Arsenic Accumulation in Rice (*Oryza sativa*): An Overview

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Abstract— *Accumulation of arsenic (As) in rice is highly variable across the globe and depends on a number of factors. Presently, there are no set standards on what can be considered as a regulatory concentration in rice, yet studies related to As toxicity to humans are abundant. This study is an overview of the range of As concentrations in rice grown globally and examples of the relevant contributing factors. Based on this overview, As concentration in rice can range from 0.01 to 0.8 mg kg^{-1}, and some of the factors that can cause it are growing conditions, varieties, soils and water quality.*

Keywords— rice, arsenic, accumulation, soils, uptake, global.

I. INTRODUCTION

Rice (*Oryza sativa*) is one of the major staple food crops in the world, with daily consumption of up to 0.5 kg (dry weight) per adult per day in Asian countries (FAO 2002). In the United States alone, approximately 4.1 million metric tons of rice was consumed in 2014/2015 (Statista 2015). Rice in the U.S. is primarily grown in California and the southern states of Arkansas, Texas, Louisiana, and Mississippi, with approximately 50 and 20 % of total rice production coming from Arkansas and California, respectively (Zavala and Duxbury 2008). Of all grain crops, rice accumulates the highest amount of arsenic (As), largely because of the high availability of arsenic under anaerobic (reduced oxygen) soil conditions (Marin et al. 1993; Williams et al. 2007 a). In addition, flooded (paddy) rice is more efficient in As uptake compared to other small grains like wheat and barley. This is attributed to (i) arsenite ($As_xO_y^{z-}$) mobilization and its enhanced bioavailability to rice plants under anaerobic conditions (Xu et al. 2008), and (ii) the ability of arsenite to share the highly efficient silicon (Si) uptake pathway in rice (Ma et al. 2006; Zhao et al. 2009) (Fig. 1). It has been shown that by maintaining a steady aerobic state throughout the entire growing season was a highly effective way to reduce As accumulation in rice (Xu et al., 2008), however, this is not a practical solution. The same mechanisms that sequester Si in rice can also transport and incorporate arsenic into the plant because the metalloid readily accumulates when rice is grown in arsenic rich flooded soils. Among the non-hyperaccumulators of As, rice ranked highest in the xylem transport (Zhao et al. 2009).

The toxicity of As will depend on its chemical speciation. Methylated As compounds are considered less toxic than the inorganic forms (Schoof et al. 1999). While the methylated species (dimethylarsinic acid) can account up to 80% of the total As, it is predominantly present in the grain; whereas, inorganic As is the predominant species in rice straw (Abedin et al. 2002).While the pathway of As methylation in microorganisms has been well studied, the genes responsible for As methylation in rice and other higher plants have not been identified (Zhao et al. 2009).

II. MATERIAL AND METHODS

This study is a synthesis of meta-data related to As concentration contained in rice from around the world. Over a dozen peer-reviewed studies were integrated in developing the global As status observed in rice.

III. ARSENIC CONCENTRATION IN RICE

Mehrag et al. (2009) conducted a global survey of ~900 samples of polished market white rice, the results ranged in total As from 0.01 to 0.82 mg kg^{-1}, with a mean and median of 0.15 and 0.13 mg kg^{-1}, respectively.Zavala and Duxbury (2008) used comprehensive data sets from different regions around the world including Asin Asia (Bangladesh, China, India, Pakistan, Sri Lanka, and Thailand), Europe (Spain and Italy), and the U.S.to estimate what can be considered Asa "normal" range for arsenic in rice grain. Based on their study, 50% of the data, between 25th and 75th percentiles were in the range from 0.082 to 0.202 mg As kg^{-1}, which can be considered the global "normal" range for arsenic in rice. The majority of Asian rice had an arsenic concentration <0.098 mg kg^{-1} suggesting that the rice was grown in environments with low soil arsenic levels. In contrast, 40% of the rice from the U.S. contained arsenic concentrations above the "normal" range suggesting production in soils containing high arsenic concentrations. Zavala and Duxbury (2008) showed that mean arsenic concentration in rice from Texas was 0.258 ±0.117 mg kg^{-1} and Arkansas was 0.196 ±0.095 mg kg^{-1}. The mean arsenic concentration of rice from California of 0.133 ±0.047 mg kg^{-1} was significantly less than that from Texas or Arkansas, and similar in range to the market basket survey results of Williams et al. (2007 b). Contrary to Bangladesh, where arsenic contaminated irrigation water has been identified as the cause for high arsenic concentration in rice grain, elevated arsenic concentrations in U.S. rice have been linked to use of arsenic containing compounds on historic cotton fields and therefore soil contamination (Reed and Sturgis 1936). Even though the commercial applications of most arsenic containing chemicals were banned in the 1980s and 1990s, more than 30,000 tons of arsenic compounds in the form of arsenic acid, Ca arsenate, and organo-arsenicals were applied to more than 3 million ha of land in the southern cotton farming states (Peters and Blackwood 1977), so it is quite possible that legacy arsenic residues still remain in those environments. Arsenic concentrations can vary significantly in rice varieties cultivated in the U.S.(Fig. 2); however, levels of inorganic arsenic are well below the levels that would result in any immediate or short-term health risks (Hamburg 2013). Currently, no U.S. regulatory limit on the amount of arsenic exists in any solid food product. In 2002, U.S.Environmental Protection Agency established a new drinking water standard of 10 ppb replacing the previous 50 ppb criteria in an effort to reduce exposure to the metal. At that time, water was considered a greater source of arsenic exposure than food.

IV. FACTORS AFFECTING ARSENIC CONCENTRATION IN RICE

4.1 Growing conditions

Flooded (paddy) rice is more efficient in arsenic uptake compared to other cereal crops because anaerobic conditions in flooded soil leads to arsenite mobilization and thus enhanced bioavailability to rice plants compared to upland rice grown under aerobic conditions.

4.2 Pesticide application

Many rice fields in south central U.S. where 75% of U.S. rice is grown have high levels of arsenic due to historical use of pesticides.

4.3 Water

Irrigation water used to flood rice fields can contain high levels of arsenic. For example, high arsenic content in rice grown in Bangladesh is related to the very high levels of arsenic in groundwater.

4.4 Variety/Genotype

The arsenic content of brown rice is generally greater than that of white rice and almost twice that of basmati rice. This discrepancy among varieties is expected because arsenic disproportionately accumulates in the rice bran and husk, which are polished off in almost all commercial white rice productions.

4.5 Natural occurrence

Some soils naturally have higher arsenic levels than others. Globally, soils containing 5-7 mg kg^{-1} (ppm) can be considered as "uncontaminated" soils (Smith et al. 1998; Kabata-Pendias and Pendias 2001).

4.6 Antibiotics & Fertilizers

Drugs containing arsenic are used in livestock production for various reasons. Manure from these livestock can contain concentrated amounts of arsenic that can be taken up by rice when added to rice fields.

4.7 Divalent cations

Calcium (Ca) and magnesium (Mg) ions in soils are reported to enhance arsenic adsorption. Enhanced arsenic retention with Ca and Mg may include cation bridging complexes between negatively charged clays and arsenate ions (Fakhreddine et al. 2015).

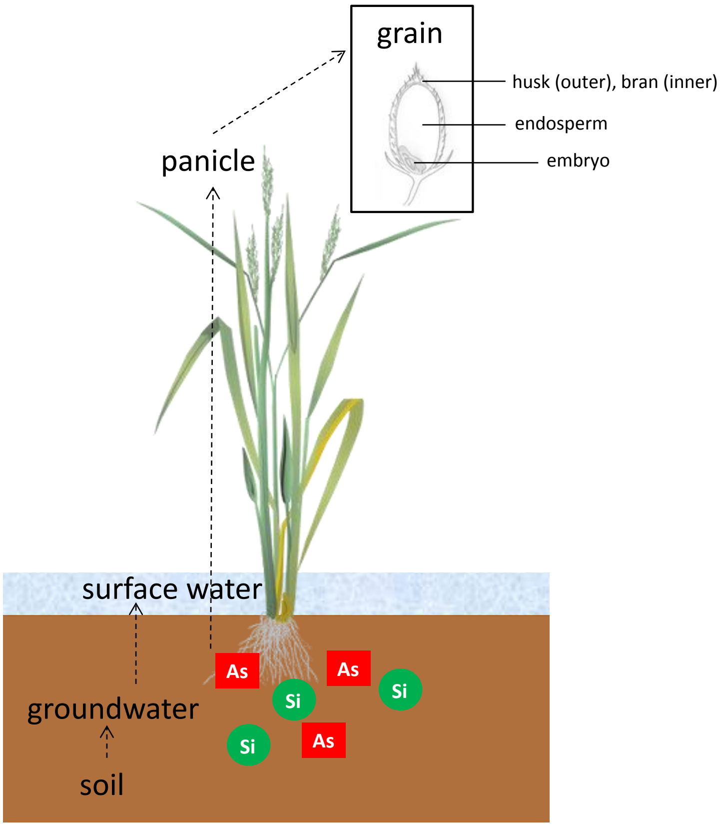

FIG.1 RICE READILY ACCUMULATES ARSENIC (AS) COMPARED TO OTHER FOOD PLANTS BECAUSE AS RICE GROWS, THE ROOTS TAKE UP SILICON (Si) TO FORTIFY THE PLANT, AND THE SAME MECHANISM TRANSPORTS ARSENIC PRESENT IN THE WATER AND SOIL. ARROWS INDICATE THE PATHWAY OF ARSENIC FROM SOIL TO GROUNDWATER, AND VIA THE ROOTS TO THE PANICLE, AND FINALLY TO THE GRAIN.

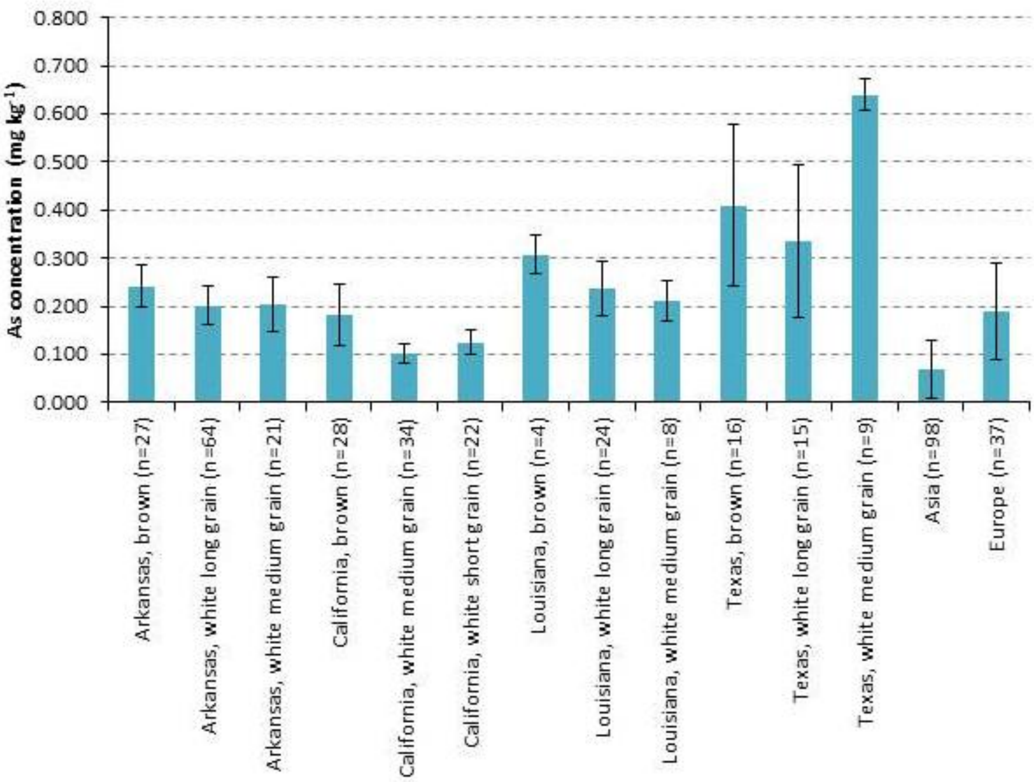

FIG. 2 ARSENIC CONCENTRATION IN DIFFERENT VARIETIES OF RICE GROWN IN UNITED STATES. DATA SUMMARIZED FROM USFDA (2013), AND ZAVALA AND DUXBURY (2008).

ACKNOWLEDGEMENTS

We wish to thank the University of Florida-Institute of Food and Agricultural Sciences for their continued support towards Sustainable Agriculture Research.

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