An Overview of Arsenic Dynamics in Lowland Rice Ecosystem

Perves Ahmed1*, Mrinal Choudhury2 and Ranjita Brahma3
1,2Assistant Professor, Department of Agronomy,
2Assistant Professor, Department of Soil Science,
SCS Collage of Agriculture, AAU, Dhubri, Assam, India
*Corresponding Author E-mail: pervesahmed@gmail.com
Received: 2.06.2020 | Revised: 7.07.2020 | Accepted: 11.07.2020

ABSTRACT
Arsenic naturally occurs in many environmental media, such as rocks, soil, sediments, and surface/groundwater and it can further be released into the aquatic and terrestrial ecosystem via natural and anthropogenic activities. Amongst the main contributing sources of As contamination of soil and water are geologic origin, pyritic mining, agriculture and coal burning. Soils contain both organic and inorganic arsenic species. Inorganic As species are more toxic to living organisms than organic forms. The majority of As in aerated soils exists as H₂AsO₄⁻ (acid soils) or HAsO₄²⁻ (neutral and basic). However, H₃AsO₃ is the predominant species in anaerobic soils, where arsenic availability is higher and As (III) is more weakly retained in the soil matrix than As(V). The availability of As in soils is usually driven by multiple factors and processes such as the presence of Fe-oxides and/or phosphorus, (co)precipitation in salts, pH, organic matter, clay content, rainfall amount, etc. The available and most labile As fraction can potentially be taken up by plant roots, although the concentration of this fraction is usually low. The status of current scientific knowledge allows us to manage as contamination in the soil-plant system and to mitigate arsenic’s effects. Hence it is imperative to understand the mechanisms of As uptake and translocation by rice and the present paper focuses on the journey of As from soil to human through the rice grains.

Keywords: Arsenic, Dynamics, Lowland, Management, Rice ecosystem

INTRODUCTION
Arsenic (As) is a ubiquitous element that ranks 20th among the most abundant elements in the earth’s crust. Arsenic naturally occurs in many environmental media, such as rocks, soil, sediments, and surface/groundwater and it can further be released into the aquatic and terrestrial ecosystem via natural and anthropogenic activities (Lombi et al., 2000). The toxicity of As is mainly dependent on the forms of arsenic. Inorganic As species are more toxic to living organisms than organic forms (Meharg & Whitaker, 2002). Inorganic arsenic is present in soil, water, air, and food such that humans are constantly exposed to this contaminant (Mandal & Suzuki, 2002).

Cite this article: Ahmed, P., Choudhury, M., & Brahma, R. (2020). An Overview of Arsenic Dynamics in Lowland Rice Ecosystem, Ind. J. Pure App. Biosci. 8(4), 467-476. doi: http://dx.doi.org/10.18782/2582-2845.8202
Arsenic toxicity in humans can cause severe health problems ranging from skin lesions to cancers of the brain, liver, kidney, and stomach, and many other cardiovascular and neurological diseases and sometimes genotoxic effects (Smith et al., 1992; Martinez et al., 2011). On a global level, drinking contaminated water is the major source of exposure to this contaminant (Smedley & Kinniburgh, 2002). It is estimated that some 30 million people are exposed to waters contaminated with arsenic, a quarter of them showing symptoms associated with long-term exposure in at least five South Asian countries: Bangladesh, India, Nepal, Thailand, and Myanmar. According to the World Health Organization (WHO) guideline, the baseline limit of As concentration in safe drinking water is 10 microgram/litre (μg/L), which is similar to the European Union (EU), US Environmental Protection Agency (USEPA), Netherlands, and Germany limits of As in drinking water (Ahsan & Del Valls, 2011). However, in Bangladesh and many other developing countries, such as India, China, and Nepal, it is set to 50 μg/L (World Bank, 2005).

Arsenic poisoning via drinking of As contaminated groundwater is well documented (Smedley & Kinniburgh, 2002); however, recent investigation revealed that rice, which is the staple food for nearly half of the world’s population, is another potential As exposure pathway to human health. It can add significant amounts of dietary intake of As than most crops because rice plants have the special ability to soak up As from soil compared to other cereals (Heikens, 2006), and use of arsenic-contaminated groundwater for irrigation of rice cultivation (Heikens et al., 2007). Further, rice is one of the most efficient silica accumulators among all crop plants and As (III) too enters through silicic acid transporters in rice (Ma et al., 2008; Norton et al., 2010). However, accumulation of As in rice grains in quantities greater than recommended safe limits is influenced by various environmental, geochemical, and biological factors which controls As solubility, bioavailability and uptake in the soil–rhizosphere – plant system (Walter & Wenzel, 2002; Zhao et al. 2010). The situation is of grave concern considering the very high per capita rice consumption rate in As contaminated South East Asian countries ranging from 250 to 650 g of rice per day (Arslan et al., 2017). Hence it is imperative to understand the mechanisms of As uptake and translocation by rice (Li et al., 2011). The present paper focuses on the journey of As from soil to human through the rice grains.

**GEOCHEMISTRY OF ARSENIC**

Arsenic is a redox-sensitive element, which exists mainly in four oxidation states, + V (arsenate), + III (arsenite), 0 (arsenic), and – III (arsine) and occurs as cation as well as oxyanion species. It can occur in the environment both in organic and inorganic forms. Inorganic forms usually associate with many minerals and other elements, especially oxygen, sulfur, and chlorine, while organic forms associate with carbon and hydrogen. The most important inorganic species are arsenate As (V) and arsenite As(III), while the most important organic species are monomethylarsonic acid (MMA) and dimethylarsinic acid (DMA).

**MECHANISMS OF RELEASE OF ARSENIC INTO GROUND WATER**

The primary sources of As are thought to be eroding coal seam and rocks containing sulfide minerals within the Himalayas whose weathering and transport leads to downstream deposition of As in Gangetic plains (Acharya et al., 1999). The minerals contained within these deposits are oxidized when exposed to the atmosphere, and much of their As content is transferred to secondary phases including iron (Fe) hydroxides, oxyhydroxides and oxides, collectively referred to as Fe oxides. As is released from Fe oxides into groundwater through microbial processes (Fendorf et al., 2010). Hence As has been found to be distributed in wide spread areas of Gangetic plains spread across Uttar Pradesh, Bihar and West Bengal. Large areas of paddy soils are contaminated by As due to irrigation with As-tainted groundwater.
Based on the As geochemistry, there are three major mechanisms controlling As mobility in the groundwater, which have been reported by various workers. These are:

1. **Mobilization of arsenic due to the oxidation of As-bearing pyrite minerals**

   Insoluble As-bearing minerals such as arsenopyrite (As-FeS) are rapidly oxidized when in contact with oxygen, releasing soluble As (III) and Fe (II) (Smedley & Kinniburgh, 2002) (Fig. 1). The oxidation of the As-bearing minerals is dependent on availability of oxygen. High oxygen in pyritiferrous system suffers by the excess pumping and water-table drawdown. The rate of oxidation of pyrite is dependent on the redox potential (Eh) and pH. The release of Fe from pyrite oxidation can form Fe oxides that can immobilize As.

   ![Fig. 1: Mobility of As due to oxidation of As-bearing pyrite minerals](image1)

2. **Dissolution of As-rich iron oxyhydroxides (FeOOH) due to onset of reducing conditions in the subsurface:**

   During reductive dissolution mechanism, As gets adsorbed onto Fe (III)-oxyhydroxides and is released under reduction condition (Islam et al., 2004; Nickson et al., 1998) (Fig. 2). Moreover, dissolved oxygen in groundwater is consumed during microbial oxidation, inducing an increase in HCO₃⁻ concentration (Liaoa et al., 2011; Kar et al., 2010). This microbial activity causes a reducing, alkaline environment where mobility and thereby the concentration of As increases.

   Arsenic in Fe-oxyhydroxides is mobilized when the environment becomes anaerobic (Smedley & Kinniburgh, 2002). Bhattacharya et al. (1997) first proposed the reductive dissolution of Fe oxyhydroxides process for arsenic release. Other studies from Bengal basin reported that low Eh, O₂, NO₃⁻, and SO₄²⁻, and high Fe and Mn in groundwater are the indication of reducing conditions. Similarly Kim et al. (2009) and Sahoo et al. (2013) stated that the higher arsenic concentration in groundwater associated with lower Eh, NO₃⁻, and SO₄²⁻ and higher alkalinity, Fe and PO₄ is the indication of reductive dissolution of Fe (hydro) oxides.

   ![Fig. 2: Mobility of As due to dissolution of As-rich iron oxyhydroxides](image2)
3. Desorption of Fe-Oxyhydroxides

Besides anaerobic conditions for releasing As from Fe oxyhydroxides, there is also effect of pH, particularly at pH > 8.5, which can cause mobilization of As from Fe-oxides. This is identified by some workers (Bhattacharya et al., 2006; Kar et al., 2010). The As concentration in groundwater (μg/L) in relation with major release mechanism reported from different countries are presented in Table 1.

Table 1: As concentration in groundwater (μg/L) in relation with major release mechanism reported from different countries

| Country  | As in groundwater (μg/L) | Major release mechanism | Reference                        |
|----------|--------------------------|-------------------------|----------------------------------|
| USA      | Up to 12,000             | Oxidation of As-rich sulfides | Schreiber et al., (2000)         |
| Thailand | 1.25 – 5114              | Oxidation of As-rich sulfides | Williams et al., (1996)          |
| Korea    | 23- 178                  | Oxidation of As-rich sulfides | Kim et al., (2012)               |
| Bangladesh | Up to 640              | Reductive dissolution of Fe or Mn (hydro)oxides | Harvey et al., (2002) |
| India    | 0.77 – 1059              | Reductive dissolution of Fe or Mn (hydro)oxides | Bhattacharyya et al., (2009)    |
| Nepal    | < 10- 740                | Reductive dissolution of Fe or Mn (hydro)oxides | Gurung et al., (2005)            |
| China    | 0.6 – 572                | Reductive dissolution of Fe or Mn (hydro)oxides | Guo et al., (2008)               |
| Taiwan   | Up to 12,000             | Reductive dissolution of Fe or Mn (hydro)oxides | Chen and Liu (2007)              |
| Vietnam  | 1 – 741                  | Reductive dissolution of Fe or Mn (hydro)oxides, Oxidation of As-rich sulfides | Naguyen and Itoi (2009)          |

FACTORS RESPONSIBLE FOR AVAILABILITY OF ARSENIC IN SOIL AND PLANT

Arsenic is naturally present in soil. Its average concentration in non-contaminated soils is ~ 5 mg/kg; however, the concentration can increase up to 27,000 mg/kg or more than that in contaminated soil. The solubility and bioavailability of As in soil is influenced by various factors which are discussed below.

As Speciation

Arsenic in soil exists in both inorganic and organic forms. The most common inorganic As species in soil are As (V) and As (III), while organic forms are MMA and DMA. As(III) is more toxic than As(V), and also much more toxic than MMA or DMA. Inorganic As species are dominating in paddy soils, whereas organic species are in low quantities (Fitz and Wenzel, 2002). Inorganic species can be converted to organic form by methylation linked with microbial action in paddy soil (Takamatsu et al., 1982). Each species has different solubility and bioavailability. It was reported that the As availability to rice plants followed the order As(III) > MMA > As(V) > DMA. Meharg and Whitaker (2002) also observed that both As(III) and MMA are more available to rice plants. This indicates that speciation of As in soil environment is essential to assess As toxicity to plants.

Redox Potential

The balance of reducing and oxidizing condition (redox status) in the soil controls arsenic mobility and speciation (Fitz & Wenzel, 2002). Under oxidizing conditions (aerobic), As (V) usually dominates, which has strong affinity for soil minerals such as Fe-oxyhydroxides, leading to decrease As solubility and bioavailability to plants. However, under reducing conditions, such as soil flooding, As (III) is the most common inorganic species, and its mobility is sharply increased in the soil-rhizosphere. This is due to the reductive dissolution of Fe-oxyhydroxides,
and relatively high abundance of Fe reducing bacteria and algae in reduced soil, which help in As solubility via reduction of As(V) and methyl As species to more soluble As(III) species. Therefore, in flooded soil, As is readily available for plant uptake. This may be the cause for higher As content in lowland crops usually growing in a reducing environment, such as paddy rice, than upland cereal crops (Williams et al., 2007a).

**pH**

Arsenic (AsV) tends to be sorbed by Fe–Al oxyhydroxides at near neutral to acidic pH (Mukherjee et al., 2009). However, at extremely acidic pH (pH < 3), arsenic mobility can increase due to the dissolution of arsenic binding species, such as Fe and Al oxycompounds. Furthermore, the mobility of As in soil can increase at higher soil pH above pH 8.5, because at high pH, mineral surfaces (mainly Fe-oxides) become progressively negatively charged that facilitate desorption of As from Fe-oxides, and increases labile As in the rhizosphere, leading to more As accumulation in plants (Fitz & Wenzel, 2002).

**Organic Matter**

Organic matter (OM) can have a profound effect on As solubility in the soil since it tends to form insoluble and soluble complexes with As (Mukhopadhyay & Sanyal, 2004). Organic matter has a greater potential for As sorption due to formation of organo-As complex. Thus, high OM containing soil can reduce As availability to plants. Considering this effect, the negative correlation between As concentration in rice grain and soil OM was found by Fu et al. (2011).

On the contrary, organic matter can increase arsenic mobility in soil by forming water-soluble complexes with As, leading to inhibit As sorption on mineral surfaces. Dissolved organic matter contains negative charge, which has high potential to compete with As for sorption sites in the soil, thus, it can increase As mobility. Furthermore, dissolved organic matter can promote As release by changing the redox chemistry of site surfaces and As species. Selim Reza et al. (2010) reported that As is released by the reductive dissolution of Fe-Ox hydroxides linked to organic matter.

**Soil Texture**

In general, clay or finer texture soils have much more surface area than coarse or sandy soils. In addition, Fe oxides are mainly present in the clay size soil fraction; therefore, clayey soils can have a higher As retention potential compared to sandy soils, and soils with clayey texture are supposed to be less toxic of arsenic to plants compared to sandy soils (Heikens et al., 2007).

**As Bound to Fe–Mn Oxides**

Oxides of Fe and Mn are common in soils, and these phases are very efficient in sorbing As due to their high sorption capacity. However, their sorption property is strongly dependent on the environmental conditions (Mukherjee et al., 2009). Under flooding conditions, oxyhydroxides release As from soil by the reductive dissolution of Fe oxyhydroxides, leading to more As available for plant uptake (Fitz and Wenzel, 2002; Takahashi et al., 2004). Fu et al. (2011) found the positive relations between Fe–Mn bound As and grain As. Moreover, amorphous or poorly crystalline Fe oxides are much more readily dissolved than the crystalline Fe oxides under flooding conditions (Biswas et al., 2003). Ahmed et al. (2011) observed the significant positive relations between As in Fe-amorous fraction and rice. This indicates that As content in amorous/poorly crystalline Fe-oxides in soil can be an important factor for rice As.

**Phosphate**

Phosphate (PO₄) also controls As phytoavailability in agricultural fields. Generally, phosphate is a chemical analogue of As(V) (Fitz & Wenzel, 2002); thus, it competes with As(V) to occupy the same sorption sites in soils, leading to increase As solubility. Many studies reported that addition of PO₄ increases As mobility in soil, which can subsequently increase As uptake by plants. Contrary to this, PO₄ also competes with As(V) at the same transport during uptake, and can reduce arsenate accumulation in plants (Fitz & Wenzel, 2002).
ARSENIC IN SOIL-WATER-PLANT CONTINUUM

Arsenic dynamics under flooded rice culture is quite complex. A number of chemical and physical processes impact overall As dynamics and net As balance in flooded rice culture, e.g., irrigation protocols, adsorption/desorption, dissolution/precipitation, redox processes, As volatilization, vertical flow, lateral redistribution of soil and As resulting from surface flooding, repartitioning into surface water, and bypass flow as impacted by wetting/drying cycles.

Rice is known to be a “natural arsenic accumulator”. Rice plants take up large amounts of silicon from the soil to strengthen the stems and husks, which protect the plant against pests. Arsenic and silicon are chemically similar in soil conditions found in flooded rice paddies. Thus, arsenic is literally integrated into a rice plant as it grows. Arsenic is concentrated in the outer layers, or husks, of the grain. So, higher levels of arsenic are found in brown rice as compared white rice. Inorganic arsenic species are retained in soils by adsorption on mineral oxide surfaces, with Fe-oxides generally considered to be the major sink for As in paddy rice soils when they are oxidized. Under the reducing conditions of the paddy, Fe-oxides dissolve and inorganic As is released into the soil-water matrix from which it can be assimilated by the growing rice plant.

Uptake of As by rice is complicated by various chemical and physiological processes that occur in the rice paddy, namely
- a change in oxidation state of As from arsenate (As-V) to arsenite (As-III) as reduction in the paddy intensifies
- the formation of oxidized Fe plaque on rice root surfaces that readsoorbs As, but in competition with phosphate
- the possible formation of insoluble As sulfur species
- competitive uptake of phosphate and arsenate through the same ion channel
- competitive uptake of arsenite and silicate through a general aquaporin channel and
- microbial methylation of inorganic As to mono- and dimethyl-As species that have different rates of uptake than those of inorganic As species.

With the exception of hyper accumulators such as certain ferns, the translocation of inorganic As from the roots to the above ground parts is limited. Organic As is more readily translocated but the uptake is much lower compared to inorganic As. In pot experiments with rice plants exposed to As added via As-V in irrigation water, plant parts were ranked according to the As concentrations as follows: root > straw > husk > grain. Concentrations in all plant parts increased with the exposure concentration (Abedin et al., 2002).

MITIGATION OPTIONS ON ARSENIC ENTRY IN FOOD CHAIN

The following practices have shown great potential in mitigating the arsenic contamination hazards.
1) Using surface water sources
2) Exploring and harnessing alternative arsenic free aquifer
3) Removal of arsenic from ground water using arsenic treatment plants/filters
4) Rain water harvesting
5) Agronomic management like use of balance fertilizer, irrigation management, use of organic manure.

CONCLUSION

Arsenic is a natural trace element found in the environment. In some cases and places, human activities have increased the soil concentration of As to levels that exceed hazard thresholds. Amongst the main contributing sources of As contamination of soil and water are geologic origin, pyritic mining, agriculture, and coal burning. Soils contain both organic and inorganic arsenic species. Inorganic As species include arsenite and arsenate, which are the most abundant forms found in the environment. The majority of As in aerated soils exists as $\text{H}_2\text{AsO}_4^-$ (acid soils) or $\text{HAsO}_4^{2-}$ (neutral and basic). However, $\text{H}_3\text{AsO}_3$ is the predominant species in anaerobic soils, where arsenic availability is higher and As(III) is more weakly retained in the soil matrix than As(V). The availability of As in soils is
usually driven by multiple factors. Among these factors is the presence of Fe-oxides and/or phosphorus, (co)precipitation in salts, pH, organic matter, clay content, rainfall amount, etc. The available and most labile As fraction can potentially be taken up by plant roots, although the concentration of this fraction is usually low.

**FUTURE LINE OF WORKS**

The status of current scientific knowledge allows us to manage As contamination in the soil-plant system and to mitigate arsenic’s effects. Phytoremediation is an emerging technology suitable for reclaiming As-contaminated soils and waters. Phytoextraction has been used to clean As-contaminated soils, although its applicability has not yet reached maturity. Phytostabilization has been employed to reduce environmental risk by confining As as an inert form in soils and has shown success in both laboratory experiments and in field trials. Phytofiltration has been used to treat As-enriched waters. Such treatment removes As when it is accumulated in plants grown in or on water. In agricultural food production, appropriate soil management and plant variety/species selection can minimize As-associated human diseases and the transfer of As within the food chain. Selecting suitable plants for use on As-contaminated soils may also enhance alternative land use, such as for energy or raw material production.

**REFERENCES**

Abedin, M.J., Howells, J.C., & Meharg, A.A. (2002). Arsenic uptake and accumulation in rice (*Oryza sativa* L.) irrigated with contaminated water. *Plant Soil* 240, 311–319

Acharya, S. K., Chakraborty, P., Lahiri, S., Raymahashay, B. C., Guba, S., & Bhowmik, A. (1999). Arsenic poisoning in the Ganges delta. *Nature* 401, 545–546

Ahmed, U.Z., Panaullah, G.M., Jr, H.G., et al. (2011). Genotype and environment effect rice (*Oryza sativa* L.) grain arsenic concentration in Bangladesh. *Plant Soil* 338, 367–382.

Ahsan, D.A., & DelValls, T.A. (2011). Impact of arsenic contaminated irrigation water in food chain: an overview from Bangladesh. *International Journal of Environmental Research* 5(3), 627–638.

Arslan, B., Djamgoz, M. B. A., & Akun, E. (2017). Arsenic: a review on exposure pathways, accumulation, mobility and transmission into human food chain. *Reviews on Environmental Contamination & Toxicology* 243, 27–51.

Bhattacharya, P., Chatterjee, D., & Jacks, G. (1997). Occurrence of arsenic-contaminated groundwater in alluvial aquifers from delta plains, eastern India: options for safe drinking water supply. *International Journal of Water Resource Development* 13(1), 79–92.

Bhattacharya, P., Claesson, M., Bundschuh, J., Sracek, O., Fagerberg, J., Jacks, G., Martin, R.A., Storniolo, A.R., & Thir, J.M. (2006). Distribution and mobility of arsenic in the Río Dulce alluvial aquifers in Santiago del Estero Province, Argentina. *Science of the Total Environmental* 358, 97–120.

Bhattacharya, P., Samal, A.C., Majumdar, J., & Santra, S.C. (2009). Accumulation of arsenic and its distribution in rice plant (*Oryza sativa* L.) in Gangetic West Bengal, India. *Paddy and Water Environment* 8(1), 63-70.

Biswas, B.K., Loeppert, R.H., Hossain, M.B., et al. (2003). Impact of soil oxides on retention of arsenic in Bangladesh rice-producing soils. In: Proceedings of 7th international conference on the biogeochemistry of trace elements, Uppsala, Sweden, June 15–19, 2003.

Chen, K.Y., & Liu, T.K. (2007). Major factors controlling arsenic occurrence in the groundwater and sediments of the Chianan coastal plain, SW Taiwan. *Terrestrial Atmospheric Oceanic Science* 18, 975-994.

Fendorf, S., Michael, H. A., & van Geen, A. (2010). Spatial and temporal
variations of groundwater arsenic in South and Southeast Asia. Science 328, 1123–1127.

Fitz, W.J., & Wenzel, W.W. (2002). Arsenic transformations in the soil–rhizosphere–plant system: fundamentals and potential application to phytoremediation. Journal of Biotechnology 99, 259–278.

Fu, Y., Chen, M., Bi, X., et al. (2011). Occurrence of arsenic in brown rice and its relationship to soil properties from Hainan Island, China. Environment and Pollution 159, 1757–1762

Guo, H.M., Tang, X.H., Yang, S.Z., & Shen, Z.L. (2008). Effect of indigenous bacteria on geochemical behaviour of arsenic in aquifer sediments from the Hetao basin, Inner Mongalia: evidence from sediments incubations. Applied Geochemistry 23, 3267–3277

Gurung, J.K., Ishiga, H., & Khadka, M.S. (2005). Geological and geochemical examination of arsenic contamination in groundwater in the Holecene Terai Basin, Nepal. Environmental Geology 49(1), 98-113.

Harvey, C.F., Swartz, C.H., & Badruzzaman, A.B., et al. Arsenic mobility and groundwater extraction in Bangladesh. Science 298(5598), 1602-1606.

Heikens, A. (2006). Arsenic contamination of irrigation water, soil and crops in Bangladesh: risk implications for sustainable agriculture and food safety in Asia. Food and Agricultural Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok.

Heikens, A., Panaullah, G.M., & Meharg, A.A. (2007). Arsenic behavior from groundwater and soil to crops: impacts on agriculture and food safety. Reviews on Environmental Contamination and Toxicology 189, 43–87.

Islam, F.S., Gault, A.G., & Boothman, C., et al. (2004). Role of metal reducing bacteria in As release from Bengal delta sediments. Nature 430, 68–71.

Kar, S., Maity, J.P., Jean, J.S., Liu, C.C., Nath, B., Yang, H.J., & Bundschuh, J. (2010). Arsenic-enriched aquifers: occurrences and mobilization of arsenic in groundwater of Ganges Delta Plain, Barasat, West Bengal, India. Applied Geochemistry 25(12), 1805–1814.

Kim, K., Kim, S.H., Jeong, G.Y., & Kim, R.H. (2012). Relations of As concentrations among groundwater, soil, and bedrock in Chungam, Korea: implications for As mobilization in groundwater according to the As-hosting mineral change. Journal of Hazardous Materials 15, 25–35.

Li, G., Sun, G. X., Williams, P.N., Nunes, L., & Zhu, Y.G. (2011). Inorganic arsenic in Chinese food and its cancer risk. Environmental International 37(7), 1219–1225.

Liaoa, V.H.C., Chua, Y.J., Sua, Y.C., et al. (2011). Assessing the mechanisms controlling the mobilization of As in the As contaminated shallow alluvial aquifer in black foot disease endemic area. Journal of Hazardous Materials 197, 397–403.

Lombi, E., Sletten, R.S., & Wenzel, W.W. (2000). Sequentially extracted arsenic from different size fractions of contaminated soils. Water Air and Soil Pollution 124, 319–32.

Ma, J.F., Yamaji, N., Mitani, N., & Xu, X.Y., et al. (2008). Transporters of arsenite in rice and their role in arsenic accumulation in rice grain. Proceedings National Academy Science USA 105, 9931–9935.

Mandal, B.K., & Suzuki, K.T. (2002). Arsenic round the world: a review. Talanta 58(1), 201–235.

Martinez, V.D., Vucic, E.A., Becker-Santos, D.D., Gil, L., & Lam, W.L. (2011). Arsenic exposure and the induction of human cancers. Journal of Toxicology, 43, 1287.
Meharg, A.A., & Whitaker, J.H. (2002). Arsenic uptake and metabolism in arsenic resistant and non resistant plant species - review. New Phytologist 154, 29–43.

Mukherjee, A., Fryar, A., & O’shea, B.M. (2009). Major occurrences of elevated arsenic in groundwater and other natural waters. In: Henke K (ed) Arsenic: environment chemistry, health threats and waste treatment, Ch. 6. Wiley, New York.

Mukhopadhyay, D., & Sanyal, S.K. (2000). Effect of phosphate, arsenic and farmyard manure on the changes of the extractable arsenic in some soils of West Bengal and reflection thereof on crop uptake. Proceedings National Seminar on Developments in Soil Science – 2000, Indian Society of Soil Science, Nagpur, December 28-31, 2000.

Nguyen, K. P., & Itoi, R. (2009). Source and release mechanism of arsenic in aquifers of the Mekong delta, Vietnam. Journal of Contaminant Hydrology 103(1-2), 58-69.

Nickson, R.T., McArthur, J.M., & Burgess, W.G., et al. (1998). As poisoning of Bangladesh groundwater. Nature 395, 338.

Norton, G.J., Deacon, C.M., & Xiong, L.Z., et al. (2010). Genetic mapping of the rice ionone in leaves and grain: Identification of QTLs for 17 elements including arsenic, cadmium, iron and selenium. Plant Soil 329, 139–153.

Sahoo, P.K., Zhu, W., Kim, S.H., Jung, M.C., & Kim, K. (2013). Relations of arsenic concentrations among groundwater, soil and paddy from an alluvial plain of Korea. Geosciences Journal, 3, 363–370.

Schreiber, M.E., Simo, J.A., & Freiberg, P.G. (2000). Stratigraphic and geochemical controls on naturally occurring arsenic in groundwater, eastern Wisconsin, USA. Hydrogeology Journal 8, 161-176.

Selim Reza, A.H.M., Jena, J.S., & Yang, H.J., et al. (2010). Occurrence of arsenic in core sediments and groundwater in the Chapai-nawabgang District, northwestern Bangladesh. Water Research 44, 2021–2037.

Smedley, P.L., & Kinniburgh, D.G. (2002). A review of source, behavior and distribution of arsenic in natural water. Applied Geochemistry 17, 517–568.

Smith, A.H., Hopenhayn-Rich, C., & Bates, M.N., et al. (1992). Cancer risks from arsenic in drinking water. Environmental Health Perspectives. 97, 259–267.

Takahashi, Y., Minamikawa, R., Hattori, K.H., Kurishima, K., Kihou, N., & Yuita, K. (2004). Arsenic behaviour in paddy fields during the cycle of flooded and non-flooded periods. Environmental Science and Technology 38, 1038–1044.

Takamatsu, T., Aoki, H., & Yoshida, T. (1982). Determination of arsenate, arsenite, monomethylarsonate and dimethylarsinate in soil polluted with arsenic. Soil Science 133, 239–246.

Walter, J.F., Wenzel, W.W. (2002). Arsenic transformation in the soil–rhizosphere–plant system: fundamentals and potential application to phytoremediation. Journal of Biotechnology 99, 259–278.

Williams, M., Fordyce, F., Pajitprapapon, A., & Charoenchaisri, P, (1996). Arsenic contamination in surface drainage and groundwater in part of the southeast Asian tin belt, Nakhon Si Thammarat Province, southern Thailand. Environmental Geology 27, 16–33.

Williams, P.N., Villada, A., & Deacon, C. et al. (2007a). Greatly enhanced arsenic shoot assimilation in rice leads elevated grain levels compared to wheat and barley. Environment Science and Technology 41, 6854–6859.

World Bank (2005). Environment and social unit—South Asia region. Towards a
more effective operational response. Arsenic contamination of groundwater in south and east Asian countries volume II technical report. Environmental Study (Report No 31303), The World Bank.

Zhao, F.J., McGrathMc, S.P., & Meharg, A.A. (2010). Arsenic as a food chain contaminant: mechanisms of plant uptake and metabolism and mitigation strategies. *Annual Reviews on Plant Biology* 61, 535–559.