake by plants that translocate cadmium in water to cadmium in plant tissues such as roots and leaves (Wan *et al.,* 2019). The higher concentrations caused lower percent cadmium available in water because cadmium concentration is the factor that positively affects the precipitation of cadmium species.

Table 1. Ammonium, nitrate, phosphate concentrations in hydroponics at varying cadmium doses and pH levels

Exp no. /pH	Cadmium dose (mg/L)	pH level	Ammonium (mgN/L)	Nitrate (mgN/L)	Phosphate (mgP/L)
1/7.5	control	$7.49 \pm 0.03^{A,*}$	1.26 ± 0.59^{A}	0.73 ± 0.16^{A}	0.29 ± 0.12^{A}
	1.0	7.46 ± 0.04^{A}	1.23 ± 0.55^{A}	0.71 ± 0.13^{A}	0.26 ± 0.08^{A}
	2.0	7.45 ± 0.06^{A}	1.10 ± 0.66^{A}	0.72 ± 0.17^{A}	0.22 ± 0.08^{A}
	3.0	7.44 ± 0.04^{A}	1.24 ± 0.62^{A}	0.75 ± 0.13^{A}	0.22 ± 0.08^{A}
2/6.5	control	6.46 ± 0.04^{A}	1.09 ± 0.38^{A}	0.32 ± 0.11^{A}	0.26 ± 0.11^{A}
	1.0	6.43 ± 0.06^{A}	1.08 ± 0.32^{A}	0.34 ± 0.10^{A}	0.26 ± 0.10^{A}
	2.0	6.45 ± 0.05^{A}	1.12 ± 0.36^{A}	0.33 ± 0.08^{A}	0.26 ± 0.08^{A}
	3.0	6.45 ± 0.04^{A}	1.11 ± 0.36^{A}	0.34 ± 0.09^{A}	0.24 ± 0.10^{A}
3/5.5	control	5.45 ± 0.04^{A}	0.45 ± 0.12^{A}	0.45 ± 0.19^{A}	0.36 ± 0.12^{A}
	1.0	5.43 ± 0.06^{A}	0.41 ± 0.14^{A}	0.44 ± 0.21^{A}	0.41 ± 0.14^{A}
	2.0	5.46 ± 0.03^{A}	0.39 ± 0.14^{A}	0.45 ± 0.17^{A}	0.43 ± 0.14^{A}
	3.0	5.45 ± 0.04^{A}	0.43 ± 0.10^{A}	0.47 ± 0.18^{A}	0.38 ± 0.10^{A}

Note: Symbol * represents mean ± standard deviation.

Table 2. Cadmium concentrations in hydroponics at varying cadmium doses and pH levels

Exp no.	Cadmium dose (mg/L)	pH level	Cadmium in water (mg/L)	% Cadmium available (%)
1/7.5	control	7.49 ± 0.03^{A}	0.04 ± 0.001^{D}	-
	1.0	7.46 ± 0.04^{A}	0.59 ± 0.01^{C}	59
	2.0	7.45 ± 0.06^{A}	0.83 ± 0.02^{B}	41.5
	3.0	7.44 ± 0.04^{A}	0.96 ± 0.02^{A}	32.0
2/6.5	control	6.46 ± 0.04^{A}	0.04 ± 0.006^{D}	-
	1.0	6.43 ± 0.06^{A}	0.58 ± 0.04^{C}	58
	2.0	6.45 ± 0.05^{A}	0.80 ± 0.11^{B}	40.0
	3.0	6.45 ± 0.04^{A}	1.27 ± 0.10^{A}	42.3
3/5.5	control	5.45 ± 0.04^{A}	0.01 ± 0.005^{D}	
	1.0	5.43 ± 0.06^{A}	0.87 ± 0.06^{C}	87
	2.0	5.46 ± 0.03^{A}	1.81 ± 0.02^{B}	90.5
	3.0	5.45 ± 0.04^{A}	2.67 ± 0.10^{A}	89.0

Note: Symbol *represents mean ± standard deviation.

3.2 Effects of cadmium concentrations on plant growth

Cadmium concentrations affected plant and root growth. Significant differences of means ($p < 0.05$) show that plant growth was high in the control condition. Results show that increasing doses of cadmium resulted in an increased adverse response of pak choi by inhibiting plant and root growth. Compared with the control condition, wet weight of pak choi decreased by 23.9% – 58.8%, 1.4% – 39.6%, and 6.3 – 24.0% at cadmium doses of 1 mg/L, 2 mg/L, and 3mg/L, respectively. Pak choi growth also decreased at alkaline pH levels. For example, at cadmium dosage of 3 mg/L, the highest inhibition was found at pH 5.5 (93.7%) followed by pH 6.5 (90.7%), and pH 7.5 (76.0%), respectively. This could be due to plant growth is affected by phosphate solubility that are increased low pH levels.

Cadmium was found to inhibit plant growth and induced other toxic effects such as germination inhibition, reduction in root elongation, reduction in protein synthesis and nitrogen content in leaves, decrease in photosynthesis, and chlorosis in leaves (Haider *et al.,* 2021). Cadmium was also reported to induce reactive oxygen species that stimulate oxidative stress and negatively plant productivity (Haider *et al.,* 2021). Cadmium inhibition depends on plant species with toxic levels from about 1 – 50 mg/L. Inhibition level of plant growth was found at cadmium concentration about 10 mg/L and 6 mg/L for lettuce and pak choi, respectively (Ma *et al.,* 2017; Tang *et al.,* 2020). In this study, it was found that the lowest-observed-adverse-effect level (growth reduction) of pak choi at the pH range of 5.5 – 7.5 was below 0.59 mg/L of cadmium in hydroponic water (or below 1 mg/L of total cadmium in the system). Although these cadmium concentrations were not at severe inhibition level, pak choi reduced in growth rate, and the results could suggest that growth reduction could be a bioindicator for the plant in hydroponics that adversely responds to cadmium contamination in growth media.

3.3 Bioaccumulation of cadmium in pak choi at high cadmium concentrations

Cadmium was found to accumulate in roots and plants with a positive tendency toward dosing concentrations (Table 4). Moreover, cadmium was likely to accumulate in plants at low pH levels where

Table 3. Pak choi growth and effect of cadmium inhibition on pak choi growth during 28 days at different cadmium concentrations and pH levels

Exp no.	Cadmium dose (mg/L)	Wet weight (Edible part) (g)	Dry weight (Edible part) (g)	Wet weight (root) (g)	Dry weight (root) (g)
1/7.5	control	41.49 ± 1.36^{A}	3.35 ± 0.42^{A}	3.35 ± 0.36^{A}	0.26 ± 0.02^{A}
	1.0	20.25 ± 0.44^{B}	1.94 ± 0.02^{B}	2.21 ± 0.33^{B}	0.14 ± 0.02^{B}
	2.0	16.43 ± 1.49^{C}	1.71 ± 0.20^{C}	1.66 ± 0.007^{C}	0.12 ± 0.01^{B}
	3.0	9.96 ± 0.51^{D}	1.16 ± 0.33^{D}	1.48 ± 0.05^{D}	0.09 ± 0.007^{C}
2/6.5	control	289.63 ± 2.02^{A}	36.10 ± 1.76^{A}	12.94 ± 1.46^{A}	1.56 ± 0.54^{A}
	1.0	170.26 ± 4.16^{B}	22.85 ± 1.23^{B}	10.42 ± 2.00^{A}	1.04 ± 0.13^{A}
	2.0	33.09 ± 7.36^{C}	4.20 ± 0.35^{C}	6.70 ± 0.82^{B}	0.39 ± 0.32^{B}
	3.0	26.99 ± 2.96^{C}	2.20 ± 0.49^{D}	1.48 ± 0.94^{C}	0.12 ± 0.04^{D}
3/5.5	control	236.59 ± 2.52^{A}	27.42 ± 3.13^{A}	37.74 ± 5.89^{A}	4.10 ± 0.60^{A}
	1.0	56.65 ± 1.99^{B}	5.33 ± 3.49^{B}	11.82 ± 3.25^{B}	0.62 ± 0.24^{B}
	2.0	40.95 ± 2.58^{C}	4.22 ± 2.12^{B}	5.81 ± 5.74^{B}	0.61 ± 0.23^{B}
	3.0	14.90 ± 0.77^{D}	1.88 ± 0.96^{B}	1.27 ± 0.70^{C}	0.19 ± 0.04^{C}

Note: Symbol ± represents mean ± standard deviation.

plant growth was enhanced. Other studies also fund that the amount of cadmium accumulated in plants increases with a tendency to accumulate more in pH at 5.5 greater than 6.5 and 7.5 (Guttormsen.,1995).

Roots were reported to accumulate higher concentrations of heavy metals than leaves (Page *et al.,* 2006). This suggests that different plants could tolerate cadmium concentrations and accumulate a certain amount until observed stress conditions such as growth inhibition and chlorosis (Malea *et al.,* 2018). At stress conditions, which the plant could not tolerate and accumulate cadmium in the upper (edible) part, it could result in accumulation in roots due to inhibition in translocation; thus, high cadmium concentrated in roots (Woraharn *et al.,* 2021). The highest BCFs in edible part and root were found at pH levels of 6.5 followed by 5.5 and 7.5, respectively, although the highest cadmium accumulation in plants was found at the pH of 5.5 (Table 5).This is because BCF is relative to cadmium concentration in water. The pH of 6.5 – 7.5 resulted in lower cadmium solubility in hydroponic water compared to the pH of 5.5. Therefore, highest BCF was found at the pH level of 6.5 due to lower Cd concentrations in hydroponic water at pH of 6.5 than those at pH of 5.5.

Table 4. Cadmium accumulations in pak choi and roots at varying cadmium doses and pH levels

Exp no./pH	Cadmium dose (mg/L)	Cd in edible part (mg/kg DW)	Cd in root (mg/kg DW)
1/7.5	control	0.029 ± 0.005^{A}	0.022 ± 0.007^{A}
	1.0	0.277 ± 0.002^{B}	0.184 ± 0.07^{B}
	2.0	0.303 ± 0.070^{BC}	0.402 ± 0.07^{C}
	3.0	0.340 ± 0.015^{C}	0.440 ± 0.05^{C}
2/6.5	control	0.060 ± 0.001^{A}	0.049 ± 0.02^{A}
	1.0	0.424 ± 0.077^{B}	0.403 ± 0.08^{B}
	2.0	0.527 ± 0.068^{B}	0.838 ± 0.07^{C}
	3.0	0.650 ± 0.007^{C}	0.970 ± 0.08^{C}
3/5.5	control	0.002 ± 0.001^{A}	0.016 ± 0.001^{A}
	1.0	0.400± 0.001^{B}	0.352 ± 0.07^{B}
	2.0	0.900 ± 0.063^{C}	0.800 ± 0.17^{C}
	3.0	1.450 ± 0.004^{D}	0.920 ± 0.18^{C}

Note: Symbol * represents mean ± standard deviation.

Table 5. Bioconcentration factor (BCF) of cadmium in pak choi and roots at different pH levels

Exp no./pH	Plant – Water		Root – Water	
	BCF	R^2	BCF	R^2
1/7.5	0.501	0.965	0.035	0.809
2/6.5	1.038	0.962	2.963	0.996
3/5.5	0.434	0.97	0.574	0.976

3.4 Health risk analyses of consuming pak choi from cadmium contaminated hydroponics

Consumption of pak choi grown at total cadmium doses above 1 mg/L could not cause non-carcinogenic (HQ < 1, Table 6) but could cause carcinogenic ($R_c > 10^{-6}$, Table 7) health risks to consumers during 30 - year consumption. Average non-carcinogenic risk levels varied from 0.005 to 0.303 (Table 6) and 3×10^{-5} to 1.95×10^{-3} (Table 7). The level of risk increased with cadmium contents in the edible part of pak choi, which positively corresponded with cadmium doses in water. In this study, it was found that cadmium can be contaminated with hydroponic nutrient solutions (0.01 – 0.04 mg/L), which was found in the control condition (Table 2). Although cadmium contaminated at control condition did not cause non-carcinogenic risk, consuming pak choi at control condition and at cadmium supplemented conditions were identified to cause carcinogenic risk.

Table 6. Non-carcinogenic risk assessment via ingestion route of pak choi grown by different total cadmium doses and pH levels over 30-year consumption

Exp no./ pH	Cadmium dose (mg/L)	ADD (mg/g-day)	HQ Average	HQ (95% CI)
1/7.5	control	0.0089	0.009	0.006 – 0.010
	1.0	0.0865	0.086	0.056 – 0.101
	2.0	0.0947	0.095	0.062 – 0.111
	3.0	0.1052	0.105	0.082 – 0.116
2/6.5	control	0.0153	0.015	0.006 – 0.020
	1.0	0.1259	0.126	0.090 – 0.144
	2.0	0.2615	0.261	0.227 – 0.278
	3.0	0.3026	0.303	0.264 – 0.321
3/5.5	control	0.0051	0.005	0.004 – 0.006
	1.0	0.1099	0.110	0.079 – 0.125
	2.0	0.2488	0.249	0.172 – 0.287
	3.0	0.2870	0.287	0.207 – 0.326

Table 7. Carcinogenic risk assessment via ingestion route of pak choi grown by different total cadmium doses and pH levels over 30-year consumption

Exp no./ pH	Cadmium dose (mg/L)	ADD (mg/g-day)	R_C Average	R_C (95% CI)
1/7.5	control	0.0038	0.00006	0.00004 – 0.00008
	1.0	0.0371	0.00056	0.00036 – 0.00075
	2.0	0.0406	0.00061	0.00040 – 0.00082
	3.0	0.0451	0.00068	0.00053 – 0.00082
2/6.5	control	0.0065	0.00010	0.00004 – 0.00015
	1.0	0.0539	0.00081	0.00058 – 0.00104
	2.0	0.1121	0.00168	0.00146 – 0.00190
	3.0	0.1297	0.00195	0.00170 – 0.00219
3/5.5	control	0.0022	0.00003	0.00003 – 0.00004
	1.0	0.0471	0.00071	0.00051 – 0.00090
	2.0	0.1066	0.00160	0.00110 – 0.00210
	3.0	0.1230	0.00184	0.00133 – 0.00236

Studies also reported similar results of both non-carcinogenic and carcinogenic risk of cadmium contamination in rice grown by contaminated soil (cadmium content in soil = 0.325 – 26 mg/kg) in China (Zeng *et al.,* 2015). Despite soil could adsorb cadmium ions, long-term heavy metal exposure from brown rice consumption poses both non-carcinogenic and carcinogenic health hazards to the local population. Therefore, in terms of health risk assessment cadmium contaminations in soil and water must be considered before reusing in irrigation and agriculture. For hydroponics, heavy metal removal processes are needed to purify water for reusing in hydroponics. Moreover, regulation and standard of inorganic chemical fertilizers used for hydroponics must be strictly controlled to prevent carcinogenic risk from such low levels of cadmium concentrations.

4. Conclusions

Pak choi was employed in this study to assess cadmium bioaccumulation and the health risk associated with vegetable consumption. The experiment was done over a four-week period with four initial cadmium dosages (control, 1 mg/L, 2 mg/L, and 3 mg/L). For experiment I, II, and III, three starting pH values (7.5, 6.5, and 5.5) were employed. The results indicate that cadmium concentrations of 1 – 3 mg/L substantially decreased the development of pak choi ($p < 0.05$) when compared to control. The bioaccumulation of cadmium in plant roots (0.035 – 2.963) and edible parts (0.434 – 1.038) increased as the cadmium concentration increased. The maximum concentration of cadmium in water (2.67 ± 0.1 mg/L) was discovered at an initial pH of 5.5, owing to cadmium solubility at acidic pH levels. According to the USEPA's average daily intake and health risk assessment, consumption of pak choi grown in a cadmium-contaminated water resource at a concentration of 1 – 3 mg/L is unlikely to cause chronic non-carcinogenic (HQ < 1) risk. However, at the low cadmium concentrations (0.01 – 0.04 mg/L), ingesting pak choi cultivated in cadmium-contaminated water was determined to pose a carcinogenic risk.

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