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Remediation of soil arsenic toxicity in *Ipomoea aquatica*, using various sources of organic matter

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Abstract

Various sources of organic matter (namely poultry litter, cow dung and sewage sludge) were used to remediate arsenic accumulation in plants (*Ipomoea aquatica*) in a pot-culture experiment. Organic matter was applied at the rates of 5 t/ha and 10 t/ha to soils spiked with arsenite at 20, 50 and 100 mg As/kg soil. Plants were grown for 30 days after germination. The presence of arsenic in the growth medium had a negative impact on the vegetative growth of the plants, for both organic matter treatments and control. However, organic-matter application had a more positive effect than no application, at all levels of arsenic spiking. Poultry litter performed the best, and at the application rate of 5 t/ha, the vegetative growth was more than 81.55% over the control; whereas the increases were 17.74% and 10.98%, respectively, for cow dung and sewage sludge at the same rate of application. Organic-matter application was able to reduce arsenic accumulation by as much as 75% in the vegetative part of the plant. For the various sources of organic matter, the performance in reducing the accumulation of As in *Ipomoea aquatica* followed the order: poultry litter > cow dung > sewage sludge.

Key words: arsenic, *Ipomoea aquatica*, organic matter, remediation

INTRODUCTION

Arsenic (As) contamination in the groundwater was reported in Bangladesh during the early 1990s. Extensive contamination in Bangladesh was confirmed in 1995, when a further survey showed contamination of mostly shallow tube-wells (STW) across much of southern and central Bangladesh (Imamul Huq *et al.* 2006*a*). More than 35 million people in Bangladesh are exposed to As contamination in drinking water exceeding the national standard of 50 g/L, while an estimated 57 million people are at risk of exposure to As contamination exceeding the WHO guideline level of 10 g/L (BGS/DPHE 2001). Bangladesh is currently facing the challenge of mitigating soil contamination related to arsenic-laden groundwater irrigation. About 40% of the total arable land of Bangladesh is now under irrigation, and more than 60% of irrigation needs are met from groundwater extracted by deep tube-wells, shallow tube-wells or hand tube-wells (Imamul Huq and Naidu 2005). Approximately 27% of STWs and 1% of DTWs in 270 *upazilas* (sub-districts) of the country are classified as contaminated with As according to the Bangladeshi standards, whereas about 46% of STWs are classified as contaminated according to the WHO standard. So far 38 000 people have been diagnosed, with an additional of 30 million people at risk of As exposure (APSU 2005). The widespread use of As-contaminated groundwater for irrigation has been reported to pose the risk of As build-up in soil, and its subsequent transfer to plants and vegetables (Imamul Huq *et al.* 2001; Ali *et al.* 2003; Imamul Huq and Naidu 2003; Imamul Huq and Naidu 2005; Imamul Huq *et al.* 2006*b*). The average soil As level is below 10 mg/kg, with values exceeding levels as high as 80 mg/kg in

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areas where irrigation using As-contaminated water is practised continuously, and the annual build-up from irrigation in soil has been calculated to be 5.5 kg/ha (Imamul Huq and Naidu 2005). The form of arsenic found in the groundwater is mostly As(III). In more than 90% of cases, As in groundwater occurs in this form (Imamul Huq and Naidu 2003). It has been observed that the arsenic in irrigation water and the water-soluble fraction of soil arsenic is more bioavailable than the total fraction (Imamul Huq *et al.* 2003). The release and retention of As in the soils of Bangladesh have been found to be governed by, among other factors, the clay fraction and the clay mineralogy of the soils (Joardar *et al.* 2005; Imamul Huq *et al.* 2006*a*; Imamul Huq *et al.* 2006*c*). Numerous greenhouse/field studies have found that an increase in As in cultivated soils leads to an increase in the levels of As in edible vegetables (Helgensen and Larsen 1998; Burló *et al.* 1999; Carbonell-Barrachina *et al.* 1999; Chakravarty *et al.* 2003; Farid *et al.* 2003), with many factors affecting bioavailability, uptake and phytotoxicity of As (Carbonell-Barrachina *et al.* 1999). Furthermore, phytotoxicity due to increased arsenic in soil/water, and its long-term impact on agricultural yield, are also major concerns (Ali *et al.* 2003). Combating the adverse effects of arsenic will be of prime importance in the years to come. Novel strategies have to be developed in this area. One strategy could be to amend the soil in such a way that the materials used for amendment would not degrade the soil properties, but rather improve them. Such a strategy could involve the use of organic matter that might be able to reduce the phytoavailability of arsenic.

In Bangladesh, there are many dairy farms that have been producing large volumes of cow dung. About eight million metric tonnes of cow dung were used as fuel in 1997, and a large amount of cow dung was used annually as domestic fuel in rural areas (BBS 2004). Poultry litter is another important source of organic matter that can be used on agricultural land. Today, poultry manures are becoming popular in some areas of Bangladesh. Sewage sludge has been found to be effective when used in combination with fertilizer as an additional source of nutrients in agriculture, in order to economize on fertilizer costs (Sikder *et al.* 2007).

Composts and cow dung have been found to reduce the phytoavailability of As, Cd, Pb and Zn (Erickson 1988; Shiralipour *et al.* 2002; Molla and Imamul Huq 2004; Kwiatkowska and Maciejewska 2006; Martins *et al.* 2006). Inorganic arsenic is methylated to less-toxic, and perhaps less-labile, organic arsenic, which could be a strategy to remediate As-contaminated soils for crop production, thus minimizing As transfer to plants. We have tried other remedial possibilities, such as water-regime manipulation (Imamul Huq *et al.* 2006*d*), and using green and blue-green algae (Imamul Huq *et al.* 2007). These tests were performed on rice. However, production of vegetables in As-contaminated areas also carries the risk of As accumulation in the produce (Farid *et al.* 2003; Imamul Huq *et al.* 2006*b*; Sanyal *et al.* 2007). The present work is a further extension of our attempts to remediate As-contaminated soil using cheap and easily available organic sources. The present work aims to study the impact of cow dung, poultry litter and sewage sludge on controlling the transfer of As from soil to plants, and to compare the effectiveness of the different sources of organic matter in this regard.

MATERIALS AND METHODS

The experiment was conducted in the net house of the Department of Soil, Water and Environment, University of Dhaka, Bangladesh, during April to September 2006.

Sampling site

Soil from a farmer's field in Dhamrai, Savar, near Dhaka, was selected for sampling. The soil belonged to the Dhamrai soil series (UN Development Programme and Food and Agriculture Organization of the UN 1998; Imamul Huq *et al.* 2006*d*, 2007). The location of the sampling area is 23° 54.776' N and 90°10.938' E (Figure 1). According to the USDA Soil Taxonomy the soil is a Typic Endoaquept and is mixed and non-acid; according to the General Soil Type it is a Non-Calcareous Grey Floodplain Soil (GST No. 6), and according to the FAO-UNESCO Legend it is a Chromi-Eutric Gley Sol.

Soil sample collection and sample preparation

The bulk soil samples representing depths of 0–150 mm depth below the surface were collected using the composite soil sampling method, as suggested by the soil survey staff of the United States Department of

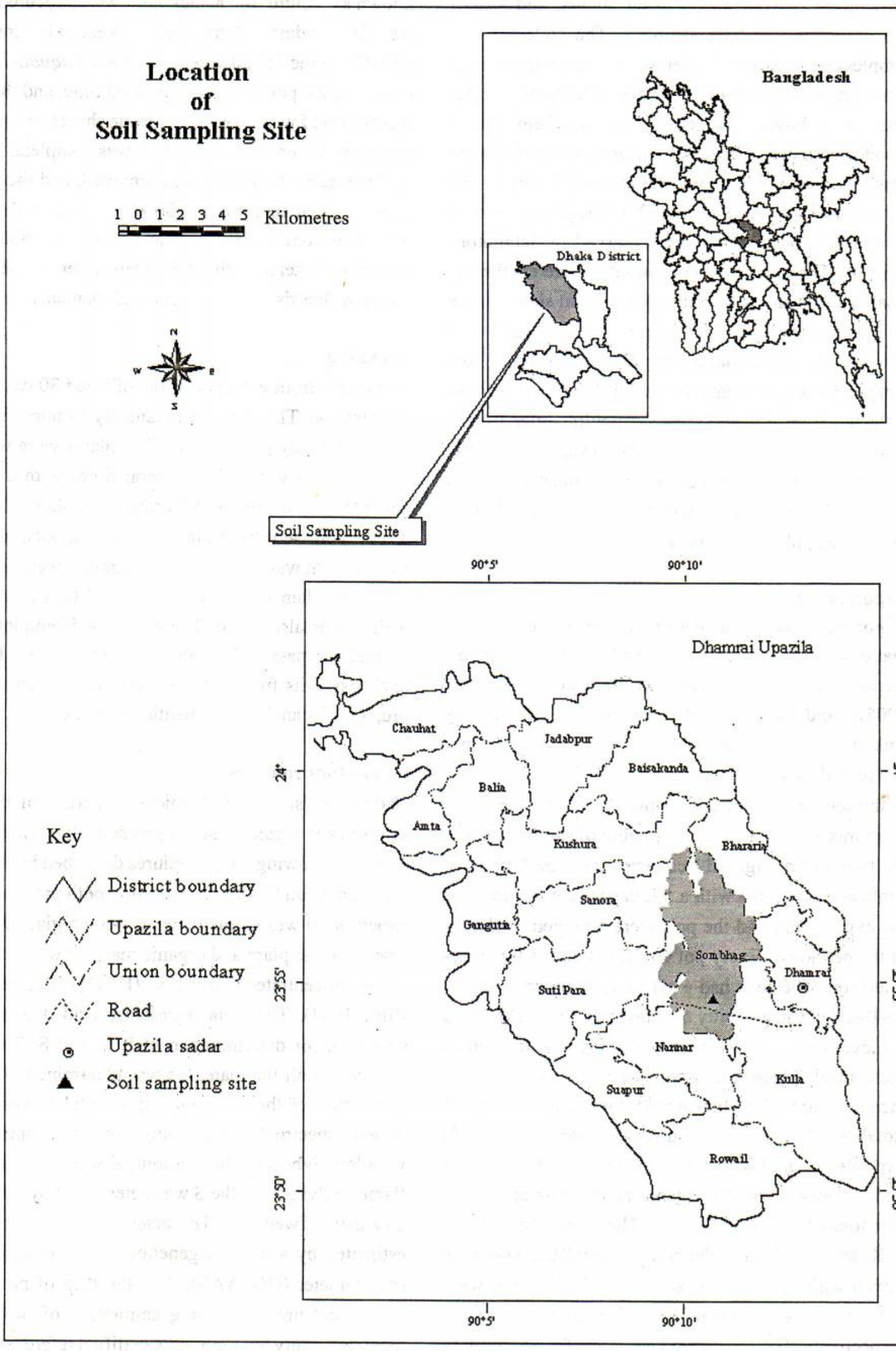


Figure 1. The location of the sampling site

Agriculture (USDA 1951) using augers, and spades and crowbars (for bulk samples). The collected soil samples were air-dried after visible roots and debris were removed. Some of the larger and massive aggregates were broken by gently crushing them with a wooden hammer, after which the ground samples were passed through a 0.5 mm stainless-steel sieve. The sieved samples were then mixed thoroughly to create a composite sample, and were preserved for laboratory analysis. The rest of the soil samples were crushed to smaller clods and passed through a 5 mm sieve. These soils were used for the pot experiment. Three different sources of organic matter, namely poultry litter, cow dung and sewage sludge, were used. The cow dung was collected from a dairy farm; the poultry litter from a chicken farm near Dhaka; and the sewage sludge was collected from the sewage treatment plant of Dhaka WASA. The organic materials were air-dried before they were applied to the pots.

Experimental set-up

A pot experiment was set in the net house. Organic matter was applied at rates of 5 and 10 t/ha (the recommended application rates in Bangladesh (BARC 2005)), and there was also a control. The soil was spiked with arsenic at rates of 0, 20, 50 and 100 mg As/kg soil. Sodium meta arsenite ($NaAsO_2$) was used as the source of arsenic. The spiking was done by thorough mixing of the required amount of salt with soil at the time of potting. All treatments were performed in triplicate. Clay pots with a 5 L capacity were used for the experiment, and the pots were arranged randomly in the net house. Every pot was filled with 5 kg of air-dried soil. The soils had a pH of 7.08, organic carbon 0.91%, and had a of silty clay texture. The background As level in the soil was 1.6 mg/kg. This was taken as the control. There were a total of 84 pots (three treatments along with a control = 4); three replications = 3 (total, $4 \times 3 = 12$); three sources of organic matter = 3; two rates of application = 2 (total = $12 \times 3 \times 2 = 72$); and 12 pots where no organic matter was applied; a sum total of $72 + 12 = 84$ pots). The required amount of P, K, and one-third of the N doses (BARC 2005) were mixed with the soil. The sources of N, P and K were urea, triple superphosphate and muriate of potash respectively. The soils were kept moist for one week to allow the organic matter to mineralize and react with the spiked arsenic. Seeds of *Ipomoea aquatica*, locally known as 'Kalmi' or 'Kangkong', were procured from the Bangladesh Agricultural Research Institute (BARI). Some 15–20 seeds of *Ipomoea aquatica* were sown in each pot after the stipulated time, and the pots were covered with an opaque plastic sheet to allow germination. When the germination was complete, in two to three days, the plastic was removed, and the plants were allowed to grow for 30 days. This is the time when it becomes comestible as a leafy vegetable. The pots were watered with As-free tap-water as and when required. Weeds were also removed manually.

Sampling

The plants from each pot were collected 30 days after germination. This was done manually by uprooting the plants carefully from the pot. The plants were washed first with tap water, then several times with distilled water to remove any soil adhering to the plant. Then the plants were separated into roots and shoots, and the fresh weight was measured. The samples were first air-dried and then oven-dried at 70 ± 5°C, and the dry weight was also taken. The oven-dried samples were ground and passed through a 0.2 mm sieve for further analysis. Soils from each pot were also collected and prepared for analysis, as mentioned earlier.

Laboratory analysis

Various physical and chemical properties of the soil samples and organic materials were analysed in the laboratory, following the procedures described by Imamul Huq and Alam (2005). Soil arsenic (both pre- and post-experiment) was extracted using aqua regia, while the arsenic in the plant and organic material was extracted using concentrated nitric acid (HNO_3) (Portman and Riley 1964). The aqua regia/nitric acid digests were also used for determination of P, K and S. The total nitrogen of all the materials was determined by alkali distillation of the Kjeldahl digest; total P was determined spectrophotometrically by developing the vanadomolybdate yellow colour; K was determined by flame analyser; and the S was determined by turbidimetry using Tween-80. The arsenic in the extract was estimated by a hydride generation–atomic absorption spectrometer (HG–AAS), with the help of potassium iodide and urea, following calibration of the equipment. For every ten samples, a certified reference material (CRM) was included to ensure the QC/QA. Lead, cadmium and zinc content were determined by an

Table 1. Some properties of the organic matter (cow dung, poultry litter and sewage sludge) and the soil used in the experiment

Properties	Cow dung	Poultry litter	Sewage sludge	Soil
Organic carbon (%)	15.40	17.60	4.95	0.91
Nitrogen (%)	1.86	2.23	0.38	0.13
Phosphorus (%)	6.97	6.82	2.77	0.03
Potassium (%)	0.38	0.58	0.68	0.41
Sulphur (%)	2.15	3.25	2.55	0.22
Arsenic (mg/kg)	1.85	1.55	1.66	3.29
Cadmium (mg/kg)	1.25	1.09	1.94	4.37
Lead (mg/kg)	1.10	1.45	1.15	69.08
Zinc (mg/kg)	1.13	1.23	2.36	7.46

Table 2. Fresh weight (g/pot) of total plants (values without parentheses are for the 5 t/ha applications, and those within parentheses are for the 10 t/ha organic-matter applications)

Treatment (mg As/kg soil)	NM	SS	CD	PL
0	75.4 ± 2.7	83.6 ± 2.2 (99.0 ± 2.6)	88.7 ± 2.9 (114.9 ± 4.1)	136.8 ± 3.3 (146.0 ± 3.3)
20	73.4 ± 2.4	82.9 ± 1.8 (96.0 ± 2.6)	85.7 ± 2.9 (112.0 ± 3.1)	135.2 ± 3.0 (144.6 ± 4.1)
50	68.0 ± 1.7	78.6 ± 3.0 (84.4 ± 2.1)	83.0 ± 2.2 (107.3 ± 2.5)	129.7 ± 4.1 (139.3 ± 2.9)
100	61.0 ± 1.7	75.8 ± 2.2 (76.8 ± 2.1)	77.3 ± 2.5 (104.7 ± 3.3)	124.4 ± 4.2 (135.3 ± 4.2)

NM = no organic matter; CD = cow dung; PL = poultry litter; SS = sewage sludge

atomic absorption spectrometer (AAS) on the same digest as for As determination. Statistical analyses (ANOVA, regression and correlation) were carried out, using the MINITAB 13.0 package.

RESULTS AND DISCUSSION

The collected organic-matter and soil samples used in the experiment were analysed in the laboratory before set-up of the experiment, in order to establish the nutrient content and some elemental properties, and the analytical values are shown in Table 1.

Visual symptoms

Seed germination and plant growth were normal in all the pots, even at high doses (100 mg As/kg soil) of arsenic. Plant growth was better in organic-matter-treated pots than in the control pots. For the various sources of organic matter, the growth performance followed the order: poultry litter > cow dung > sewage sludge. Moreover, with regard to the two rates of organic-matter addition, plants performed better in the 10 t/ha treated pots than in 5 t/ha treated pots.

Vegetative growth

The fresh weight of the plants per pot grown with different rates of As application, and with various sources and rates of organic-matter treatment, are shown in Table 2. The values presented in the table are the averages of three individual replications. The values in the table without parentheses, and within parentheses, are for 5 t/ha and 10 t/ha organic-matter applications, respectively.

From Table 2 it is observed that the vegetative growth of the plants was suppressed due to the As spiking, irrespective of the rates and types of organic amendments. However, growth suppression was not significantly different to that seen for the control treatments. On the other hand, it is clear from Table 2 that the application of organic matter played a role in increasing the vegetative growth of *Ipomoea aquatica*. Out of the three different sources of organic matter, poultry litter made the best contribution, and the application rate of 5 t/ha of poultry litter produced a biomass more than 81% higher than the control treatments (no arsenic). Cow dung and sewage sludge increased the vegetative growth by about 18% and 11% respectively, for the same application rate. Not only that, but, at 20, 50 and 100 mg As/kg soil, the increases were 84%, 89% and 104%, respectively for poultry litter. The growth increase was even better at the 10 t/ha application rate. This could be due to the fact that the poultry litter contained more of the nutrients, particularly N and P, as compared to the other two sources. The growth increases seen for the 5 and 10 t/ha application rates were significantly different for cow dung and sewage sludge ($p < 0.001$), but not for poultry litter.

Arsenic accumulation in plants

Arsenic accumulation in the roots and shoots of *Ipomoea aquatica* grown in arsenic-spiked soil and amended with different sources of organic matter at two different rates is shown in Table 3. The values presented in the table are averages of the three individual replicates. Values in the table without parentheses and within the parentheses are for 5 t/ha and 10 t/ha organic-matter applications, respectively.

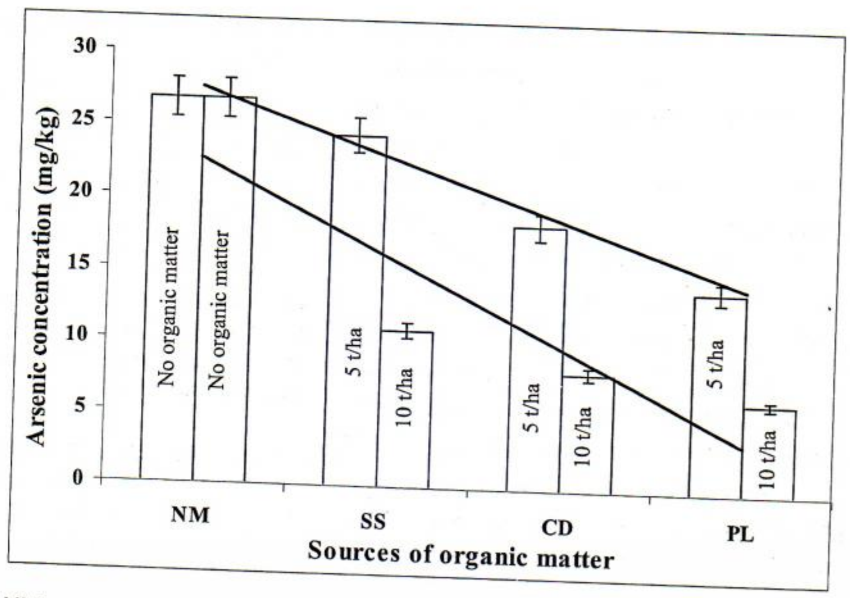
From Table 3 it is clear that the accumulation of arsenic in the roots and shoots of *Ipomoea aquatica* increased with increased As in the growth media, irrespective of organic-matter treatment. In most cases, the roots accumulated more As than the shoots. This is a common phenomenon of As accumulation in non-phytoremediators (Ma *et al.* 2001; Imamul Huq *et al.* 2005; Hossain *et al.* 2006). It was observed that the 10 t/ha application rate performed better than the 5 t/ha rate in reducing As accumulation in the plant ($p < 0.01$). In this context, it could be ascertained that organic-matter addition is capable of reducing As accumulation in plants, more particularly the vegetable crop *Ipomoea aquatica* used in the present study.

In Bangladesh, average soil As is close to 10 mg/kg, and, in soils irrigated with As-contaminated groundwater, this value stands at around 20 mg As/kg, with a few, much higher outliers (Imamul Huq *et al.* 2003). As such, the 20 mg As/kg soil treatment is considered here for further discussion. Arsenic accumulation in the whole *Ipomoea aquatica* plants grown in pots with arsenic-spiked soil and treated with different sources of organic matter at 5 t/ha and 10 t/ha, is shown in Figure 2. The application of organic matter at the rate of 5 t/ha reduced As accumulation in plants as follows: poultry manure – *c.* 48.0%; cow dung – *c.* 32.0%; and sewage sludge – *c.* 9.0%, compared to the control. By contrast, the application rate of 10 t/ha reduced the As accumulation in plants in the order: poultry manure – *c.* 77.0%; cow dung – *c.* 70.0%; and sewage sludge – more than 59.0%. The figures clearly show that when the application rate of organic matter was doubled, the reduction of As accumulation in plants for all types of organic sources was more than 55% (sewage sludge – 55.5%, cow dung – 55.8%, poultry litter – 55.2%). It is

Table 3. Arsenic accumulation (mg/kg dm) in the roots and shoots of *Ipomoea aquatica* (the values without parentheses are for the 5 t/ha organic-matter application, and within parentheses are for the 10 t/ha application)

Treatment (mg As/kg soil)	NM		SS		CD		PL	
	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot
0	4.6 ± 0.34	3.3 ± 0.46	3.5 ± 0.42 (4.3 ± 0.39)	3.3 ± 0.38 (4.0 ± 0.46)	4.3 ± 0.47 (3.0 ± 0.39)	4.6 ± 0.51 (2.5 ± 0.38)	2.8 ± 0.32 (2.2 ± 0.28)	2.1 ± 0.27 (0.5 ± 0.11)
20	28.7 ± 1.25	25.5 ± 1.15	25.5 ± 1.16 (13.0 ± 0.74)	23.7 ± 1.08 (9.5 ± 0.96)	21.0 ± 1.08 (9.6 ± 0.87)	16.7 ± 0.87 (7.5 ± 0.61)	15.5 ± 0.98 (5.6 ± 0.56)	13.3 ± 0.31 (6.5 ± 0.26)
50	76.6 ± 1.96	59.0 ± 1.79	51.0 ± 2.01 (41.0 ± 1.13)	46.5 ± 1.87 (36.3 ± 1.39)	40.9 ± 2.07 (30.3 ± 1.95)	32.9 ± 1.71 (27.2 ± 1.27)	25.4 ± 1.27 (15.4 ± 1.03)	21.7 ± 1.05 (10.1 ± 0.86)
100	101.1 ± 2.39	114.7 ± 2.44	59.3 ± 2.34 (41.2 ± 1.42)	52.4 ± 2.47 (51.0 ± 2.72)	45.3 ± 2.74 (43.3 ± 2.54)	35.8 ± 1.47 (30.0 ± 1.54)	28.2 ± 1.97 (25.3 ± 1.78)	24.4 ± 1.27 (16.2 ± 0.97)

NM = no organic matter, CD = cow dung, PL = poultry litter, SS = sewage sludge



NM = no organic matter; CD = cow dung; PL = poultry litter; SS = sewage sludge

Figure 2. Arsenic accumulations in whole plants of *Ipomoea aquatica* at 20 mg As/kg treated soil and at two different rates of organic-matter application

interesting to note here that the addition of organic matter, while reducing the As accumulation in the plant, also caused a reduction in the accumulation of the heavy metals Cd, Pb and Zn. There was significant correlations between As and these elements in plants (p values are 0.028, 0.003 and 0.001 for Cd, Pb and Zn respectively). Thus, organic-matter addition can, not only alleviate As accumulation, but it can also alleviate heavy-metal toxicity in the food chain.

Soil humic acids are active in retaining As(III) and As(V) through adsorption. The methylation reactions of arsenic may decrease the toxicity of As by decreasing its mobility in soil. When an element is less mobile, its uptake by plants is also lower (Suzuki 2002). In the present case, the As accumulation in the plants for the different organic-matter treatments was in the order: poultry manure < cow dung < sewage sludge, and this corresponded to the carbon content of the organic sources. The higher the carbon content of the organic source, the lower was the As accumulation in plants treated with that source. This could be related to a higher methylation rate in the presence of the respective organic sources. Wastewater, sewage sludge and refuse composts have an effect on the accumulation and movement of arsenic in cultivated soil (Azcue and Nriagu 1994). Arsenic is chemically similar to phosphorus (Carbonell-Barrachina *et al.* 1994), and roots take up arsenic and phosphorus by the same mechanism (Meharg and Macnair 1990). Therefore, the chance of As–P interaction could always be expected. The poultry litter contained much higher amounts of phosphate, and interestingly enough, the plants grown on the poultry-litter-treated soil also accumulated higher amounts of phosphate (data not shown in this paper). Therefore, it is assumed that the improved efficacy of the poultry litter in obviating As accumulation in *Ipomoea aquatica* could be attributed both to a greater methylation reaction and to greater As–P interactions. Our findings corroborate the observations of Kabata-Pendias and Pendias (1985), who found that arsenic is less toxic when the plant is well supplied with phosphorus, as well as the observation by Pais and Jones (1997) that the phytotoxicity of arsenic is reduced with high phosphorus availability. The results of the present study are also consistent with the work by Shiralipour *et al.* (2002), who observed that compost has the ability to hold As in the exchange sites, making it less available to plants. High As accumulation in roots and shoots of *Ipomoea aquatica* at high As levels in soil could be attributed to the higher phytoavailability of the element. This has been reported for this plant, as well as others (Farid *et al.*

2003; Imamul Huq *et al.* 2006*a*; Sanyal *et al.* 2007). Our findings also indicate that, even at high soil arsenic levels, the addition of organic matter – specifically, poultry litter, could be a strategy to remediate As accumulation in growing crops. The fraction of As reacting with P and methylating needs to be assessed further. Using organic waste, particularly poultry manure and cow dung, in agriculture could raise the issue of the spreading of avian flu and cow-related diseases. This possibility is remote in Bangladesh, as both poultry litter and cow dung are sun-dried before application to soil, and the avian virus is destroyed at high temperatures. As for cow-related diseases, there is no mad cow disease problem in Bangladesh. Foot-and-mouth disease is well contained and not very widespread.

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REFERENCES

Ali, M.A., Badruzzaman, A.B.M., Jalil, M.A., Hossain, M.D., Ahmed, M.F., Masud, A.A., Kamruzzaman, M. and Rahman, M.A. (2003) Arsenic in plant–soil environment in Bangladesh. In: *Fate of Arsenic in the Environment* (Ahmed, F.M., Ali, M.A. and Adeel, Z. eds), pp. 85–112. ITN centre, BUET, Dhaka, Bangladesh

APSU (2005) *The Response to Arsenic Contamination in Bangladesh: a Position Paper.* DPHE, Dhaka, Bangladesh. 57 pp.

Azcue, J.M. and Nriagu, J.O. (1994) Arsenic: historical perspectives. In: *Arsenic in the Environment, Part I, Cycling and Characterization* (Nriagu, J.O. ed.), pp. 1–49. Wiley, London

BARC (Bangladesh Agricultural Research Council) (2005) *Fertilizer Recommendation Guide 2005* (Miah, M.M.U., Farid, A.T.M., Miah, M.A.M., Jahiruddin, M., Rahman, S.M.K., Quayyum, M.A., Sattar, M.A., Motalib, M.A., Islam, M.F., Ahsan, M. and Razia, S. eds) BARC, Dhaka, Bangladesh. 260 pp.

BBS (Bangladesh Bureau of Statistics) (2004) Energy supplied by traditional fuels in the unrecognized sectors. *Statistical Yearbook of Bangladesh.* Bangladesh Bureau of Statistics, Statistics Division, Ministry of Planning, Govt. of the People's Republic of Bangladesh. 233 pp.

BGS/DPHE (2001) Arsenic contamination of groundwater in Bangladesh. In: *British Geological Survey Final Report* (Kinniburg, D.G. and Smedley, P.L. eds), WC/00/19. Vol. 2.

Burló, F., Guijarro, I., Carbonell-Barrachina, A.A., Valero, D. and Martinez-Sanchez, F. (1999) Arsenic species: effects on and accumulation by tomato plants. *J. Agric. Food Chem.*, **47**, 1247–1253

Carbonell-Barrachina, A., Carbonell, F.B. and Beneyto, J.M. (1994) Effect of arsenite on the concentrations of micronutrients in tomato plants grown in hydroponic culture. *J. Plant Nutr.*, **17**, 1887–1903

Carbonell-Barrachina, A.A., Burló, F., Valero, D., Lopez, E., Martinez-Romero, D. and Martinez-Sanchez, F. (1999) Arsenic toxicity and accumulation in turnip as affected by arsenic chemical speciation. *J. Agric. Food. Chem.*, **47**, 2288–2294

Chakravarty, I., Sinha, R.K. and Ghosh, K. (2003) Arsenic in food chain – study on both raw and cooked food. In: *Arsenic Contamination: Bangladesh Perspective* (Ahmed, M.F. ed.), pp. 227–240. ITN centre, BUET, Dhaka, Bangladesh

Erickson, J.E. (1988) The effects of clay, organic matter and time on adsorption and plant uptake of cadmium added to the soil. *J. Water, Air and Soil Pollution*, **40** (3–4), 359–373

Farid, A.T.M., Roy, K.C., Hossain, K.M. and Sen, R. (2003) A study of arsenic contaminated irrigation water and its carried over effect on vegetable. In: *Fate of Arsenic in the Environment* (Ahmed, F.M., Ali, M.A. and Adeel, Z. eds), pp. 113–121. ITN centre, BUET, Dhaka, Bangladesh

Helgensen, H. and Larsen, E.H. (1998) Bioavailability and speciation of arsenic in carrots grown in contaminated soil. *Analyst*, **123**, 791–796

Hossain, A., Joardar, J.C. and Imamul Huq, S.M. (2006) Comparison of arsenic accumulation by two ferns – *P. vittata* and *N. molle*. *Dhaka Univ. J. Biol. Sci.*, **15** (2), 95–103

Imamul Huq, S.M. and Alam, M.D. (eds) (2005) *A Handbook on Analyses of Soil, Plant and Water.* BACER-DU, University of Dhaka, Bangladesh. 246 pp.

Imamul Huq, S.M. and Naidu, R. (2003) Arsenic in groundwater of Bangladesh: contamination in the food chain. In: *Arsenic Contamination: Bangladesh Perspective* (Ahmed, M.F. ed.), pp. 203–226. ITN centre, BUET, Dhaka, Bangladesh

Imamul Huq, S.M. and Naidu, R. (2005) Arsenic in ground water and contamination of the food chain: Bangladesh scenario. In: *Natural Arsenic in Groundwater: Occurrence, Remediation and Management* (Bundschuh, J., Bhattacharya, P. and Chandrasekharam, D. eds), pp. 95–101. Balkema, New York

Imamul Huq, S.M., Ahmed, K.M., Sultana, N. and Naidu, R. (2001) Extensive arsenic contamination of ground water and soils of Bangladesh. In: *Arsenic in the Asia-Pacific Region: Managing Arsenic for Our Future. Book of Abstracts*, pp. 94–96. Adelaide, South Australia

Imamul Huq, S.M., Rahman, A., Sultana, N. and Naidu, R. (2003) Extent and severity of arsenic contamination in soils of Bangladesh. In: *Fate of Arsenic in the Environment* (Ahmed, F.M., Ali, M.A. and Adeel, Z. eds), pp. 69–84. ITN centre, BUET, Dhaka, Bangladesh

Imamul Huq, S.M., Joardar, J.C. and Parvin, S. (2005) Marigold (*Tagetes patula*) and ornamental arum (*Syngonia* sp.) as phytoremediators for arsenic in pot soil. *Bangladesh J. Bot.*, **34** (2), 65–70

Imamul Huq, S.M., Correll, R. and Naidu, R. (2006*a*) Arsenic accumulation in food sources in Bangladesh: variability with soil type. In: *Managing Arsenic in the Environment: From Soil to Human Health* (Naidu, R., Smith, E., Owens, G., Bhattacharya, P. and Nadebaum, P. eds), pp. 283–293. CSIRO, Melbourne, Australia

Imamul Huq, S.M., Joardar, J.C., Parvin, S., Correll, R. and Naidu, R. (2006*b*) Arsenic contamination in food chain: transfer of arsenic into food materials through groundwater irrigation. *J. Health Popul. Nutr.*, **24** (3), 305–316

Imamul Huq, S.M., Islam, M.S., Joardar, J.C. and Khan, T.H. (2006*c*) Retention of some environmental pollutants (As, Pb and Cd) in soil and subsequent uptake of these by plants (*Ipomoea aquatica*). *Bangladesh J. Agric. and Environ.*, **2** (1), 61–68

Imamul Huq, S.M., Shila, U.K. and Joardar, J.C. (2006*d*) Arsenic mitigation strategy for rice by water regime management. *Land Contamination & Reclamation*, **14** (4), 805–813

Imamul Huq, S.M., Abdullah, M.B. and Joardar, J.C. (2007) Bioremediation of arsenic toxicity by algae in rice culture. *Land Contamination & Reclamation,* **15** (3), 327–333

Joardar, J.C., Rashid, M.H. and Imamul Huq, S.M. (2005) Adsorption of arsenic (As) in soils and in their clay fraction. *Dhaka Univ. J. Biol. Sci.*, **14** (1), 51–61

Kabata-Pendias, A. and Pendias, H. (1985) *Trace Elements in Soils and Plants*. CRC Press Inc., Boca Raton, Florida. 315 pp.

Kwiatkowska, J. and Maciejewska, A. (2006) The effect of organic materials on the uptake of heavy metals by maize (*Zea mays*) in heavy metals polluted soil. *18th World Congress of Soil Science*. Philadelphia, Pennsylvania

Ma, L.Q., Komar, K.M., Tu, C., Zhang, W., Cai, Y. and Kennelley, E.D. (2001) A fern that hyperaccumulates arsenic. *Nature*, **409**, 579

Martins, J.M.F., Griesel, M., Barnier, C. and Spadini, L. (2006) Effect of organic matter inputs on copper speciation, bio-availability and leaching in two vineyard soils. *18th World Congress of Soil Science*. Philadelphia, Pennsylvania

Meharg, A.A. and Macnair, M.R. (1990) An altered phosphate uptake system in arsenate tolerant *H. lanatus*. *New Phytologist*, **16**, 29–35

Molla, S.R. and Imamul Huq, S.M. (2004) Availability of some heavy metals in soil due to the compost application and its correlation with the growth of *Amaranthus gangeticus* L. *J. Asiat. Soc. Bangladesh Sci.*, **30** (1), 47–56

Pais, I. and Jones, J.B. Jr (1997) *The Handbook of Trace Elements*. St. Lucie Press, Boca Raton, Florida. 223 pp.

Portman, J.E. and Riley, J.P. (1964) Determination of arsenic in seawater, marine plants and silicate and carbonate sediments. *Anal. Chem. Acta.*, **31**, 509–519

Sanyal, S.K., Dutta, P., Das, S., Bose, A., Mondal, N., Bose, P., Pal, S., Kole, S.C., Bandyopadhyay, P., Mondal, S. and Bhattacharyya, S. (2007) An investigation into accumulation of arsenic in biological systems of the agro-ecology of the Nonaghata area of Nadia, West Bengal. In: *Proc. Int. Workshop on Arsenic Sourcing and Mobilisation in Holocene Deltas* (Basu, B. ed.), pp. 99–100. School of Fundamental Research, Kolkata, India

Shiralipour, A.L., Ma, Q. and Cao, R.X. (2002) *Effects of Compost on Arsenic Leachability in Soils and Arsenic Uptake by a Fern*. State University System of Florida, Report No. 02-04. Florida Center for Solid and Hazardous Waste Management, University of Florida, Gainesville

Sikder, T., Joardar, J.C. and Imamul Huq, S.M. (2007) Sewage sludge as soil ameliorator. *Bangladesh J. Agric. and Environ.*, **3** (1), 63–73

Suzuki, K.T. (2002) A speciation study focused on the identification of proximate toxic arsenic metabolites. In: *Proc. of the UNU-NIES Int. Workshop on Arsenic Contamination in Groundwater – Technical and Policy Dimensions, Tokyo, Japan*

United Nations Development Program and Food and Agriculture Organization of the UN (1988) *Land Resources Appraisal of Bangladesh for Agricultural Development. Agroecological regions of Bangladesh*. Report 2. pp 570

USDA (United States Department of Agriculture) (1951) *Soil Survey Manual*. Soil Survey Staff, Bureau of Plant Industry, Soils, and Agricultural Engineering, United States Department of Agriculture, Washington. 503 pp.