

ARSENIC CONTAMINATION OF GROUNDWATER IN WEST BENGAL (INDIA): BUILD-UP IN SOIL-CROP SYSTEMS

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Abstract: *The widespread arsenic (As) contamination in groundwater in parts of West Bengal (India) and Bangladesh is well documented. In West Bengal alone, 75 blocks, located primarily in 5 districts on the eastern bank of the river Bhagirathi, are affected, with 5-6 million population reportedly drinking groundwater laden to various degrees with As contamination. A large number of people have actually shown the symptoms of As poisoning culminating into several deaths. A large part of the Bengal delta basin bound by the rivers Bhagirathi and Padma is affected. Since a greater part of this delta has fallen in Bangladesh, the districts of Bangladesh contiguous to the contaminated zones of West Bengal are more widely affected by arsenic contamination of groundwater. The source of such contamination is believed to be of geogenic origin. The exact sequence of geochemical reactions that lead to the release of As in groundwater from the aquifer sediments, however, is still debated.*

This indeed calls for an immediate attention since what remains essentially a point and fixed source of As contamination as for drinking water (e.g., a tubewell discharging contaminated water) may very well become a diffuse and uncertain source of contamination when As finds its way into the food web accompanied by possible biomagnification up in the food chain. Indeed different crop plants raised in a crop cafeteria experiment exhibited varying tendencies to accumulate As. Such accumulation in different plant parts also tended to fall off in the following sequence: root>stem>leaf>economic produce. Moreover, inclusion of pulses/other legumes/green manure crops in the cropping sequences, coupled with organic manure addition, was found helpful in moderating As build-up in soil and plant parts. Notwithstanding what is stated above, much more and sustained research work remains to be done to characterize the entire gamut of intricacies of As contamination spectrum in soil-plant-animal system, as well as evolve effective remedial measures to contain the toxin in the said system.

INTRODUCTION

Arsenic (As) is a widely occurring toxic metalloid in natural ecosystems. Arsenic input to the environment either through natural processes of weathering of arsenic-bearing rocks and/or use of arsenic-contaminated groundwater for irrigation, or through a host of anthropogenic activities, such as mining operations, smelting of base metal ores, combustion of coal and application of arsenicals as agricultural

pesticides is widely reported. There has been a rapidly growing global concern for arsenic contamination in drinking water (WHO, 2001).

Arsenic contamination of groundwater in the Gangetic alluvial zones of West Bengal has assumed the proportion of a drinking water related disaster in recent years with reports of arsenic related health hazards for millions of people. As many as 75 blocks in 9 districts covering an area of 38865 km² are reported to be severely affected (Chowdhury et al., 2000). The main focus of attention, until recently, has been exclusively on As contamination in groundwater-derived drinking water. However, since groundwater is also used extensively for crop irrigation in the arsenic belt of West Bengal, the possibility of a build-up of arsenic concentration in agricultural soils and agronomic produce was anticipated. Elevated As levels in groundwater-irrigated soils in West Bengal are now well documented. Arsenic uptake by crop plants grown in soils contaminated with high concentrations of arsenic, and irrigated with arseniccontaminated groundwater has also been reported (ICAR 2001; Abedin et al., 2002). Soil acts as a major sink of As inflow to agroecosystems (Carey et al., 1996; Ghosh et al., 2002; Livesey and Huang, 1981; Majumdar and Sanyal, 2002; Mukhopadhyay, 2002), thereby reducing the availability of the toxicant to the cropped species. Thus, the capacity of soil to retain As gains substantial significance in relation to the passage of the toxicant in the groundwater-soil-plant/animal/human continuum.

It is in this context that a thorough understanding of soil-arsenic interactions is necessary in order to judge as to how well such a sink would be able to contain the toxin (i.e., arsenic), and prevent it from entering the food chain *via* plant uptake and leaching to surface run-off and groundwater, as well as examine the possibility of bio-magnification of As as it moves up in the food web.

This paper overviews the complex problem of As toxicity in agroecosystems receiving contaminated groundwater for irrigation purpose with emphasis on soil as an efficient sink.

NATURAL ABUNDANCE

Dissolved As concentrations in natural waters (except groundwater) are generally low, except in areas characterized by geothermal water and/or mining activities. The sedimentary rocks generally have higher As content than igneous and metamorphic rocks, while suspended and bottom sediments in most aquatic systems contain more As than most natural waters (Welch et al., 1988). The capacity to retain As is primarily governed by the sediment grain-size and the presence of surface coating composed of clays, clay-sized iron and manganese oxides and organic matter.

Arsenic held by solid phases within the sediments, especially iron oxides, organic matter and sulphides may constitute the primary arsenic sources in groundwater under conditions conducive to As release from these solid phases. These include abiotic reactions (oxidation/reduction, ion exchange, chemical transformations) and biotic reactions (microbial methylation) (Mok and Wai, 1994).

GUIDELINE VALUE OF MAXIMUM AS CONTAMINATION

The World Health Organisation (WHO) recommended provisional guideline value of *total* As concentration in drinking water as 0.01 mg As/L in 1993 (WHO, 1993), mainly because lower levels preferred for protection of human health are not reliably measurable on a large scale. However, the National Standard for maximum acceptable concentration (MAC) of As in drinking water is 0.05 mg As/L in several countries including India and Bangladesh based on an earlier WHO (1971) advice.

The proposed new standard value of 0.005 mg As/L is under consideration (WHO, 2001). This is due mainly to the fact that inorganic As compounds are classified in Group 1 (carcinogenic to humans) on the basis of adequate evidence for carcinogenicity in humans and limited evidence for carcinogenicity in animals (IARC, 1987). Adequate data on the carcinogenicity of organic arsenic have not been generated. The joint FAO/WHO Expert Committee on Food Additives (JECFA) set a provisional maximum tolerable daily intake (PMTDI) of inorganic arsenic as 0.002 mg/kg of body weight for humans in 1983 and confirmed a provisional tolerable weekly intake (PTWI) as 0.015 mg/kg of body weight in 1988 (FAO/WHO, 1989). Such guideline values for soil, plant and animal systems are not available.

ARSENIC CONTAMINATION IN GROUNDWATER

Arsenic contamination in groundwater has been reported at different times from West Bengal, India, and countries like U.S.A., Argentina, Chile, Mexico, Taiwan, Hungary, Finland, Nepal and Bangladesh (Sanyal, 1999). In West Bengal, the presence of As in groundwater in concentrations exceeding MAC was first detected in 1978, while the first case of As poisoning in humans was diagnosed at the School of Tropical Medicine in Calcutta in 1983 (Acharya, 1997).

Arsenic in groundwater is generally present as dissolved deprotonated/protonated oxyanions, namely arsenites ($\text{As}^{\text{III}}\text{O}_3^{3-n-}$; $\text{H}_n\text{As}^{\text{III}}\text{O}_3^{(3-n)-}$, with $n = 1, 2$) or arsenate ($\text{As}^{\text{V}}\text{O}_4^{3-}$, $\text{H}_n\text{As}^{\text{V}}\text{O}_4^{(3-n)-}$, with $n = 1, 2$), or both, besides the organic forms.

The toxicity of As compounds in groundwater/soil environment depends largely on its oxidation state, and hence on redox status and pH, as well as whether As is present in organic combinations. The toxicity follows the order: arsine (valence state of As: -3) > organo-arsine compounds > arsenites (+3) and oxides (+3) > arsenates (+5) > arsonium metals (+1) > native arsenic (0). The arsenites are much more soluble, mobile, and toxic than arsenates in aquatic and soil environments. At pH 6-8, in most aquatic systems, both $\text{H}_2\text{As}^{\text{V}}\text{O}_4^-$ and $\text{HAS}^{\text{V}}\text{O}_4^{2-}$ ions occur in considerable proportions in an oxidized environment ($E_h = 0.2-0.5\text{V}$), while $\text{H}_3\text{As}^{\text{III}}\text{O}_3$ is the predominant species under reduced conditions ($E_h = 0-0.1\text{V}$) (Sadiq, 1997). Reduction of As (V) to As (III) would be accompanied by mobilization of As in aquatic system.

ARSENIC CONTAMINATION OF GROUNDWATER IN THE BENGAL BASIN

High arsenic concentration in groundwater is generally associated with the geothermal environments of volcanic deposits, geothermal systems and basin-fill deposits of alluvial lacustrine origin (Welch et al., 1988). As regards the widespread As contamination in groundwater in parts of West Bengal, India, and Bangladesh, confined within the delta bound by the rivers Bhagirathi and Ganga-Padma, two major hypotheses, both of geogenic origin, have been proposed. According to the earlier one (Mandal et al., 1996), iron-containing minerals in the alluvial sediments, or formed *in situ*, combine with sulphur to form iron pyrites which have associated arsenic. The latter finds its way into groundwater through oxidation of arsenopyrite in aquifer sediments as atmospheric oxygen invades the aquifer in response to lowering of groundwater level by its large-scale abstraction for agricultural irrigation, especially for cultivation of summer (*boro*) paddy during the lean period of January to April when the groundwater recharge is at its minimum (Sanyal, 1999). This process would lead to the formation of iron sulphates and sulphuric acid. This hypothesis is not consistent with the slightly alkaline status of groundwater in the affected delta, nor with its low (trace) concentration of sulphate, or high concentrations of bicarbonate, iron (II), arsenite, calcium and magnesium (Sanyal, 1999). Bhattacharya et al. (1997) and Nickson et al. (1998) put forward the alternative hypothesis that the burial of the sediments, rich in organic matter, has led to strongly reducing conditions in groundwater aquifer, which is facilitated by high water table, fine-grained surface layers and widely practised wetland paddy cultivation, as well as microbial oxidation of sedimentary organic matter, depleting thereby the dissolved oxygen in groundwater. Arsenic is released when arsenic-rich iron oxyhydroxides, which are efficient arsenic-scavengers, are reduced in anoxic groundwater. Such reduction is driven by concentrations of sedimentary organic matter. Notwithstanding these hypotheses, the exact sequence of geochemical reactions, leading to As release in groundwater from the aquifer sediments, is still debated.

In West Bengal alone, in particular, presently 75 blocks, located primarily in five districts on the eastern bank of the river Bhagirathi, are affected, with 5 to 6 million population reportedly drinking groundwater, laden to various degrees with As contamination. A large number of people have actually shown the symptoms of As poisoning, culminating into several deaths. Since a greater part of the above stated delta has fallen in Bangladesh, the districts of Bangladesh, contiguous to the contaminated zones of West Bengal, are more widely affected by arsenic contamination of groundwater.

BCKV EXPERIENCE

In such a background, almost the entire effort at the Government, Semi-Government and NGO levels both internationally and in India has been directed

towards solving the problem of As contamination of groundwater used as drinking water source. However, of the total groundwater used in the affected belt of West Bengal, India, less than 10% accounts for drinking purpose. More than 90% of the total groundwater is used in the agricultural sector to meet the crop irrigational requirements. Despite this, no study was conducted to explore the influence of As in contaminated groundwater irrigation source on soil-plant-animal continuum until recently.

To fill this gap, an inter-institutional inter-disciplinary study (concluded in mid-2001), funded by the Indian Council of Agricultural Research (ICAR), was led by the Bidhan Chandra Krishi Viswavidyalaya (BCKV). This study has provided important leads, worth pursuing, as to the source of As contamination in groundwater, accumulation of the toxin in soils and crops grown in the affected belt of West Bengal irrigated with contaminated groundwater, and in animal tissues and products. Indeed, more than 90% of the daily intake of As in farm animals in the affected area under study was found to be from the feed sources, with a rather small contribution from the drinking water source. These findings (to which appropriate references in greater details will be made hereinafter) have aptly demonstrated the pathways, other than drinking water, through which As may have access to human systems. This indeed calls for an immediate attention since what remains essentially a point and fixed source of As contamination as for drinking water (e.g., a tubewell discharging contaminated water) may very well become a diffuse and uncertain source of contamination when As finds its way into the food web, accompanied by possible biomagnifications up in the food chain.

Interestingly, the surface water bodies, located in the affected belt, have remained largely free of As. This tends to suggest that the soil, which receives As-contaminated water, acts as an effective sink to contain the toxin (as stated earlier), thereby preventing the surface run-off to carry it to the adjoining water systems (Sanyal, 1999).

ARSENIC ACCUMULATING PLANTS/MICROBIAL SPECIES: HYPERACCUMULATION OF ARSENIC

The reported hyperaccumulation of arsenic from the contaminated soils by the brake-fern, *Pteris vittata*, and its subsequent translocation into the above-ground biomass (Ma et al., 2001) suggests that the plant-accumulated arsenic was present almost entirely in the toxic inorganic forms, with the proportion of highly toxic As (III) being, in fact, much greater in the plant body than that of the less toxic As (V) form, as compared to the distribution of these two forms in the contaminated soil in which the fern grows (Ma et al., 2001). Conversion of the plant-accumulated inorganic forms of the toxin to non (or less)-toxic organometallic forms by plant metabolism would certainly aid the detoxification process. Such detoxification within the plant body assumes importance, particularly in view of the report that arsenic in plant residues may be mobilized by a unicellular algae, namely *Polyphysa peniculus* (Cullen et al., 1994), resident in normal (moist) agricultural soils.

A scan of literature reveals a number of plant/microbial species, known for arsenic accumulation/bioindicator, which can effectively remove arsenic (and other heavy metals) from the aquatic system, for instance, to the tune of 170 and 340 μg As/g dry weight of water hyacinth in its stem and leaves, respectively, when grown in a pond containing 10 mg As/dm³ (Chigbo et al., 1982). However, such accumulated arsenic in water hyacinth (*Eichhornia crassipes*) is also liable to leaching out in the water body, particularly so on decomposition of such aquatic weed. Consequently, appropriate precaution has to be exercised while interpreting the arsenic status of aquatic environment by water hyacinth accumulation (Low and Lee, 1990). Hydrilla (*Hydrilla verticillata* Casp.) is another such aquatic plant (Lee et al., 1991). Pointed gourd, a vegetable creeper plant (*Trichosanthes dioica*), has also been found to accumulate arsenic when cultivated in the contaminated soils of West Bengal (Panda and Das, 2001 a).

Several other crop plant species (rice, elephant-foot yam, green gram, etc.) are also reported to accumulate As in substantial quantities (ICAR, 2001). Abedin et al. (2002) have reported accumulation of As, and transformation of As species in rice plant. However, information on the transformation of As species within plants is limited. The toxicity of As species in its plant body is reported to follow the order $\text{AsH}_3 > \text{As(III)} > \text{As(V)} > \text{MMA}$ (monomethylarsonic acid) $> \text{DMMA}$ (dimethylarsinic acid) (NRCC, 1978).

Arsenate tolerance by the grassy weeds, namely *Agrostis castellana* and *A. delicatula*, has been discussed in terms of the comparison of the corresponding reduction of maximum root growth (MRG) with that in the sensitive populations upon exposure to arsenic (Koe and Jaques, 1993). These findings tend to suggest that most, if not all, cropped plant species irrigated with As contaminated water, or such as those cultivated on soils, or in water bodies containing high levels of the toxic metalloid, tend to accumulate As.

A number of microbial species (e.g., the bacterial species, namely *Proteus* sp., *Escherichia coli*, *Flavobacterium* sp., *Corynebacterium* sp., and *Pseudomonas* sp.; the fungus, namely *Candida humicola*; the freshwater algae, namely *Chlorella ovalis*, *Phaeodactylum tricornutum*, *Oscillatoria rubescens*) have been reported to possess varying degrees of arsenic accumulating abilities. However, the extent of transformation of species and detoxification of such accumulated arsenic is varied, and also to an extent, uncertain.

ARSENIC FORMS IN SOILS

The solubility, mobility, bioavailability and hence toxicity of As in soil-crop system depends on its chemical form, primarily the oxidation state. The inorganic forms of As in soils and sediments include arsenites and arsenates. The organic forms, namely dimethylarsinic acid or cacodylic acid, which on reduction (e.g., in anoxic soil conditions) forms di- and trimethyl arsines (Woolson, 1977), are also present. Under oxidizing aerobic conditions (characterized by high E_h), arsenic acid species ($\text{H}_3\text{AsO}_4^\circ$, H_2AsO_4^- , HASO_4^{2-} , AsO_4^{3-}) are stable in soil environment,

whereas under mildly reducing conditions (such as one encounters in flooded soils), arsenous acid species ($\text{H}_3\text{AsO}_3^\circ$, H_2AsO_3^- , HAsO_3^{2-}) are the stable forms (Sun and Doner, 1998). Furthermore, it has been recognized that As (III) is more prevalent in soils of neutral pH range (and in most groundwater), as in the soils of the affected belt of West Bengal, India, and Bangladesh, than otherwise thought, and hence is of concern. This is primarily because As (III) exists as a neutral, uncharged molecule, $\text{H}_3\text{AsO}_3^\circ$ ($\text{pK}_a=9.2$), at the pH of neutral soils and most natural groundwater as one would expect based on the Henderson's equation (Sanyal, 1999). The latter is thus more mobile in being less strongly retained by most mineral surfaces, (Sanyal, 1999). Arsenic species in soil environment are subject to both chemically and microbially mediated oxidation or reduction and methylation reactions (Walsh and Keeney, 1975).

In course of several attempts to fractionate soil arsenic in different fractions, the 'freely exchangeable' arsenic (anion exchange resin-extractable As), rather than total As in soil, has been found to provide a satisfactory index of potential bioavailability and mobility, and hence toxicity of As in soil (McLaren et al., 1998; Mukhopadhyay, 2002).

ARSENIC RETENTION/RELEASE IN SOIL

Arsenic retention by soils trends to be governed by adsorption process rather than precipitation of sparingly soluble As compounds in soils (Livesey and Huang, 1981; Carey et al., 1996; Majumdar and Sanyal, 2002). Arsenate and arsenite adsorption by and soil components often-conformed to the Langmuir and Freundlich adsorption isotherms. The kinetics of the process have been satisfactorily described by a modified Freundlich type of kinetic equation and the Elovich equation (Elkhatib et al., 1984).

Numerous studies have described arsenic adsorption by soils to Fe, Mn and Al oxides, in particular, the oxalate-extractable amorphous Fe (Livesey and Huang, 1981; McLaren et al., 1998). Such arsenic retention has been shown to ensue from the formation of inner-sphere complexes with the adsorbent *via* ligand-exchange mechanism (Sun and Doner, 1998).

The heterogeneous oxidation of adsorbed As (III) to As (V) on soils and mineral surfaces (such as goethite) has been observed to be strongly catalysed by manganese oxides (Sun and Doner, 1998). Such findings suggest that the adsorption-oxidation system, composed of goethite and birnessite ($\delta\text{-MnO}_2$), may be significant in decreasing arsenic toxicity in terrestrial environment (Sanyal, 1999).

Soil humic acids were also active in retaining As (III) and As (V) through adsorption, with the latter depending on the ash content and presence of polyvalent cations in humic matrix (Thanabalasingam and Pickering, 1986). The pH dependence of arsenic adsorption in soil (Pierce and Moore, 1982; Manful et al., 1989; Carey et al., 1996, Majumdar and Sanyal, 2002) reveals contrasting trends, but the latter can be reconciled by considering the effect of background electrolyte (Barrow, 1985; Sanyal and De Datta, 1991).

The competitive interactions in soils of arsenate with other oxyanions/anions demonstrated that phosphate, in particular (but not molybdate, sulphate or chloride, nitrate), significantly suppressed arsenate sorption (Roy *et al.*, 1986; Manning and Goldberg, 1996), as well as its transport down a column of an Oxisol (Melamed *et al.*, 1995). Such competitive arsenic-phosphate interactions in selected As-contaminated soils of West Bengal have also been demonstrated in the absence and presence of well decomposed organic manures (Mukhopadhyay *et al.*, 2002). The latter may have its origin in the common sorption sites in soils for arsenate and phosphate.

ARSENIC IN FLOODED SOILS

The biological availability and phytotoxicity of arsenic in soil increases on reduction to As (III) which is facilitated on flooding the soil, leading to fall in E_h and an increase of pH (Rochette *et al.*, 1998; Sanyal, 1999). Under such conditions, arsenic lost from soil solution could be accounted for primarily as surface-bound with some losses of gaseous arsines (Onken and Hossner, 1996).

ARSENIC IN SOIL-PLANT SYSTEM

Soil contamination with arsenic may have toxic effect on vegetation and the animals feeding on the same. Arsenic may not be readily translocated from root to shoot, and different crop plants exhibit different tendencies to accumulate and tolerate As (Table 1). Lowland paddy seems to be especially susceptible to As toxicity, due possibly to prevailing reducing conditions in flooded paddy soils.

SELECTED FINDINGS FROM RESEARCH WORK CONDUCTED AT BCKV

Some important findings have emerged from an ICAR-sponsored interdisciplinary and inter-institutional research scheme (1998-2001; ICAR, 2001) on the studies on impacts of As contamination in groundwater *vis-a-vis* management of agricultural systems. Some important highlights of the study are given below.

The As concentration tends to build up from the contaminated groundwater, *via* the soil, to the crop, irrigated with such water. Among the plant parts, As concentration was higher in roots, followed by stem and leaves, in that order, while the economic or edible parts recorded the lowest concentration of the toxin (Adak and Mandal, 2000).

However, potato tuber, despite being an underground part (a modified stem), contained relatively lower amount of As (Adak and Mandal, 1999). Further studies are necessary to confirm and extend such initial findings and document the mobilization and transformation of species of As in food web.

Table 1 Comparative sensitivity of various crop plants to arsenic

Tolerant	Moderately Tolerant	Low Tolerance
Fruit Crops		
Apples	Cherries	Peaches
Grapes	Strawberries	Apricots
Raspberries		
Dewberries		
Vegetables and Fruit Crops		
Rye	Beets	Peas
Mint	Corn	Onion
Asparagus	Squash	Cucumber
Cabbage	Turnips	Snap beans
Carrots	Radish	Lima beans
Parsnips		Soya beans
Tomato		Rice
Potato		Spinach
Swiss chard		
Wheat		
Oats		
Cotton		
Peanuts		
Tobacco		
Forage Crops		
Sudan grass	Crested Wheat grass Timothy	Alfalfa
Bluegrass		Bromegrass
Italian ryegrass		Clover
Kentucky bluegrass		Vetch
Meadow fescute		
Red top		

Source: Adriano, 1986

A crop cafeteria experiment was conducted in the farmers' fields in the affected area in West Bengal, involving several farmer-attractive/remunerative cropping sequences, designed to take off partially the pressure on the contaminated groundwater resource for irrigation, especially during the lean period of groundwater recharge. A number of these sequences proved profitable and worth further examination. In particular, inclusion of pulses/other legumes/green manure crops in the cropping sequences, coupled with organic manure incorporation, was found helpful in moderating As build-up in soil and plant parts.

A field study, examining lowland rice (*bora* paddy), revealed that the extractable As in soil and As build-up in plants was drastically reduced by zinc application. The grain yield of rice in this experiment was also found not to vary significantly between the treatments of continuous ponding and judicious intermittent ponding (Garai et al., 2000); however, the latter saved the irrigation water, thereby bringing less toxin to the soil/crop system.

Laboratory studies on coupled transport of aqueous arsenic across and down the plugs/columns of soils from the affected zone revealed that these soils did act as effective sink for As through its accumulation and relative hold-up from the contaminated irrigation water, in agreement with findings from the corresponding breakthrough curves (Mukhopadhyay and Sanyal, 2002). These laboratory findings were supported by the field observations that the extractable As content of soils

decreased sharply in subsurface and subsoils of the profiles in the contaminated zone (Ghosh et al., 2002), and that the leachate water, collected from auger holes in the As-affected command area of deep tubewell (discharging contaminated water), showed low As concentrations (Das and Panda, 2000). Seasonal fluctuations in As content in groundwater and pond water in the affected zone was noted (Panda and Das, 2001 b). Suspended solids in pond water were observed to contribute to the total As content of unfiltered pond water. These findings suggest that storing of groundwater in ponds would aid in reducing As content in water, while sedimentation of the suspended solids in ponds would further lower such concentration. The process of dearsenification of Ascontaminated groundwater on storing in ponds would be an effective method involving peoples' participation at the rural level (Das and Panda, 2000; Panda and Das, 2001b).

The findings from an incubation study tended to demonstrate the dependence of As release in the soil solution of the As contaminated soil samples (from the affected zone of West Bengal) on the applied phosphate and FYM, with FYM being able to bind As in the soil matrix (Mukhopadhyay et al., 2002). This is illustrated by the step-wise multiple regression equations given in Table 2 (Mukhopadhyay et al., 2002). This also reflects itself in the findings obtained from a supporting pot-culture experiment with rice crop, where application of FYM helped to moderate the As accumulation in both the soil/plant as illustrated in Tables 3-5 (Mukhopadhyay and Sanyal, 2000). The latter tended to derive support from much higher yield of the crop observed in the As-treated soils in presence of the said organic manure (Table 4). Organo-arsenic complexation with humic/fulvic colloids of the native soil and the incorporated organic manures, which would be expected to moderate hazards of As toxicity, was also demonstrated in the present study (Mukhopadhyay, 2002). Thereby adding confidence to the trend of the findings as reported in Tables 2-5.

Table 2 Stepwise multiple regression equations showing influence of different treatments on NaHCO₃ (pH 8.5)-extractable arsenic content (mg kg⁻¹) in soils.

Soil	Regression equations	R ²
Gotera*	Y = 0.7951 + 0.4326X ₁	0.618
	Y = 0.5665 + 0.4326 X ₁ +0.0069X ₂	0.757
	Y = 0.7713 + 0.4287X ₁ +0.0070X ₂ -0.4162X ₃	0.899
	Y = 0.6087 + 0.4287X ₁ +0.0070X ₂ -0.4199X ₃ +0.0097X ₄	0.943
Ghentugachhi*	Y = 0.7723+ 0.3848X ₁	0.638
	Y = 0.965 + 0.3813X ₁ -0.3828X ₃	0.788
	Y = 0.7717 + 0.3812X ₁ + 0.0059X ₂ -0.3902X ₃	0.931
	Y = 0.7007 + 0.3812X ₁ + 0.0059X ₂ -0.3918X ₃ +0.0040X ₄	0.940
Baruipur**	Y = 0.9837 + 0.0467X ₄	0.530
	Y = 0.5476 + 0.4361X ₁ +0.0467X ₄	0.872
	Y = 0.4195 + 0.4361X ₁ + 0.0038X ₂ - 0.0467X ₄	0.895
	Y = 0.4861 + 0.4348X ₁ +0.0039X ₂ -0.1387X ₃ +0.0468X ₄	0.901
Gayeshpur***	Y = 0.5077 + 0.3041X ₁	0.384
	Y = 0.1738 + 0.3041X ₁ +0.0196X ₄	0.596
	Y = 0.0541 + 0.3041X ₁ + 0.0068X ₂ -0.0196X ₄	0.779
	Y = 0.0851 + 0.3014X ₁ +0.0069X ₂ -0.2894X ₃ +0.1980X ₄	0.866

*Mouza of Chakdah Block, Nadia Distric; **Block of S-24 Parganas District, ***Mouza of Haringhata Block, Nadia District. Y = Extractable arsenic content in soil; X₁ = Arsenic addition; X₂ = Phosphorus addition; X₃ = FYM incorporation; X₄ = Incubation period. Source: Mukhopadhyay et al., 2002.

Table 3 Arsenic content (mg kg⁻¹) in straw and grain of rice at harvest under pot-culture study

Treatment	Straw			Grain		
	O ₀	O ₁	O ₂	O ₀	O ₁	O ₂
As ₀	5.11	1.91	1.47	0.07	0.09	0.05
As ₁	9.17	8.53	7.36	2.11	2.11	2.29
As ₂	19.3	11.2	11.1	3.24	2.47	2.45
C.D. (P = 0.05)	As: 0.87 O: 0.87 As x O: 1.52			As: 0.39 O: 0.39 As x O: NS		

O₀ = No FYM incorporation; O₁ and O₂ = FYM incorporation @ 0.5% and 1%, respectively, by weight of soil. As₀ = No arsenic addition; As₁ and As₂ = Arsenic addition @ 50 mg kg⁻¹ and 100mg kg⁻¹ soil, respectively weight of soil in each pot = 5 kg. Source: Mukhopadhyay and Sanyal 2000.

Table 4 Effect of FYM and arsenic on yield attributes and yield (g/pot) of rice (IET-4786) at harvest in pot experiment

Treatment	Panicle number/plant	Grain/panicle	Filled grain (%)	1000 grain weight/g	Yield g/pot
As ₀ O ₀	14	76	75	23	18.4
As ₀ O ₁	16	81	77	26	25.9
As ₀ O ₂	19	86	82	28	37.5
As ₁ O ₀	11	69	66	19	9.52
As ₁ O ₁	14	73	72	21	15.5
As ₁ O ₂	16	83	76	23	23.2
As ₂ O ₀	10	62	66	19	7.77
As ₂ O ₁	15	73	71	21	16.3
As ₂ O ₂	15	73	75	24	19.7
C.D. (P=0.05)	As: 1.19 O: 1.19 As x O: 2.06	As: 1.38 O: 1.38 As x O: 2.38	As: 1.63 O: 1.63 As x O: 2.82	As: 1.71 O: 1.71 As x O: 2.97	As: 3.68 O: 3.68 As x O: 6.36

Source: Mukhopadhyay and Sanyal, 2000.

Table 5 Residual arsenic (mg kg⁻¹) in soil at harvest of rice crop under pot-culture study

Treatment	O ₀	O ₁	O ₂
As ₀	0.39	0.20	0.21
As ₁	8.88	7.54	5.17
As ₂	24.6	15.1	12.1
C.D. (P = 0.05)	As: 0.66 O: 0.66 As x O: 1.14		

Source: Mukhopadhyay and Sanyal, 2000.

The As-decontaminating ability of the microorganisms, prevalent in the contaminated soils, was monitored. This led to the identification of two genera of blue-green algae (BGA) (namely, *Anabaena* sp. and *Nostoc* sp.), and four different types of bacteria showing promise of As-decontamination ability (B. Mohanty, Unpublished results, by personal communication).

CONCLUSION AND RECOMMENDATIONS

Arsenic toxicity of contaminated drinking water in human beings in many parts of the world, including West Bengal, has deservedly received increasing concern. Arsenic toxicity in livestock and other animal species like poultry, fish and seafood has been given comparatively much less attention. On the other hand, As contamination in agroecosystem, that acts as a conduit for the passage of the toxicant to human population *via* food web, came under serious consideration only recently.

The present communication has demonstrated that, equal if not greater, attention is necessary for understanding the complex aspects of accumulation of arsenic in the food web *vis-a-vis* in drinking water alone, and its ultimate passage to the human populations. This study also highlights the distinct possibility of exposure to toxicity of human and livestock populations consuming arsenic laden agricultural produce at locations away from arsenic affected areas of West Bengal, and elsewhere. This overview also indicates that the accumulation of arsenic in soils, plants, plant organs, livestock, plant and livestock products is a combined function of arsenic input to, the time period of arsenic loading in, and arsenic retentability of the system (soil, plant, etc.).

Notwithstanding what is discussed above, much more and sustained research work remains to be done to characterize the entire gamut of intricacies of As contamination spectrum in soil-plant-animal system, as well as evolve effective remedial measures to contain the toxin in the said system. Immediate needs, among others, are improvement of field and laboratory protocols for large-scale measurement of As, and for different forms/species of As in groundwater-soil-plant-animal-human continuum, strengthening of inter-institutional and interdisciplinary action programme, on-demand testing of As-presence in abiotic and biotic systems, long-term technical alternatives to reduce dependence on As contaminated resources, awareness and involvement of the affected populations for the confinement through mass movements, gradually leading to the zeroing of As related problem and promotion of international networking in support of As mitigation.

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