

Arsenic contamination and its toxicity in algae

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Abstract: Arsenic, a metalloid, is considered nonessential for human beings. However, excess amount of As is extremely toxic, leading to many pathological conditions that are consistent with oxidative damage, carcinogenic and mutagenic properties. Arsenic compounds widely enter in environment through food chain and water supply and excess of them producing worldwide pollution threat. Due to this, millions of people around the world are suffering from arsenic toxicity which leads to major health problems including liver damage, cancer, diabetes, skin lesions and hyperkeratosis. In water bodies the high amount of arsenic compounds enter in the algal cells. After accumulation arsenic interferes with algal metabolic processes which lead to impairment of photosynthesis, respiration, depletion in protein, carbohydrate, lipid and cell viability. Higher amount of arsenic also induced the generation of reactive oxygen species (ROS). These ROS can easily oxidize different macromolecules present in the algal cells. To counteract arsenic toxicity, algae have evolved complex protective mechanisms to mitigate the deleterious effects and repair the damage caused by ROS.

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1. Introduction

Arsenic is a ubiquitous metalloid which is found in air, soil, and water bodies (Duker et al., 2005). Due to its potential toxicity and carcinogenic properties, it poses the greatest threat to living organisms including human beings (Abernathy et al., 1999). The long term exposure to arsenic may cause severe diseases like diabetes, skin cancer, lung cancer, bladder cancer, hepatocellular carcinoma, hyperpigmentation, black foot disease, and melanokeratosis (Brown and Ross, 2002; Liu et al., 2001; Mukherjee et al., 2003; Saha, 2003; Wai et al., 2003). Arsenic contamination in water bodies mainly occurs due to natural processes and anthropogenic activities. The major sources of arsenic contaminants are parent rock, volcanic eruption, industrial and household waste discharge and fuel combustion (Adriano, 2001). Excessive use of arsenic compound in agriculture and forestry practices (as insecticide, herbicide, rodenticide and fungicide) is additional source of arsenic contamination to soil and water (Hathaway et al., 1991). Various sources of arsenic contamination are summarized in figure 1.

Arsenic concentration in natural water ranges from 0.5 to 5,000 μgL^{-1} (Smedley and Kinniburgh, 2002). Environmental arsenic exists in both organic and inorganic form. Inorganic arsenic forms are generally toxic whereas the organic forms are considered as non toxic (Gochfield, 1995). Inorganic arsenic usually exists in two forms namely, arsenite, As(III), and arsenate, As(V), which are interconverted through redox and methylation reactions (Duker et al., 2005; Eisler, 2004). Several studies have been conducted to understand the interaction of arsenic with

various plants e.g. rice, fern, beans, spinach, tomato and red clover (Chakrabarty et al., 2009; Shri et al., 2009; Srivastava et al., 2005; Stoeva et al., 2003; Shaibur and Kawai, 2010; Barrachina et al., 1995; Mascher et al., 2002). However, studies concerning the impact of arsenic stress on algal system are relatively few. Unfortunately, limited efforts have been made to understand the response of microalgae to arsenic stress. Therefore, the present article summarizes the responses of microalgae to arsenic.

Arsenic contamination in natural water

Arsenic contamination in drinking water is a global concern particularly in South East Asia. In recent years arsenic level indiscriminately increases due to anthropogenic activities. In contaminated water high amount of inorganic arsenic is found, which mainly exist in As(III) and As(V) forms however small amount of DMA (dimethylarsenic acid), MMA (monomethylarsonic acid) and methylated forms also found. Different forms of arsenic found in aqueous system are given in table 1. As(III) is generally considered as most mobile and biologically toxic form. As(III) dominates under anaerobic condition whereas As(V) found stable under aerobic condition but more common than As(III) species (Duker et al., 2005). Arsenic accumulation in water bodies generally take place due to adsorption/desorption or oxidation/reduction process. In water sediments under oxidized conditions, arsenic may have precipitated by iron and manganese oxyhydroxide thus remain unavailable or available in less amount in water (Smedley and Kinniburgh, 2002; Kneebone et al., 2002; Nicholas et al., 2003). On the onset of reducing

condition, the reduction of As rich oxyhydroxide takes place that can leads to the release of arsenic, reduced oxyhydroxide ion, iron and manganese. In water ecosystem, microorganisms play active role in transformation of As into several biological forms.

Oxidation of As(III) to As(V) also catalyzed by microorganisms like bacteria and algae (Johnson, 1972; Myers et al., 1973; Andreae and Klumpp, 1979; Sanders and Windom, 1980; Sanders, 1983).

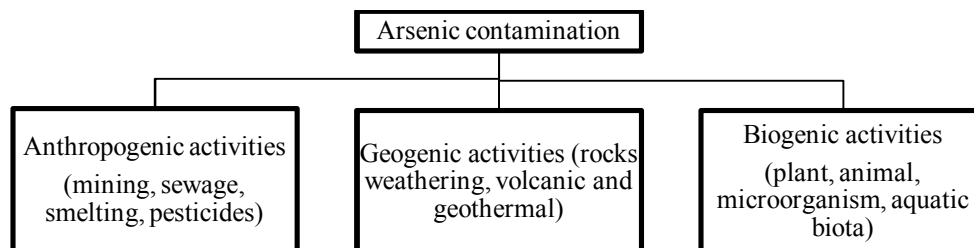


Figure 1. Sources of arsenic contamination in soil and water.

Effect of As on algae

Algae, the key primary producers found in an array of habitats ranging from fresh water to saline water, from hot spring to iceberg (Richmond et al., 2003; Leon-Banares, 2004). Any change due to the discharge of chemicals, such as, As and other metals in the aquatic environment is first noticed and encountered by these tiny organisms. Therefore, in water ecosystem, algae may serve as a useful biomarker of arsenic exposure and for stress and metabolic studies (Rachlin and Grosso, 1993; Lustigman et al., 1995).

Previously the interaction of algae with As has been reviewed by several researchers, including Rai et al. (1981), Yamaoka et al. (1992), Genter (1996), Abd-El-Monem et al. (1998), Mishra et al. (2008) and Bhattacharya and Pal (2010). As(V) is chemically similar to phosphate (PO_4^{3-}), and readily taken up by phytoplankton by phosphate transporters (Sanders and Windom, 1980). It competes with phosphate in the formation of organic esters and upset the metabolic activities that require phosphorylation reactions. Plants and algae have ability to uptake more arsenate rather than PO_4 under PO_4 limited conditions (Knauer and Hemond, 2000). However, at high PO_4 concentration, the transport of As become reduced (Farhadi et al., 2013). The binding of As(III) to sulfhydryl groups of enzymes causes disruption of enzyme structure leading to enzyme inhibition (Cox, 1995). Additionally, arsenic toxicity causes lipid peroxidation, protein and enzyme oxidation, GSH

depletion, DNA oxidation and further generates reactive oxygen species (ROS) like, superoxide radical, hydroxyl radical, singlet oxygen etc (Wang et al., 1996; Lynn et al., 1997; Sharma et al., 2007). These ROS can easily oxidize various macromolecule of the cell (Mascher et al., 2002) and hence disrupts the dynamic equilibrium between the prooxidants and antioxidants and develop the condition known as oxidative stress (Scandalios, 1993).

It has been suggested that high level of arsenic can inhibit the growth rate of algae (Rai et al., 1981; Rana and Kumar, 1974; Whitton, 1970; Stauber and Florence, 1989; Genter et al., 1987, 1988; Genter, 1996). Arsenate induces a fluidization of liposome membrane of algal cell thus enhances the transport of toxicant across the membrane of algal cell and finally resulted into cell death (Tuan et al., 2008). Studies concerning the impact of As on algae found that the higher concentrations of As in water have been shown to sharply reduce the cell viability (Tuan et al., 2008) and to interfere with pentose phosphate pathway which leads to impairment in photosynthesis of alga (Srivastava et al., 2009; Zutshi et al., 2014). In addition to this, a significant reduction in protein and carbohydrate content of *Phormidium laminosum* and *Scenedesmus acutus* treated with different concentrations of As was also noticed (Abd-El-Monem et al., 1998; Bhattacharya and Pal, 2010). Moreover, the alleviation in MDA and H_2O_2 level of algal cells has been reported (Srivastava et al., 2009; Bhattacharya and Pal, 2010).

Table 1. Different forms of arsenic in aquatic environment.

Form	Arsenic compounds
Inorganic trivalent	Sodium arsenite, arsenic trioxide, arsenic trichloride
Inorganic pentavalent	Arsenic pentaoxide, arsenic acid, arsenates (calcium arsenate, lead arsenate, sodium arsenate)
Organic	Methylarsenic acid, arsanilic acid, dimethylarsinic acid and arsenobetaine.

To overcome the harmful effects of ROS, algal cells have developed a highly complex and intertwined antioxidant defense system which includes both enzymatic (superoxide dismutases, catalases, peroxidases) and non-enzymatic (ascorbate, glutathione, carotenoids and α -tocopherol) antioxidants (Pinto et al., 2003; Tripathi and Gaur, 2004; Tripathi et al., 2006). These components help in the re-establishment of redox-homeostasis by direct scavenging of ROS.

Enzymatic antioxidants

Enzymatic antioxidants actively work against ROS and neutralize their effect by converting them into less harmful products. These include superoxide dismutase, catalase and ascorbate peroxidase.

Superoxide dismutase

Superoxide dismutase (SOD) is one of the important antioxidant enzymes which act as first line of defense against ROS mediated damage (Bannister et al., 1987). SOD is a multimeric metalloenzyme that catalyze the conversion of superoxide radical ($O_2^{\bullet-}$) to dioxygen and H_2O_2 (Hassan, 1989). SOD enzymes contain metal ion cofactors that, depending on the isozyme, can be copper, zinc, manganese or iron. SODs have been categorized into three main types found: copper zinc superoxide dismutase (CuZnSOD), manganese superoxide dismutase (MnSOD) and iron superoxide dismutase (FeSOD). The CuZnSOD is found in cytosol, plastid, chloroplast and peroxisome. In plant, chloroplasts CuZnSOD is known to be the major form. However some plants also contain FeSOD in the chloroplasts (Kurepa et al., 1997). MnSOD is found in the mitochondria however its activity has also been reported in the chloroplast (Allen et al., 2007).

Catalase

Catalase (CAT) is a tetrameric heme containing enzyme that catalyze the dismutation of two H_2O_2 molecules to water and molecular oxygen (Hunt et al., 1998). CAT is found in all aerobic organisms and known to be localized in peroxisomes, glyoxisome, cytosol and in mitochondria. Catalase has low affinity for its substrate and it is found in the millimolar concentration range (Foyer and Noctor, 2000). This enzyme does not consume cellular reducing equivalents therefore known to be unique among H_2O_2 scavenging enzymes (Mallick and Mohn, 2000).

Ascorbate peroxidase

Ascorbate peroxidase (APX) are the main enzymes in the chloroplast that scavenges H_2O_2 , because catalase is absent in chloroplasts. A micromolar range of APX is found in the mitochondria, chloroplasts, cytosol, peroxisomes and apoplast. APX shows high affinity to its substrate and utilize ascorbate as an e- donor (Asada, 1992). APX neutralize ROS by reducing H_2O_2 into H_2O and

monodehydroascorbate (MDA) (Noctor and Foyer, 1998). In chloroplast two types of APX, stroma-localized forms (sAPX) and thylakoid-bound (tAPX), are found. Along with PSI-associated SOD, tAPX acts as the first defense against ROS (Asada, 2006).

Non-enzymatic antioxidants

Non-enzymatic antioxidants also play a vital role to counteract the damage caused ROS. These non-enzymatic antioxidants scavenge the ROS to protect the algal cell. These include glutathione reductase, carotenoids and ascorbic acid.

Glutathione reductase

Glutathione reductase (GR) is a potential antioxidant, predominantly located in chloroplast however trace amount has also been located in mitochondria, cytosol and other plastids. The enzyme glutathione reductase catalyzes the reduction of glutathione disulfide (GSSG) back to glutathione (GSH) by utilizing electron from NADPH (Noctor and Foyer, 1998; Filomeni et al., 2002). GR play an important role against oxidative stress in almost all organisms (Pinto et al., 2003). Under oxidative stress, glutathionylation helps in preventing proteolysis, regulating gene transcription and cellular redox state, and changing protein turnover (Foyer and Noctor, 2000; Rouhier et al., 2008).

Carotenoids

Carotenoids are derivatives of geranylgeranyl diphosphate found in chloroplast. Carotenes (α -carotene, β -carotene) and xanthophylls (zeaxanthin, violaxanthin, neoxanthin) are the two types of carotenoids. Carotenes consist of linear or cyclic (β -ionone or ϵ -ionone rings) hydrocarbons whereas xanthophylls are derived from carotenes (Siefermann-Harms, 1987). Carotenoids, known to play vital role in photosynthesis and photoprotection, are synthesized by plants, algae, some bacteria and fungi. In algae and plants, most of the carotenoids are found in the chlorophyll binding proteins embedded in the thylakoid membrane (Baroli and Niyogi, 2000). They function in stabilizing the membrane, harvesting light energy, inhibiting lipid peroxidation, and quenching a triplet sensitizer (chl^3) and singlet oxygen (Baroli and Niyogi, 2000).

Ascorbate (Ascorbic acid)

Ascorbic acid or vitamin C is an important, hydrophilic antioxidant mainly located in chloroplast but its small amount is also present in mitochondria, cytosol and in nucleus (Asada, 1999; Foyer and Noctor, 2005). It is normally produced outside the chloroplast but stored in chloroplast. Ascorbic acid has ability to scavenge H_2O_2 and free radicals (hydroxyl radicals, singlet oxygen) (Smirnoff and Wheeler, 2000). Ascorbic acid generally works as substrate for APX and finally converted into dehydroascorbic acid.

In this process, APX utilize two molecules of Ascorbic acid as e- donor and catalyze the reduction of H₂O₂ into H₂O (Noctor and Foyer, 1998).

Conclusion

This review has provided a insight into the processes taking place when algal cells confront with arsenic stress. It also explained the role of antioxidant defense system in algae against arsenic. Algae have been used as biomarker tool against metal stress in several studies. Interaction of arsenic with algae leads to oxidative damage to algal cells. Antioxidant enzymes such as SOD and APX remove the superoxides and peroxides, so that they remain unavailable for reaction with As. Non enzymatic antioxidants help in scavenging the remaining reactive species that escaped enzymatic degradation. Since fewer studies were conducted to understand the effect of arsenic on algae therefore further studies will help to deeply understand the mechanisms of tolerance.

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