Paddy Water Environ (2015) 13:11–18
DOI 10.1007/s10333-013-0401-3

ARTICLE

Accumulation of arsenic in rice plant: a study of an arsenic-contaminated site in Taiwan

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Received: 17 April 2013 / Accepted: 2 September 2013 / Published online: 19 September 2013
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Abstract A study conducted in 2006 showed that over 100 ha of rice paddies in Beitou, Taiwan, irrigated over the years using water mixed with hot spring, was heavily polluted by arsenic. Thus, the objective of the present study is to measure arsenic content in different parts of rice and paddy soils, and eventually explain the arsenic distribution in ratoon rice, including its relationship to the soil. Arsenic levels of rice in grains, straws, roots, and soils were obtained from 15 rice paddies, selected based on different arsenic soil concentrations ranging from 67 to 438 mg kg^{-1} ($n = 15$). The mean arsenic content in grains was measured at 0.20 mg kg^{-1} ($n = 60$) and the highest grain arsenic of the survey was at 1.183 mg kg^{-1}. Meanwhile, the mean total arsenic levels were 244 mg kg^{-1} ($n = 28$) in root and 4.4 mg kg^{-1} ($n = 28$) in straw. In comparison, regression of topsoil arsenic levels with rice grains ($r^2 = 0.00$) and straws ($r^2 = 0.56$) were less significant compared to that with rice roots ($r^2 = 0.93$), and the mean arsenic level in rice from root to grain was also shown to have a decreasing trend. Though concentrations of arsenic in compositive rice grain each field did not exceed food hygiene concentration limit, arsenic level in root strongly depended on arsenic concentrations of soil suggesting that the high arsenic concentration may have the potential for translocation from root to grain which ultimately effects on the human health.

Keywords Arsenic · FPXRF · Rice · Soil contamination

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Introduction

Arsenic is one of the most critical global environmental toxicants. High concentrations of arsenic in groundwater have been reported from several countries, including Argentina, Bangladesh, Chile, China, India, Japan, Mexico, Mongolia, Nepal, Poland, Taiwan, Vietnam, and some parts of the United States (Chowdhury et al. 2000; Smith et al. 2001; Anawar et al. 2002; Mitra et al. 2002; Pandey et al. 2002; Meharg and Rahman 2003). The nature of the arsenic contamination of shallow hand tube wells in the southwestern region and northeastern basin of Taiwan is believed to have been exposed to humans through drinking water (Hsu et al. 1999; Tseng et al. 2000).

Generally, in unpolluted environments, ordinary crops do not accumulate enough arsenic for them to become toxic to humans. However, in arsenic-contaminated soil, the uptake of arsenic by the plant tissue is significantly elevated, particularly in vegetables and edible crops (Larsen et al. 1992). In Bangladesh, the normal irrigated soil contains 4–8 mg kg^{-1} of arsenic, while in areas where irrigation with arsenic-contaminated water is carried out, the soil arsenic concentration can be up to 83 mg kg^{-1}(Ullah 1998). The reported average of 10 mg kg^{-1} of arsenic naturally manifests in soils worldwide (Das et al. 2002); in Taiwan, 4.54–5.65 mg kg^{-1} of arsenic has been generally

investigated in farmlands (Chen and Lee 1995; Chang et al. 1999). However, for the first time, over 100 ha of paddies in Beitou, Taipei, Taiwan were found to be heavily polluted with arsenic (4.71–513 mg kg^{-1} dry weight). These paddies have long been irrigated using water mixed with hot spring in the early years (Chang et al. 2007).

To assess the risk posed by As in the diet, As speciation must be ascertained because inorganic As (arsenate and arsenite) is more toxic than its counterpart—methylated organic forms (monomethyl arsenic acid, MMA^{v}; dimethyl arsenic acid, DMA^{v}) present in plants (Abedin et al. 2002; Meharg and Hartlet-Whitaker 2002). A previous study, albeit limited, suggested that the majority of As in Taiwan's rice is inorganic, with the rice strain influencing speciation (Schoof et al. 1998). In general, there were reports that there is an elevated arsenic concentration, that is, 0.41 mg of As kg^{-1} fresh weight in grain ($n = 341$), based on collected samples from different locations (Li et al. 1994). Similarly, 0.10 mg of As kg^{-1} fresh weight in grain ($n = 280$) had been collected from market baskets in Taiwan (Lin et al. 2004). Rahman et al. (2007a, b) conducted glasshouse and field-level experiments to investigate the concentrations of arsenic in grain (0.2–0.7 mg kg^{-1} dry weight), straw (0.9–23.7 mg kg^{-1} dry weight), husk (0.2–1.6 mg kg^{-1} dry weight), and root (46.3–51.9 mg kg^{-1} dry weight). In China, arsenic levels in rice grain reached 0.7 mg kg^{-1} from those grown on paddy soils with 68 mg of As kg^{-1} (Xie and Huang 1998), showing the potential for arsenic eventual contamination of rice grain from contaminated paddy soils. Unfortunately, paddy rice is the staple food of these regions.

Different plant parts showed different abilities to accumulate arsenic content. There have been reports on arsenic content in tissues of rice, which are distributed in fractions, although values vary greatly due to differences in varieties, fertilizers, or cultivating behavior in field sites or glasshouses (Marin et al. 1992; Abedin et al. 2002; Alam and Rahman 2003; Das et al. 2004; Rahman et al. 2004, 2007a, b). In principle, arsenic concentration in rice straw increases significantly with increasing arsenic concentration in rice root. However, arsenic translocation from straw to rice grain does not differ significantly for variations in rice strain (Abedin et al. 2002; Rahman et al. 2007b). Regardless of soil arsenic concentrations mentioned in previous studies, arsenic concentration in rice tissues followed this trend: root > straw > grain.

There is, therefore, great concern regarding accumulation of arsenic in rice planted in Taiwan. However, at the present, there is scarcity of evidence concerning accumulated quality of arsenic poisoning in different rice tissues via the absorption of root in this study area. The present study was undertaken with the objective of measuring arsenic content in different parts of ratoon rice and paddy soils during field investigation, and in particular, to understand the arsenic distribution in ratoon rice, including its relationship to soils.

Methods and materials

Study site

In this work, field experiments were conducted in the aftergrowth (July to December 2006) of rice in the Gaudau Plan (25°7′35.27″N, 121°29′42.20″E). The site covers about 842 ha of Beitou in Taipei, Taiwan. The main area selected for this study encompasses ~128 ha of rice paddies heavily polluted by arsenic, with an official reported arsenic concentration levels above 60 mg kg^{-1}, the first ever recorded in Taiwan, during November, 2006 (Chang et al. 2007). In the area, the annual average rainfall is 2,471 mm (1998–2006). Rainy season normally occurs during summer and autumn, about 69 % of the annual average according to the data of the Central Weather Bureau. From late 1970s, a great part of irrigated water was derived from a mix of urban waste and stream water around the study areas and the water source was different from that used in the early years.

The arsenic levels of irrigation water and water in the shallow tube wells, with depth of 5–6 m in situ, were obtained from the 2006 study. Their collected samples were located within the study site (see Fig. 1). Data have also been provided through the regular/seasonal monitored water quality study conducted from 2005 to 2006 by the Ecological Engineering Research Center of National Taiwan University (NTU EERC). Total arsenic in shallow tube wells ranged from 0.026 to 0.031 mg l^{-1} ($n = 3$) in 2006 and varied from 0.004 to 0.049 mg l^{-1} ($n = 8$) in irrigated water between 2005 and 2006 (Chang et al. 2007). The analyzed results of this study indicate that arsenic levels both in irrigation water or groundwater did not increase even though the soil was considered extremely polluted with arsenic, as compared with other previous studies in Bangladesh and China (Ullah 1998; Xie and Huang 1998).

Sample collection and treatment

Fifteen (15) field blocks based on a recent official investigation of the polluted arsenic soils of Gaudan Plan were chosen to collect sample grains, straws, roots, and soils for the study areas. The area size of the different field experiments ranged from 938 to 5,000 m^2. During harvesting, four samples of each field site covering two rice varieties, such as Taikeng No.8 (Tk8) and Tai Nan No.11 (TN11), were collected and positioned in a diagonal from inlet to outlet, and similar procedures were conducted for soils,

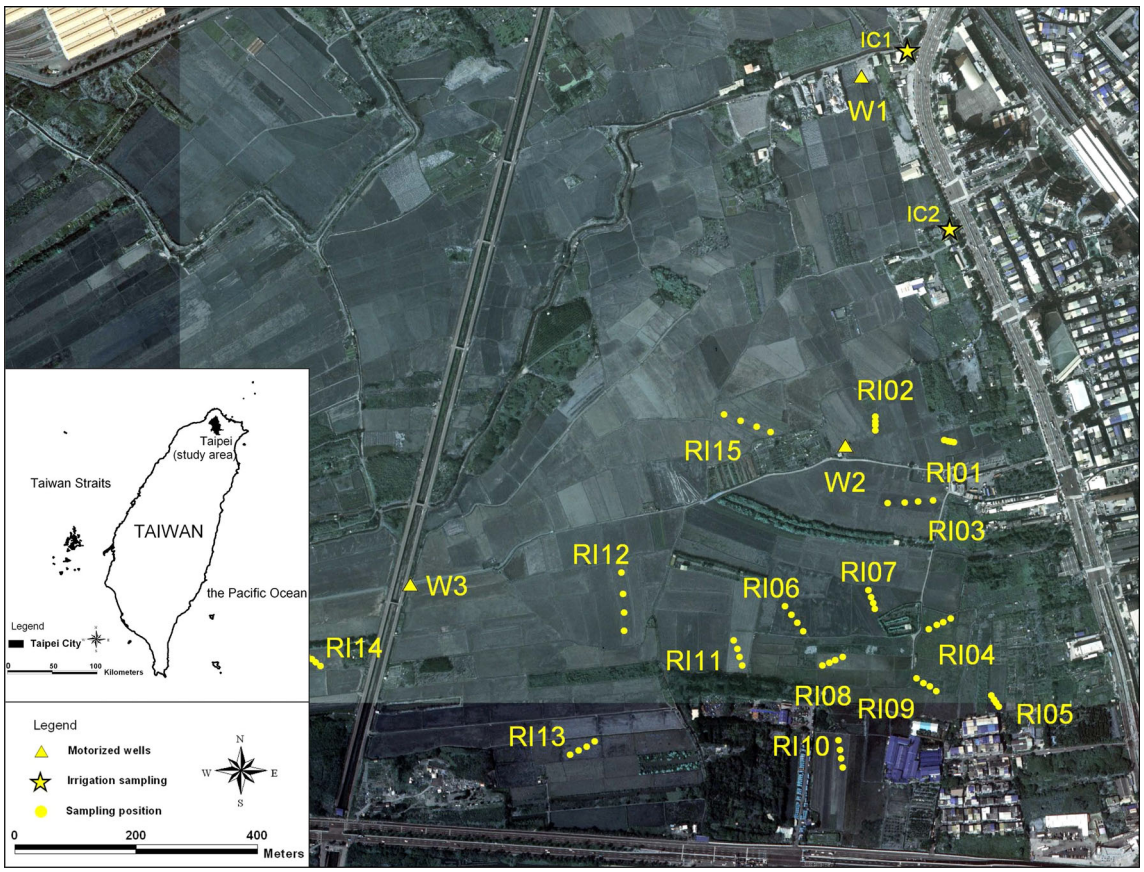

Fig. 1 Site of sampling locations including rice, monitored water in channel and tube well

including topsoil (0–15 cm) and subsoil (15–30 cm), respectively (see Fig. 1). Meanwhile, we also identified 5 of 15 field blocks to take samples of straws and roots. Overall, we gathered 60 samples of grains ($n = 20$ for TN11; $n = 40$ for Tk8), 20 samples of straws and roots ($n = 4$ for TN11; $n = 16$ for Tk8), and 120 samples of soils for the analysis of the arsenic levels.

The field-portable X-ray fluorescence (FPXRF) analyzer offers an attractive, in situ alternative to the lengthy and costly traditional laboratory analysis of contaminated soil (Piorek 1997). An experiment was conducted to determine whether there was a significant relationship between chemical digestion extractable and FPXRF-analyzed metal levels, and whether the detection limits of FPXRF were sufficient to "screen" soils for heavy metals at levels which would be deemed to be contaminated under modern guidance (CLEA 2002; Kilbride et al. 2006). All soil samples ($n = 120$) were collected from the 15 fields (four points per field) from two depths (0–15 and 15–30 cm) in December 2006. Then each soil sample was dried to constant weight in an air-circulated oven, ground, sifted through a 2-mm sieve, and stored in polypropylene containers prior to the analysis using FPXRF (Alpha 6500, Innov-X Systems, Inc. USA). Similarly, the compostive topsoil and rice samples were digested, following the study of Das et al. (2004) in which there was prior analysis using the Atomic Absorption Spectophotometry (AAS) equipped with hydride generation.

Tissues of straws and roots were first washed with de-ionized water to remove dust and soil particles, and air-dried for 3 h, and then dried at 108 °C until a constant weight was obtained. The dried samples and grains were then homogenized and wet-digested. Ground samples of the grains (2.5 g), straws (2.5 g), and roots (1 g) were digested by initially adding 25.0 ml of nitric acid (HNO_3, 65 %) and mildly heating them at 100 °C for 30 min to oxidize instable oxide. After some degree of cooling, 10 ml of perchloric acid ($HClO_4$, 70–72 %) was added, and the solution was heated to a boil, avoiding it from being fully emptied, until a clear solution and dense white smoke of trioxide sulfur (SO_3) was obtained. Afterward, 50 ml of de-ionized water was added to the reactor containers and boiled to rid the remainder smoke of dioxide nitrogen. The digested samples were then filtered using a 0.45-μm filter and analyzed for total arsenic concentrations. The volume of the digested solution was made up to 45 ml with MQ water.

Analytical instruments

Arsenic content of soil and rice tissue digests was determined through a flow-injection hydride generation AAS using a GBC-Avanta interfaced with the GBC hydride generator 3000 (HG-3000). To cut down on cost and time allocated for traditional analysis, which accurately reflect the arsenic concentration determined using the aqua regia extraction procedure, compostive soil samples from each block were analyzed using FPXRF to eventually obtain a comparative dataset. The instrument was set for 300 s analyzing time for each of the 30 samples. The correlation between chemical digestion extractable and FPXRF arsenic concentration (Table 1) in this study case was generally consistent with previously reported values (Kilbride et al. 2006), and in accordance with criteria for characterizing data quality adopted from US EPA (1998).

Physico-chemical properties of soils

The physical properties of soil, such as distribution of particle size and textural classes in situ, were determined (Table 2). The soil is composed of clay loam (sand 23.9 %, silt 25.9 %, and clay 50.2 %) and is blackish in color. The site of the experiment represented Gangotic alluvial soil. The chemical properties of soil, such as pH, CEC, and total arsenic, were also observed (Table 2).

Statistical analysis

The experimental datum was statistically analyzed. Two-way ANOVA was used to test for significant differences between the arsenic concentrations in different plant parts according to Duncan multiple range test (DMRT) at 5 % level and correlation coefficient was computed by SPSS 13.0 for windows.

Results and discussion

Arsenic levels in soil

According to the published official report from the Department of Environmental Protection by the Taipei City Government in 2006, soil arsenic content exceeded 60 mg kg^{-1} about 128 ha of paddies in Betou. In this study, a total of 120 soil samples was collected and tested. The arsenic levels in paddy topsoil and subsoil ranged from 62 to 531 mg kg^{-1} ($n = 60$) and 52–530 mg kg^{-1} ($n = 60$) dry weight, respectively (Table 3), via using FPXRF. Their mean ± SD concentrations were 192 ± 99 and 212 ± 107 mg kg^{-1}, which were far higher than both of the reported average of 10 mg kg^{-1} of arsenic naturally present in soil worldwide (Das et al. 2002) and 5.65 mg kg^{-1} of arsenic was present in the farmland in Taiwan (Chang et al. 1999). Whatever the level, arsenic was found to be present in the topsoil and subsoil of the samples collected from the study area. Simply put, these results indicate the arsenic contamination of the soil. The similar situation of arsenic levels in topsoil and subsoil probably resulted from vertical soil homogenization with the usage of plowing processes over a long period of time.

Agricultural activities, such as the use of fertilizers, pesticides, and irrigating water, could increase the arsenic content in soil (Das et al. 2004), but datum was not available on the specific contribution of the above processes in this study case. For example, the unusual irrigated soil of Bangladesh had reached 83 mg of As kg^{-1} due to irrigation with the arsenic-contaminated water (Ullah 1998). Unfortunately, in relation to the recently monitored data on irrigation water from 2004 to 2006 and tube well water in 2006, there is apparently lack of evidence to infer the study areas extremely polluted by arsenic. Before 2006, there were no official government records concerning the existence of

Table 2 Physico-chemical properties of topsoil (0–15 cm) in situ ($n = 15$)

Properties	Field soil		
	Min.	Max.	Mean
% Sand (2–0.05 mm)	10.4	48.3	23.9
% Silt (0.05–0.002 mm)	5.0	35.6	25.9
% Clay (<0.02 mm)	42.8	58.2	50.2
Textural class	Clay-fine		
pH (soil:water = 1:10)	4.6	5.7	5.1
CEC (mequiv/100 g)	9.39	33.50	19.88
Total arsenic (mg kg^{-1})	67.2	438	184.6

Table 1 X-ray tube FPXRF data showing the r^2 for the entire arsenic concentration range of the sample set

Aqua regia extractable concentration range (mg kg^{-1})	FPXRF concentration range (mg kg^{-1})	n	r^2	RSD	Gradient of line	y-Intercept	Data quality level	source
2–5646	2–3920	80	0.93	11.2	0.87	0.13	Qualitative	Kilbride et al. (2006)[a]
67–496	61–435	30	0.88	3.4	0.94	0.16	Definitive	This study[a]

[a] Total number of paired samples in which both the aqua regia and X-ray tube FPXRF analyzer detected the specified analyte

Table 3 Arsenic levels of soil and tissues of ratoon rice plant (mg kg^{-1})

Rice strain[a]	Total arsenic in tissues of rice plants			Arsenic by FPXRF	
	Grain	Straw	Root	Topsoil (0–15 cm)	Subsoil (15–30 cm)
Tk8	0.23 ± 0.24 (40)	4.7 ± 1.4 (16)	266 ± 98 (16)	209 ± 92 (40)	237 ± 98 (40)
TN11	0.15 ± 0.05 (20)	3.2 ± 0.4 (4)	157 ± 27 (4)	159 ± 106 (20)	162 ± 111 (20)
Total	0.20 ± 0.20 (60)	4.4 ± 1.4 (20)	244 ± 98 (20)	192 ± 99 (60)	212 ± 107 (60)

The results are expressed as mean ± SD (*n*), (*n*) means numbers of sampling

[a] Tk8: Taikeng No. 8; TN11: Tai Nan No. 11

extensive industries emitting arsenic in Beitou. On the other hand, drawn water with mixed hot spring of arsenic from the Thermal Valley in Taipei could have probably resulted to the arsenic-contaminated soil in the short of water about two hundred years ago among the study areas according to a report of local irrigation association.

Arsenic levels in tissues of rice plant

In this case study, the samples covering two varieties of rice (type of Tk8 and TN11) were collected and tested for concentration of arsenic in different parts of rice plants such as rice grain, straw, and root (Table 3). The mean ± SD total arsenic concentrations in rice grain was 0.201 ± 0.198 mg kg^{-1} dry weight, with a range of 0.076–1.183 mg kg^{-1} ($n = 60$) in the extremely contaminated soil (62–531 mg of As kg^{-1} dry weight in topsoil). In each field, the mean total arsenic concentration from four rice grain samples did not exceed the food hygiene concentration limit of 1.0 mg kg^{-1} dry weight recommended by the UK and Australia (Warren et al. 2003), which was approximately consistent with a previous study in Taiwan (Lin et al. 2004). However, the first and second highest concentrations of arsenic in rice grains were found to have a content of 1.183 and 1.163 mg kg^{-1} dry weight, collected from the RS3 and RS7 fields, respectively. The remainders of arsenic content were all below 0.516 mg kg^{-1} dry weight. The comparison of arsenic content of Tk8 with TN11 in rice grains indicated that the difference of two rice strains could not be clearly recognized by the test result. This might be because growth of rice plants seems to depend on the amount of arsenite in soil, and arsines damage the roots of rice, resulting in the inhibition of nutrient uptake (Abedin et al. 2002). Rahman et al. (2007b) also reported that arsenic translocation from straw to rice grain did not differ significantly for the variations of rice strain.

From the test result, arsenic distribution in tissues of rice plant was found to be 98.2 % in root, 1.7 % in straw, and 0.1 % in grain (Table 3). It was also clear that the arsenic accumulation of rice plants varied from different parts, which had the same increasing tendency from grain to root, as manifested in many countries including Bangladesh, USA, and Taiwan, among others (Marin et al. 1993; Abedin et al. 2002; Rahman et al. 2007a, b). In the selection of RS1, RS2, RS3, RS12, and RS14 field, the all mean arsenic concentrations were higher in the root (244 mg kg^{-1}) and straw (4.36 mg kg^{-1}) compared with that in rice grain (0.195 mg kg^{-1}). From the test result presented in Table 3, it was clear that the mean ± SD total arsenic concentrations in straw and root, measured individually at 4.4 ± 1.4 and 244 ± 98 mg kg^{-1} dry weight, varied from about 2.3 to 7.5 mg kg^{-1} ($n = 20$) and 126 to 464 mg kg^{-1} ($n = 20$), respectively. In both TN11 and Tk8, results indicated that most of arsenic accumulated into rice tissues remained in root. Similar associations were observed in earlier studies, but the ratio of root/straw and root/grain As, which measured 1.17–32 and 36–400, respectively (Abedin et al. 2002; Alam and Rahman 2003; Das et al. 2004; Rahman et al. 2007b), in other contaminated areas, was far lower than the ratio of approximately 60 and 980 separately in this study case. Further studies are needed to find out the practical mechanism of translocation from rice root to grain on contaminated arsenic soil.

In this study, tissues of rice that had the highest amount of arsenic in root also showed a higher amount of arsenic in straw. It was easy to perceive the contrast relation of arsenic between straw versus grain and straw versus root. A positive correlation ($r^2 = 0.53$, $p = 0.16$) of arsenic in rice straw and in rice root was higher than that ($r^2 = 0.02$, $p = 0.80$) of arsenic in rice grain and in rice root on the contaminated arsenic topsoil (0–15 cm). This might be because rice plants accumulated a large number of arsenic in the roots and only minor amounts of arsenic were translocated to the straws. Though the nature of translocation involved in rice tissues is unclear right now, some previous studies demonstrated that the concentration and chemical form of arsenic applied had significant effects on the arsenic uptake and translocation by rice plants in the pot experiment (Marin et al. 1992; Shaibur et al. 2006) and the distribution of arsenic compounds into different rice tissues were also strongly dependent on rice strains (Rahman et al. 2007c). Regardless of soil arsenic concentrations in the study, the arsenic concentrations in rice tissues

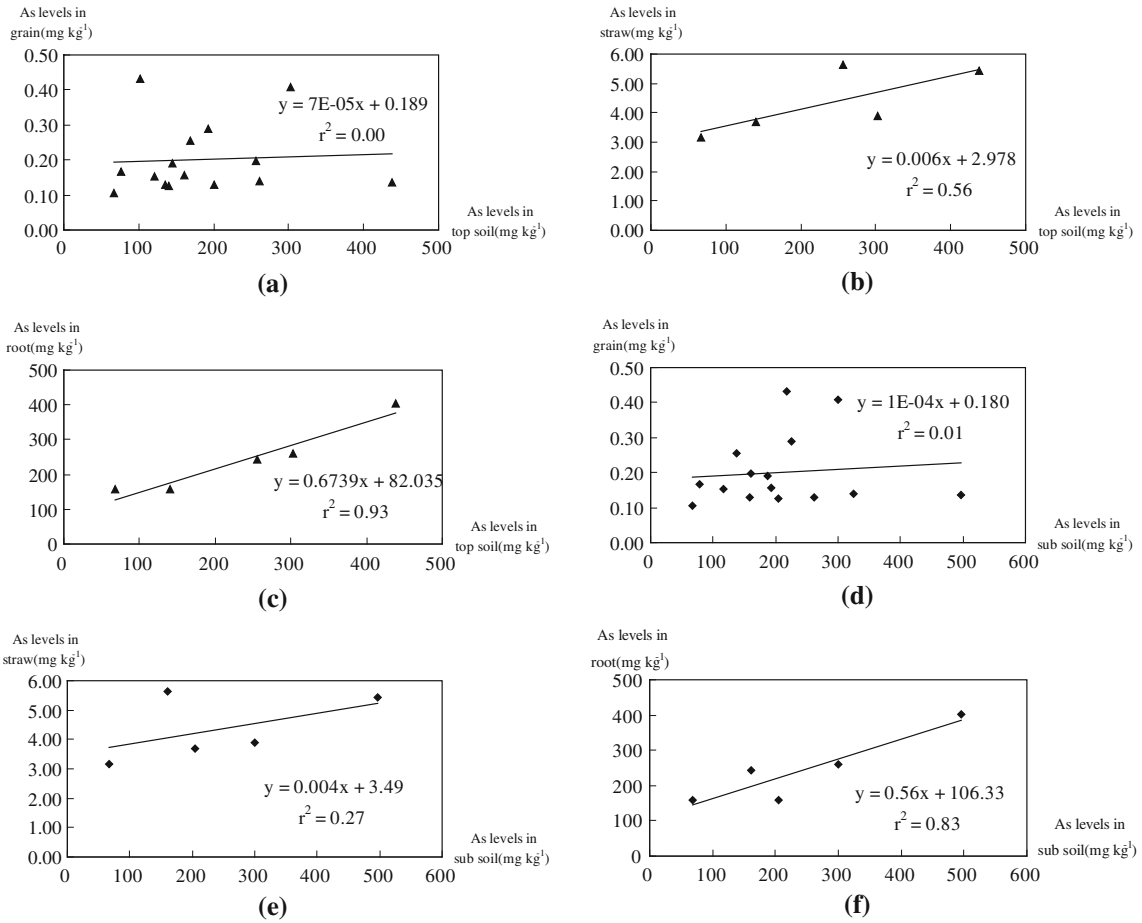

Fig. 2 Correlation between arsenic concentration in the topsoil and in rice grain (**a**), in rice straw (**b**), and in rice root (**c**); in the subsoil and in rice grain (**d**), in rice straw (**e**), and in rice root (**f**)

followed this trend: root > straw > grain. Some other previous studies (Marin et al. 1992; Abedin et al. 2002; Alam and Rahman 2003; Das et al. 2004; Rahman et al. 2004, 2007a, b, c) reported the same results.

The relationship of arsenic levels between in rice and soil

From the results, the values of arsenic concentration ratios between in tissues and in soils presented the abilities of plants to absorb arsenic soil at conditions. The highest arsenic concentration in straw was 5.6 ± 1.3 mg of As kg^{-1} dry weight ($n = 4$) at 256 mg kg^{-1} dry weight As-contaminated field. Rahman et al. (2007a) and Tsutsumi et al. (1980) reported 23.7 and 149 mg of As kg^{-1} dry weight, respectively, in rice straw when the soil arsenic concentrations were 60 and 313 mg kg^{-1} dry weight, separately. Abedin et al. (2002) also found 25 mg of As kg^{-1} dry weight in rice straw when the rice was irrigated by 2 mg of As l^{-1} water. The present study revealed that the highest level of arsenic in root at 403 ± 57 mg kg^{-1} dry weight As ($n = 4$) was located at the RS1 field with the arsenic content of 438 mg kg^{-1} dry weight in topsoil. Das et al. (2004) also stated that the highest concentrations of arsenic in rice grain (0.27 mg kg^{-1}), shoot (1.58 mg kg^{-1}), root (9.71 mg kg^{-1}), and soil (27.28 mg kg^{-1}) were found in samples collected from the irrigated fields of Kachua Upazila in Bangladesh. From the plot of arsenic content in tissue of rice versus its soil, it was clear that regardless of rice strain, the correlation ($r^2 = 0.93$, $p < 0.01$) of arsenic in rice root and arsenic in its topsoil was higher than in rice straw ($r^2 = 0.56$, $p = 0.14$), as presented in Fig. 2b, c, respectively. Results also reflected similar correlation trend in subsoil instead of the topsoil, which are presented in Fig. 2f ($r^2 = 0.83$, $p < 0.05$) and e ($r^2 = 0.27$, $p = 0.37$). Moreover, there was no evidence to demonstrate that regardless of the rice strain, the linear relation of arsenic in rice grain and arsenic in its topsoil ($r^2 = 0$, $p = 0.82$) or subsoil ($r^2 = 0.01$, $p = 0.71$) existed in this case (Fig. 2a, d). The present study also supported previous reports.

The results showed significantly higher correlation of arsenic in topsoil ($r^2 = 0.93$, $p < 0.01$) and arsenic in rice

Table 4 The ratio of arsenic concentration in rice grain to arsenic concentration in soils

Region	Grain/soil	Arsenic content in soil (mg kg^{-1})	Source
China	0.010	68	Xie and Huang (1998)
Bangladesh	0.003–0.006	30.2–102	Abedin et al. (2002)[a]
	0.040	6.5–26.7	Meharg and Rahman (2003)
	0.03–0.05	14.5	Rahman et al. (2007a, b)
Taiwan	0.020	4.5–5.7	Li et al. (1994)[b]
	0.001	67–438	This results

[a] Data from greenhouse study

[b] 341 Samples collected and tested in Taiwan (soil arsenic content below 30 mg kg^{-1})

root compared to that in subsoil ($r^2 = 0.83$, $p < 0.01$), which were presented in Fig. 2c, f. Similarly, same correlation manifests in rice straw (Fig. 2b, e) compared to the rice root. The reason for this may be the sphere of activities in rice root, which was normally within the vertical soil depth of 20 cm (Kumaraswamy et al. 1997); Whereas Dittmar et al. (2007) revealed that arsenic inputted via irrigation was mostly restricted to the soil layers above the plow pan (20–25 cm). In this study, arsenic level in rice root strongly depended on arsenic content of topsoil compared to subsoil, regardless of arsenic chemical form present in soil solution.

The survey of the soil–plant (rice grain) transfer coefficients for As was evaluated from 0.01 to 0.05 in China, Bangladesh, and Taiwan (Table 4) in common with the earlier literatures summarized by Kloke et al. (1984). Regardless of rice strain in this case, the ratio of arsenic concentration in rice grain and in its topsoil was 0.001, it was far lower than the result that previous studies reported in addition to greenhouse experiment. Maybe two explanations described this phenomenon. The first one is probably that because earlier literatures usually dealt with soils having high arsenic concentrations caused by using irrigated water with arsenic in the shallow well in Bangladesh, approximately 30 years old or residues of As-based pesticides and herbicides; the other is apparently iron oxides (iron plaques), formed around the rice root, bound the arsenic and reduced its translocation to the above-ground tissues of the plant (Marin et al. 1993; Liu et al. 2004). Though Warren et al. (2003) reported that the soil–plant transfer coefficients for As were from 0.0007 to 0.032, its result excluded rice from the investigated crops, such as Calabrese leaf, Lettuce, and spinach. Regression of topsoil arsenic levels with rice grain and straw were less significant compared with that of rice root, and arsenic levels in ratoon rice from root to grain also reflected the same trending down evidence.

Conclusion

Though concentrations of arsenic in compositive rice grain each field did not exceed food hygiene concentration limit (1.0 mg of As kg^{-1} dry weight), arsenic level in root strongly depended on arsenic concentrations of soil suggesting that the high arsenic concentration may have the potential for translocation from root to grain which ultimately effects on the human health at heavily polluted arsenic area. Regardless of rice strain, the ratio of arsenic concentration in rice grain and in its topsoil, as in this special case, was far lower than the result reported regarding the survey of ratio of arsenic concentration in the grain and soil in Taiwan and other countries. Regression of topsoil arsenic levels with rice grains and straw was less significant than that with rice root. Regardless of soil arsenic concentrations in this study, the arsenic concentration in rice tissues followed the trend: root > straw > grain. To figure out the fact regarding arsenic poisoning in rice tissues through these soil–plant pathways in the soil extremely polluted by arsenic, intensive investigation on a complete transformation mechanism is needed, which is our future interest.

Acknowledgments This research was funded by the Department of Environmental Protection, Taipei City Government, and the College of Bioresources and Agriculture, NTU. The authors are thankful to Professor Chang W.L. of Ecological Engineering Research Center, NTU; Yu D.F. of Societe Generale de Surveillance Taiwan Ltd.; and TechMax Technical Co., Ltd. for providing laboratory support.

References

Abedin MJ, Cresser MS, Meharg AA, Feldmann J, Howells JC (2002) Arsenic accumulation and metabolism in rice (*Oryza sativa* L.). Environ Sci Technol 36:962–968

Alam MZ, Rahman MM (2003) Accumulation of arsenic in rice plant from arsenic contaminated irrigation water and effect on nutrition content. In: Ahmed F, Ashraf AM, Adeel Z (eds) Fate of arsenic in the environment. Bangladesh University of Engineering and Technology, Dhaka and United Nations University: Tokyo, p 131–135

Anawar HM, Akai J, Mostofa KM, Safiullah S, Tareq SM (2002) Arsenic poisoning in groundwater: health risk and geochemical sources in Bangladesh. Environ Int 27:597–604

Chang TK, Shyu GS, Lin YP (1999) Geostatistical analysis of soil arsenic content in Taiwan. Environmental Science Health A: Toxic. Hazard Subst Environ Eng 34:1485–1501

Chang TK, Shyu GS, Chang WL, Huang WD, Huang JH, Lin JS, Lin SC (2007) Monitoring and investigation of heavy metal in soil of Taipei City. DEP-95-056. (In Chinese, with an english summary)

Chen ZS, Lee DY (1995) Heavy metals contents of representative agricultural soils in Taiwan. J Chin Inst Environ Eng 5:205–211

Chowdhury UK, Biswas BK, Chowdhury TR, Samanta G, Mandal BK, Basu GC (2000) Groundwater arsenic contamination in Bangladesh and West Bengal. India Environ Health Persp 108:393–397

CLEA (2002) The contaminated land exposure assessment model: technical basis and algorithms. Department for Environment, Food and Rural Affairs, Environment Agency, Bristol

Das HK, Sengupta PK, Hossain A, Islam M, Islam F (2002) Diversity of environmental arsenic pollution in Bangladesh. In: Ahmed MF, Tanveer SA, Badruzzaman ABM (eds) Bangladesh environment, vol 1. Bangladesh Paribeh Andolon, Dhaka, pp 234–244

Das HK, Mitra AK, Sengupta PK, Hossain A, Islam F, Rabbani GH (2004) Arsenic concentrations in rive, vegetables, and fish in Bangladesh: a preliminary study. Environ Int 30:383–387

Dittmar J, Voegelin A, Roberts LC, Hug SJ, Saha GC, Ali MA, Badruzzaman ABM, Kretzschmar R (2007) Spatial distribution and temporal variability of arsenic in irrigated rice fields in Bangladesh. 2. Paddy soil. Environ Sci Technol 41:5967–5972

Hsu KH, Hsieh LL, Chiou HY, Lee CJ, Wang CY, Lee TH, Chen CJ (1999) Comparison of characteristics and arsenic toxicity between residents of southwestern region and northeastern basin in Taiwan: a study on prevalence of hypertension. Chin J Public Health 18(suppl. 1):124–133

Kilbride C, Poole J, Hutchings TR (2006) A comparison of Cu, Pb, As, Cd, Zn, Fe, Ni and Mn determined by acid extraction/ICP-OES and ex situ field portable. Environ Pollut 143:16–23

Kloke A, Sauerbeck DR, Vetter H (1984) The contamination of plants and soils with heavy metals and the transport of metals in terrestrial food chains. In: Nriagu J (ed) Changing metal cycles and human health. Springer, Berlin, pp 113–141

Kumaraswamy S, Ramakrishnan B, Satpathy SN, Rath AK, Misra S, Rao VR, Sethunathan N (1997) Spatial distribution of methane-oxidizing activity in a flooded rice soil. Plant Soil 191:241–248

Larsen EH, Moseholm L, Nielsen MM (1992) Atmospheric deposition deposition of trace elements around point sources and human health risk assessment: II. Uptake of arsenic and chromium by vegetables grown near a wood preservation factory. Sci Total Environ 126:263–275

Li GC, Lin HT, Lai CS (1994) Uptake of heavy metals by plants in Taiwan. Biogeochem Trace Elem 16:153–160

Lin HT, Wong SS, Li GC (2004) Heavy metal content of rice and shellfish in Taiwan. J Food Drug Anal 12:176

Liu W-J, Zhu Y-G, Smith SE (2004) Do iron plaque and genotypes affect arsenate uptake and translocation by rice seedlings (*Oryza sativa* L.) grown in solution culture. J Exp Bot 55(403):1707–1713

Marin AR, Masscheleyn PH, Patrick WH (1992) The influence of chemical form and concentration of arsenic on rice growth and tissue arsenic concentration. Plant Soil 139:175–183

Marin AR, Masscheleyn PH, Patrick WH (1993) Soil redox-pH stability of arsenic species and its influence on arsenic uptake by rice. Plant Soil 152:245–253

Meharg AA, Hartlet-Whitaker J (2002) Arsenic uptake and metabolism in arsenic resistant and nonresistant plant species. New Phytol 154:29–43

Meharg AA, Rahman MDM (2003) Arsenic contamination of Bangladesh paddy field soils: implications for rice contribution to arsenic consumption. Environ Sci Technol 37:229–234

Mitra AK, Bose BK, Kabir H, Das BK, Hussain M (2002) Arsenic-related health problems among hospital patients in southern Bangladesh. J Health Popul Nutr 20:198–204

Pandey PK, Yadav S, Nair S, Bhui A (2002) Arsenic contamination of the environment: a new perspective from central-east India. Environ Int 28:235–245

Piorek S (1997) Field-protable X-ray fluorescence spectrometry: past, present and future. Field Anal Chem Tech 1(6):317–329

Rahman MA, Rahman MM, Majid MA, Khaled HM (2004) Influence of soil arsenic concentrations on rice (*Oryza sativa* L.). Subtrop Agric Res Dev 2(3):24–31

Rahman MA, Hasegawa H, Rahman MM, Miah MAM, Tasmin A (2007a) Arsenic accumulation in rice (*Oryza sativa* L.): human exposure through food chain. Ecotoxicol Environ Saf. doi:10.1016/j.ecoenv.2007.01.005

Rahman MA, Hasegawa H, Rahman MM, Rahman MA, Miah MAM (2007b) Accumulation of arsenic in tissues of rice plant (*Oryza sativa* L.) and its distribution in fractions of rice grain. Chemosphere 69:942–948

Rahman MA, Hasegawa H, Rahman MM, Islam MN, Miah MAM, Tasmin A (2007c) Arsenic accumulation in rice (*Oryza sativa* L.) varieties of Bangladesh: a glass house study. Water Air Soil Poll 185:53–61

Schoof RA, Yost LJ, Crecelius E, Irgolic K, Goessler W, Guo HR, Greene HL (1998) Dietary arsenic intake in Taiwanese districts with elevated arsenic in drinking water. Hum Ecol Risk Assess 4:117–135

Shaibur MR, Kitajima N, Sugawara R, Kondo T, HUQ SMI, Kawai S (2006) Physiological and mineralogical properties of arsenic-induced chlorosis in rice seedlings grown hydroponically. Soil Sci Plant Nutr 52:691–700

Smith AH, Lingas EO, Rahman M (2001) Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. Bull World Health Organ 78:1093–1103

Tseng CH, Tai TY, Chong CK, Tseng CP, Lai MS, Lin BJ, Chiou HY, Hsueh YM, Hsu KH, Chen CJ (2000) Long-term arsenic exposure and incidence of non-dependent diabetes mellitus: a cohort study in arseniasis-hyperendemic villages in Taiwan. Environ Health Persp 108:847–851

Tsutsumi S, Amagai T, Kawaguchi M, Ishizuka S, Matsumoto Y (1980) Effect of arsenic trioxide (As_2O_3) on the uptake of 3H-thymidine in lymphocytes of mice. Bull Tokyo Dent Coll 21(2):63–70

Ullah SM (1998) Arsenic contamination of groundwater and irrigated soils of Bangladesh. In: International conference on arsenic pollution of groundwater in Bangladesh: causes, effects and remedies. Dhaka Community Hospital, Dhaka, p 133

US EPA (1998) Environmental technology verification report. Field Protable X-ray Fluorescence Analyzer. Metorex X-MET 920-P and 940, EPA/600/R-97/146

Warren GP, Alloway BJ, Lepp NW, Singh B, Bochereau FJM, Penny C (2003) Field trials to assess the uptake of arsenic by vegetables from contaminated soils and soil remediation with iron oxides. Sci Total Environ 311:19–33

Xie ZM, Huang CY (1998) Control of arsenic toxicity in rice plants grown on an arsenic-polluted paddy soil. Commun Soil Sci Plan 29:2471–2477