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Review article

Arsenic in cooked rice foods: Assessing health risks and mitigation options

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ABSTRACT

Human exposure to arsenic (As) through the consumption of rice (*Oryza sativa* L.) is a worldwide health concern. In this paper, we evaluated the major causes for high inorganic As levels in cooked rice foods, and the potential of post-harvesting and cooking options for decreasing inorganic As content in cooked rice, focusing particularly on As endemic areas. The key factors for high As concentration in cooked rice in As endemic areas are: (1) rice cultivation on As-contaminated paddy soils; (2) use of raw rice grains which exceed 200 μg kg^{-1} of inorganic As to cook rice; and (3) use of As-contaminated water for cooking rice. In vitro and in vivo methods can provide useful information regarding the bioaccessibility of As in the gastrointestinal tract. Urinary levels of As can also be used as a valid measure of As exposure in humans. Polishing of raw rice grains has been found to be a method to decrease total As content in cooked rice. Sequential washing of raw rice grains and use of an excess volume of water for cooking also decrease As content in cooked rice. The major concern with those methods (i.e. polishing of raw rice, sequential washing of raw rice, and use of excess volume of water for cooking rice) is the decreased nutrient content in the cooked rice. Cooking rice in percolating water has recently gained significant attention as a way to decrease As content in cooked rice. Introducing and promoting rainwater harvesting systems in As endemic areas may be a sustainable way of reducing the use of As-contaminated water for cooking purposes. In conclusion, post-harvesting methods and changes in cooking practices could reduce As content in cooked rice to a greater extent. Research gaps and directions for future studies in relation to different post-harvesting and cooking practices, and rainwater harvesting systems are also discussed in this review.

1. Introduction

Arsenic (As) ingestion in humans through various food sources is a worldwide health issue. Millions of consumers around the world may have high As ingestion from imported rice and rice-based foods, due to the rapid expansion of the global food trade (Heitkemper et al. 2009; Islam et al., 2017a; Nachman et al. 2018). Rice is a major dietary source of inorganic As, particularly for people in As endemic areas (Huang et al. 2015; Kwon et al. 2017; Meharg et al. 2008). Numerous investigations have demonstrated that rice grains in As endemic areas contain over 90% of inorganic As (i.e. arsenite (As(III)) and arsenate (As(V))), and the rest is the organic As species (dimethylarsinic acid (DMA(V)) and monomethylarsonic acid (MMA(V))) which are less toxic than the inorganic As species (Halder et al. 2014; Meharg and Rahman 2003). In the case of As uptake mechanisms in rice plants, both As(III) and As(V) are acquired by $Si(OH)_4$ and PO_4^{3-} transporters, respectively (Ma et al. 2008; Zhao et al. 2009). It has been suggested that DMA(V) and MMA(V) are also taken up by $Si(OH)_4$ transporters (Li et al. 2009).

Intake of inorganic As is a recognized cause of cancers of the skin, lungs, and bladder and a potential cause of non-cancerous health outcomes including respiratory, cardiovascular, neurological, and metabolic diseases (Sanchez et al. 2016). Recent health risk assessments reported that the consumption of As-containing rice and rice-based foods (e.g. cakes, cereals, crackers, and noodles) led to increased cancer

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risks, especially in subpopulations such as infants and children (Fakhri et al. 2018; Islam et al. 2016; Lin et al. 2015; Rahman et al. 2014; Sofuoglu et al. 2014). In order to minimize inorganic As exposure during the transition stage to solid foods, infants should not consume rice products unless they are specifically mentioned as being safe for consumption (Carey et al. 2018; Signes-Pastor et al. 2018). As a result of these health issues, the European Union (EU) has recommended a maximum level of 100 μg kg^{-1} for inorganic As in rice-based products intended for young children (EC 2015). The World Health Organization (WHO) has also set a permissible level of inorganic As in polished rice grains for adults at 200 μg kg^{-1} (WHO 2014). Apart from the public health impacts of As-related chronic diseases, As ingestion in humans may also create socio-economic consequences for the victims, as well as their families (Meharg et al. 2009; Rahman et al. 2018).

Recent review articles have shown that the total As content in rice grains is dependent on paddy soil properties, microbial activities, and rice genotypes (Chen et al. 2017; Kumarathilaka et al. 2018a; Kumarathilaka et al. 2018b; Senanayake and Mukherji 2014; Zhao et al. 2009). The effects of different physico-chemical and biological methods on reduced As levels in rice grains have been extensively investigated over the past decade. For example, alternative water management practices such as intermittent and aerobic irrigation regimes have been found to decrease the availability of As in the paddy soil-water system (Mukherjee et al. 2017; Rahaman and Sinha 2013). Supplementation of nutrients (i.e. Si, PO_4^{3-}, S, and N) and amendments (i.e. Fe and Mn) into As-contaminated paddy soils may decrease the accumulation of As in rice grains (Farrow et al. 2015; Li et al. 2019; Senanayake and Mukherji 2014; Seyfferth et al. 2016). In addition, biological methods (i.e. inoculation of microorganisms and transgenic approaches) can be used to decrease the As accumulation in rice grains (Gustave et al. 2018; Li et al. 2016; Meng et al. 2011). However, only a limited number of studies have focused on the effects of post-harvesting technologies and cooking methods to decrease As content in raw and cooked rice grains in As endemic areas. Taking this into account, this review article discusses possible causes for high levels of As in cooked rice and potential post-harvesting and cooking techniques to decrease As levels in cooked rice. In addition, in vivo and in vitro methods which are used for evaluating the bioavailability and bioaccessibility of As species in cooked rice will be discussed. Research gaps and future research directions to reduce As ingestion in humans through cooked rice are also highlighted.

2. Major causes for high As levels in cooked rice

The key causes related to high As levels in cooked rice in As endemic areas are use of As-contaminated water for cooking and As contaminated rice grains. The source of cooking water has gained significant attention with regard to high As levels in cooked rice (Ackerman et al. 2005; Devesa et al. 2008; Signes–Pastor and Carbonell–Barrachina, 2012). People living in As endemic areas, particularly in Asian regions, largely rely on As-contaminated groundwater as their cooking water (Bae et al. 2002; Ohno et al. 2007; Pal et al. 2009; Rahman and Hasegawa 2011). O'Neill et al. (2013) estimated that the community using As-contaminated water (> 50 μg L^{-1}) for cooking rice in Prey Veng, Cambodia, consumed inorganic As up to 24 times more than the previous provisional tolerable daily intake value (PTDI) of 2.1 μg kg^{-1} of body weight day^{-1} which was withdrawn in 2010 by the joint FAO/WHO expert committee on food additives (JECFA). Roychowdhury (2008) demonstrated that in the Murshidabad and Naida districts in India, the use of As-contaminated cooking water (0.001–0.200 mg L^{-1}) has led to an approximate two-fold increase in As content in cooked rice compared to raw rice.

The As level in cooked rice is also dependent on the As concentration in raw rice grains. As stated in the introduction, consumption of cooked rice may increase the potential harm to human health if the raw rice exceeds the recommended maximum level for inorganic As (Liang et al. 2010; Roychowdhury et al. 2003; Smith et al. 2006). Worldwide field and market-based surveys have also pointed out that raw rice containing high As content is available in the global market and therefore, people who have a higher rate of rice consumption may be vulnerable to As related health risks (Adomako et al. 2011; Liang et al. 2010; Signes-Pastor et al., 2016). While it has been stated that the major causes for high As content in raw rice are the use of As-contaminated water for irrigating rice fields and mining activities which may increase the As concentration in nearby paddy soils due to the dry and wet depositions of As (Kwon et al. 2017; Shrivastava et al. 2017).

3. Accessing the health risks via consumption of cooked rice

The bioaccessibility of As in humans refers to the fraction of dissolved As, due to gastrointestinal digestion (Zhuang et al. 2016). Reproducible and cost-effective in vitro digestive methods are commonly used to assess As bioaccessibility of cooked rice in humans (Laparra et al. 2005; Sun et al. 2012; Zhuang et al. 2016). Basically, in vitro digestive methods can mimic both enzymatic and physico-chemical processes of the human digestive tract. Studies related to the simulated gastrointestinal digestion (i.e. using artificial gastrointestinal digestion) have shown that inorganic As species in cooked rice were largely bioaccessible in humans (63–99%) (Laparra et al. 2005). The undigested fraction of fiber in rice may undergo a microbial fermentation process in the colon. Sun et al. (2012) observed a decreased As bioaccessibility in the simulated colon (i.e. simulator of the human intestinal microbial ecosystem (SHIME) reactor). Calatayud et al. (2018) also found that the percentage of As bioaccessible fraction decreased from 36% to 14% (oral) and from 117% to 89% (colon), due to the presence of salivary bacteria along the gastrointestinal digestion.

There is very limited information available regarding the changes in As speciation in the human digestive system. Human gut microorganisms have previously been found to transform soil-derived As into methylated As species (Van de Wiele et al. 2010). Monomethylarsonate (MMA(III)), which is an intermediate product of As methylation, accounted for 10–14% in the simulated colon (Sun et al. 2012). The lethal dose (LD_{50}) of MMA(III) is 12 times lower than the LD_{50} value of the As (III) (Petrick et al. 2001; Tseng 2009). However, MMA(III) is more membrane permeable than both inorganic As species and the pentavalent organic As species (Drobná et al. 2005). Newly formed MMA(III) may become available for colon epithelial transport which increases health risks in humans (i.e. damage to DNA and enzyme inhabitation) (Drobná et al. 2005).

Urinary levels of As are also considered to be a valid measure of As exposure (i.e. through mass balance approach) via rice consumption (Banerjee et al. 2013; Davis et al. 2012; Meharg et al. 2014). After being ingested, As excretes through the kidneys as inorganic As and metabolites of methylated As species (i.e. MMA(V) and DMA(V)). Several studies have revealed that 40–60% of rice-derived total As excretes through the urine (He and Zheng 2010; Meharg et al. 2014). Correlation analyses have also confirmed that the consumption of As rich rice causes high As excretion in humans (Gilbert–Diamond et al. 2011; He and Zheng 2010). For example, Meharg et al. (2014) found that intake of 300 g of rice per day increased total As in urinary excretion by 730% in adults. In the case of As speciation, Meharg et al. (2014) demonstrated that DMA(V) was the dominant As species (90%) in the urine of individuals who has consumed rice containing inorganic As and DMA(V) at a ratio of 1:1. The end metabolite of As transformation in humans is DMA(V) (Li et al. 2013). Therefore, it is possible to have DMA(V) as the most prominent As species in human urine (Li et al. 2013). However, As excreted in urine does not reflect total bioavailability of As since As species can remain in the body but can also be excreted as feces.

A limited number of in vivo bioassays have been conducted as a surrogate of human exposure to assess the bioavailability and speciation of As by using animals such as swine and mice (Islam et al. 2017a;

Juhasz et al. 2006; Li et al. 2017). Islam et al. (2017b) administered As contained cooked rice (i.e. orally and via injection) to swine to measure the bioavailability of As in the swine blood. The results showed that approximately 90% As(III) and 85% As(V) were absorbed from the gastrointestinal tract. In contrast, organic As species had low bioavailability (~ 20% and 31% of MMA(V) and DMA(V), respectively) resulting in poor absorption by the gastrointestinal tract (Islam et al. 2017b). Similarly, Li et al. (2017) provided mice with a rice diet which was spiked with As species (2.5–15 μg of As(III), As(V), and DMA(V) per mouse) orally to evaluate the bioavailability of As and observed a strong positive correlation ($R^2 = 0.99$) between As levels in urinary excretion and cumulative As intake by mice. From a practical point of view, it is difficult to extend absolute bioavailability data of As to humans since the metabolism of As in humans and animals varies considerably. However, an estimation of As relative bioavailability may overcome this drawback to a certain extent.

4. Reducing As content in cooked rice

4.1. Post-harvesting and cooking practices

4.1.1. Polishing and storage of rice grains

Rice processing technologies may affect As levels in rice grains. Understanding of As accumulation and grain filling mechanisms is the most important aspect in this regard. Both inorganic and organic As species tend to accumulate in the bran layer of developing rice grains (Sun et al. 2008; Williams et al. 2009). Polishing of rice, by removing the bran layer, may thus reduce total As content in rice grains. Naito et al. (2015) demonstrated that total and inorganic As concentrations in white rice polished by removing 10% of bran by weight decreased total As contents by 61–66% and 51–70%, respectively, compared to those in brown rice. However, polishing of brown rice leads to the loss of important nutrients in the bran (Table 1). Liu et al. (2017) demonstrated that thiamine and riboflavin levels in rice grains decreased linearly when the degree of milling increased. During the 30 s of milling (ca. 9%) period, 58–65% of thiamine and 40–46% of riboflavin were lost from rice grains. Moreover, Mg, Mn, and Fe content decreased as the degree of milling increased (Liu et al. 2017). Paiva et al. (2016) also revealed that polishing of rice grains removed 90% of free phenolics from rice grains. Therefore, it is essential to study the optimum degree of milling and milling time to decrease As content and to maintain the level of nutrients in various rice genotypes.

Very limited studies have investigated the effects of storage conditions (i.e. storage time and storage temperature) on As content in rice grains. However, there is no conclusive evidence that storage temperature and storage time can influence the As concentration in rice grains. Naito et al. (2015) found that the concentration of total As, inorganic As, and DMA(V) in brown rice did not change when grains were kept at 15–25 °C for one year. Pizarro et al. (2003) also demonstrated that the concentration of total As and As species remained constant when rice grains were in the form of grain for more than six months at −20 °C. However, rice grains in the form of milled rice led to a reduced concentration of As(III), As(V), and MMA(V) when milled rice was stored for three months (Pizarro et al. 2003). Thus, further investigations are required to confirm whether storage conditions affect As concentrations in rice grains. In addition, it is worth studying the possible changes in As speciation in rice grains under varying storage conditions.

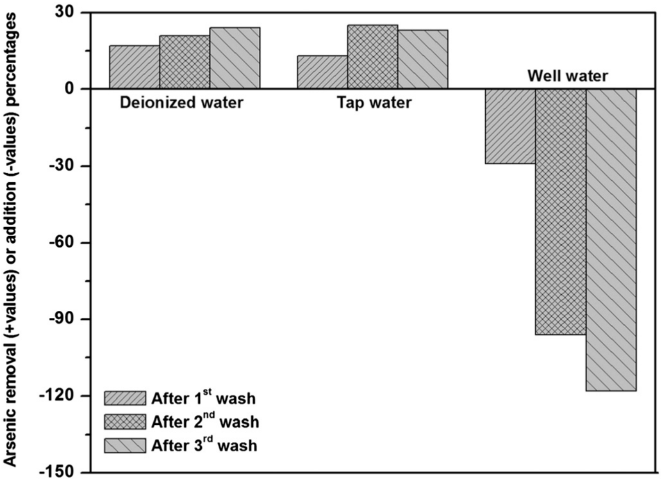

Fig. 1. The percentage removal (+ value) or addition (− value) of total As in sequentially washed rice in deionized water, tap water (28 μg L^{-1}), and well water (792 μg L^{-1}) compared to raw rice. Data adapted from Jaafar et al. (2018) and Naito et al. (2015).

4.1.2. Washing of raw rice

Modification of the practices at the kitchen level may reduce As content in cooked rice grains to a greater extent. Washing of rice before cooking has been recommended in numerous studies to reduce total As content in cooked rice (Liu et al. 2018; Raab et al. 2009). Naito et al. (2015) demonstrated that total As content in white rice and brown rice decreased to 81–84% and 71–83%, respectively, after washing 3 times with deionized water. Raab et al. (2009) also found that washing reduced total As content in basmati rice grains by 13–15%. However, Halder et al. (2014) demonstrated that washing of rice grains (i.e. at least 2–4 times) in the field experimental site in Tehatta-II block of Nadia District, West Bengal, India had a negligible effect on grain As content. According to Fig. 1, As free water or mildly As contaminated water can be used for sequential washing of rice to decrease As content of washed rice grains. Highly As-contaminated water leads to increased As content in washed rice grains, even after sequential washing (Fig. 1). The efficiency of As removal in respective sequential steps seems to be varied. The second and third washing steps under As free water had less effect on As removal from washed rice grains than that of the first washing step (Fig. 1).

Both positive and negative effects of washing of rice can be attributed to As concentrations in water and raw rice grains, the number of washing steps, and sample sizes. Washing time and mode of washing

Table 1
A comparison of As removing efficiencies and limitations of different post-harvesting and cooking practices.

Practice/method	Arsenic removing efficiency from cooked rice	Influence on nutrients	References
Polishing rice grains	~ 50–70% (in raw rice by removing 10% of bran)	Loss of nutrients	Naito et al. (2015)
Washing of raw rice	~ 13–84% (washing up to 2–4 times)	Loss of nutrients	Naito et al. (2015), Raab et al. (2009)
Cooking rice in excess water	~ 28–66% (when the ratio of deionized water: rice is 10–12:1)	Loss of nutrients	Carey et al. (2015), Gray et al. (2016)
Continual stream of percolating water	~ 96% of inorganic As from rice bran	Minimal effect on trace and macro nutrients elements. Neither vitamins or bioactive compounds were removed	Signes-Pastor, 2017

(i.e. mechanical or manual) may also influence the As content of washed rice grains. Further studies are needed to examine the effects of washing time and mode of washing on As content of washed rice grains. One negative effect of washing rice is that increasing the number of washing steps has led to a loss of minerals and vitamins in washed rice (Table 1). Jaafar et al. (2018) demonstrated that 3 step sequential washing removed 70% and 25% of Fe and Zn, respectively, from rice grains. Gray et al. (2016) also found that washing decreased folate, niacin, and thiamin by 77%, 57%, and 54%, respectively, from polished and parboiled rice, but not from whole grain brown rice. Therefore, the optimum number of washing steps and washing time for various rice varieties need to be set to decrease As content while reducing the loss of nutrients in washed rice grains.

4.1.3. *Cooking rice in excess water*

Arsenic content in cooked rice depends on the method of cooking (Mihucz et al. 2010; Perelló et al. 2008; Sengupta et al. 2006; Torres-Escribano et al., 2008). Rice is typically prepared by using a small ratio of water: rice (1–2:2) until no discarded water remains. However, a low volume of water for cooking of rice has been found to cause an increase in As levels in cooked rice. Evaporation of water under low volume cooking could be a potential reason for increasing As content in cooked rice. High ratio cooking (water: rice) of rice followed by discarding excess water has been found to effectively decrease As content in cooked rice as summarized in Table 1. For example, Raab et al. (2009) demonstrated that high ratio water (deionized water): rice (6:1) decreased total and inorganic As concentrations in long-grain and basmati rice by 35% and 45%, respectively, compared to uncooked rice. Gray et al. (2016) found that cooking of rice with excess deionized water (10:1 water: rice ratio) decreased inorganic As content in long grain polished, parboiled, and brown rice by 40%, 60%, and 50%, respectively. A relatively higher ratio of cooking water (deionized water): rice (12:1) has also been found to remove 57% inorganic As in cooked rice compared to uncooked wholegrain and polished rice samples (Carey et al. 2015). Mildly As-contaminated cooking water has been tested as a way to reduce As content in the cooked rice. For example, Signes et al. (2008) found that cooking rice in an excess volume of mildly As containing water ($40\,\mu g\,L^{-1}$) has reduced total As concentration of cooked rice by 12.7% in comparison with raw rice. Overall, cooking water to rice ratio of 6:1 seems to decrease total As content of cooked rice to $< 0.2\,mg\,kg^{-1}$ in most cases if the cooking water is free from As (Table 2). If the cooking water is highly contaminated with As, high cooking water to rice ratios do not decrease As content in cooked rice to $< 0.2\,mg\,kg^{-1}$ (Table 2). The possible mechanism related to low As content in cooked rice prepared in excess water may be the release of As species from rice grains into cooking water. Different removal rates in As content in cooked rice under excess cooking water could be seen to correspond to the As concentration in cooking water and raw rice grains, cooking water: rice ratio, cooking time, and rice variety. Another important concern is that most of the studies related to the use of excess water for cooking rice were performed under laboratory conditions by using deionized water and have focused particularly on total As content in cooked rice. Thus, realistic field experiments and a clearer focus on As speciation analysis in cooked rice are required to assess the As behaviour in cooked rice under excess cooking water.

Recent findings revealed that cooking rice with excess water has led to decreased nutrients in the cooked rice grains, in addition to As (Table 1). For instance, Gray et al. (2016) demonstrated that cooking rice in excess water: rice (10:1) has led to decreased level of Fe, folate, niacin, and thiamin in polished and parboiled rice by 50–70%. Mwale et al. (2018) also demonstrated that water: rice ratio of 6:1 has led to significant loss of P (50%), Ni (44.6%), Mo (38.5%), Mg (22.4%), Co (21.2%), Mn (16.5%), Ca (14.5%), and Zn (7.7%). Even though cooking in excess water may reduce As content in the cooked rice, the rice has become a poor source of essential elements. Thus, further research is needed to optimize the water: rice ratio to decrease As content in cooked rice and to prevent any loss of essential nutrients from cooked rice. Another important concern is whether the appearance (i.e. texture) and flavour of cooked rice are affected, due to cooking with excess water. Since cooked rice is one of the most popular market products, changes in the texture (i.e. fluffy, slightly dry, and sticky rice) and flavour of rice may seriously affect the market value of rice. Therefore, further studies are required to ensure the texture and flavour in cooked rice when cooking with excess water.

The excess volume of cooking water may be used as gruel (i.e. discarded starch water) (Mandal et al. 2019; Rahman et al. 2006). Hot gruel is a popular drink in rural villages and the habit of eating gruel is believed to act against lack of nutrient content in rural diets. Mandal et al. (2019) demonstrated that gruel, after the traditional cooking in West Bengal, India, contains a median As concentration of $144\,\mu g\,kg^{-1}$. Thus, consumption of gruel may be an important route of As exposure in rural areas and risk assessments related to the consumption of gruel in rural areas need to be implemented.

The material and the type of the cooking vessel can also be important aspects in the As content in cooked rice. A study by Sengupta et al. (2006) revealed that total As content in cooked rice is not significantly influenced by the material of the cooking vessel (i.e. aluminum, steel, earthenware and glass). However, the total As content in rice cooked in a glass vessel was lower than that cooked in aluminum, steel, or earthenware vessels (Sengupta et al. 2006). Recent findings revealed that the type of the cooking vessel has a negligible effect on As content in cooked rice. For example, Liu et al. (2018) demonstrated that there is no significant relationship between types of cooking vessels (i.e. steamer, pressure cooker and microwave oven) and total As content in cooked rice when rice is cooked in the ratio of 1.8 water: 1 rice. Liao et al. (2018) also found that cooking rice in the stainless steel pot and the pressure cooker (water: rice ratio of 2:1, 4:1, and 6:1) has no significant influence on As concentration in cooked rice. However, it is worth studying the effect of the material and the type of the cooking vessel on As content in different rice varieties cooked in different ratios of water: rice.

4.1.4. *Continual stream of percolating water*

A novel method of rice cooking, “rice preparation using a continual stream of percolating near boiling water”, for decreasing As content in cooked rice has been tested recently by Carey et al. (2015). A coffee-maker, which provides a continual stream of percolating water (i.e. near boiling water) through a filter unit, has been used to test this novel method at the laboratory scale. In this method, rice is placed in the filter unit instead of coffee and near boiling water is passed through the filter unit continuously. As a result, it has been found to remove 59% and 69% of inorganic As compared to raw rice for polished and wholegrain rice, respectively (Carey et al. 2015). Cooking rice bran in percolating As free boiling water has also reduced up to 96% of inorganic As in the cooked bran compared to controls (Signes-Pastor, 2017). Therefore, it seems obvious that use of a continual stream of percolating water leads to decreased As to a greater extent in cooked rice. Advantages of the use of percolating water for cooking rice may be as follows: (1) rice grains are not exposed to a large volume of cooking water; (2) inorganic As species may leach into the water receiving vessel. Since the boiling water does not retain longer time in the filter unit, leached As species from rice grains may be removed quickly into the water receiving vessel. This may be a reason for higher As removal through this method in comparison to other discussed cooking practices. Scientific-based mechanistic investigations would provide better understandings on how a continual stream of percolating water decreases As content in cooked rice. In comparison with other post-harvesting and cooking practices, use of a continual stream of percolating water has been found to have a minimal effect on the trace and macro nutrient elements in the rice bran (Signes-Pastor, 2017). This method did not remove either vitamins or bioactive compounds from the rice bran (Table 1). However, further studies are also needed to assess

Table 2
Effects of different cooking water: rice ratios on As content in cooked rice. Inorganic As content of raw rice grains and cooked rice are shown in parenthesis.

Rice variety/type	Cooking method (water: rice)	Total As content in cooking water (mg L^{-1})	Total As content in raw rice grain (mg kg^{-1})	Total As content in the cooked rice (mg kg^{-1})	Reference
Brown long grain	2:1	Deionized water	0.320 (0.195)	0.323 (0.198)	Gray et al. (2016)
	6:1			0.224 (0.119)	
	10:1			0.169 (0.079)	
White medium grain	2:1	Deionized water	0.204 (0.105)	0.208 (0.106)	
	6:1			0.179 (0.082)	
	10:1			0.145 (0.054)	
Parboiled	2:1	Deionized water	0.216 (0.143)	0.229 (0.143)	
	6:1			0.112 (0.070)	
	10:1			0.073 (0.044)	
Short bold, medium slender, long slender	(3–6):1	–	0.575 (0.346)	0.348 (0.194)	Halder et al. (2014)
			0.125 (0.091)	0.116 (0.067)	
			0.297 (0.223)	0.227 (0.110)	
Polished basmati	2.5:1	Deionized water	0.162 (0.093)	0.141 (0.090)	Raab et al. (2009)
	6:1			0.103 (0.056)	
	Steamed			0.122 (0.061)	
Wholegrain basmati	2.5:1	Deionized water	0.131 (0.089)	0.119 (0.082)	
	6:1			0.072 (0.048)	
	Steamed			0.119 (0.076)	
Polished long grain	2.5:1	Deionized water	0.229 (0.138)	0.238 (0.144)	
	6:1			0.165 (0.070)	
	Steamed			0.177 (0.107)	
Wholegrain long grain	2.5:1	Deionized water	0.314 (0.183)	0.324 (0.165)	
	6:1			0.219 (0.102)	
	Steamed			0.280 (0.156)	
Italian parboiled	2.5:1	Deionized water	0.211 (0.157)	0.211 (0.157)	
Long grain parboiled	2.5:1	Deionized water	0.186 (0.115)	0.163 (0.086)	
Thai white	3:1	Ultrapure water	0.241 (0.173)	0.138 (0.091)	Jitaru et al. (2016)
	6:1			0.125 (0.064)	
	steamed			0.153 (0.097)	
White risotto	3:1	Ultrapure water	0.280 (0.237)	0.149 (0.127)	
	6:1			0.091 (0.044)	
	steamed			0.197 (0.156)	
Organic rice duo	3:1	Ultrapure water	0.535 (0.471)	0.306 (0.286)	
	6:1			0.162 (0.120)	
	steamed			0.316 (0.292)	
White Basmati	3:1	Ultrapure water	0.129 (0.115)	0.064 (0.064)	
	6:1			0.050 (0.035)	
	steamed			0.090 (0.073)	
Steamed black wholegrain	3:1	Ultrapure water	0.234 (0.214)	0.211 (0.199)	
	6:1			0.113 (0.095)	
	steamed			0.212 (0.192)	
Gontra Selection-3	6:1	0.152	0.627	0.445	Basu et al. (2015)
		0.023		0.383	
		0.152	0.495	0.346	
		0.023		0.302	
		0.152	0.572	0.418	
		0.023		0.350	
		0.152	0.549	0.368	
		0.023		0.327	
Zhenshan 97	6:1	Milli-Q water	0.171	0.103	Mihucz et al. (2007)
Risabell	6:1		0.116	0.070	
Koorostaj	6:1		0.139	0.058	
–	2:1	0.040	–	0.365	Signes et al. (2008)
	6:1			0.258	
BRRI dhan28	5:1	0.130	0.570	0.390	Rahman et al. (2006)
BRRI hybrid dhan1			0.690	0.440	
–	2:1 (pressure cooker)	Deionized water	0.085	0.082	Liao et al. (2018)
	4:1 (pressure cooker)			0.081	
	6:1 (pressure cooker)			0.080	
–	2:1 (stainless steel pot)			0.082	
	4:1 (stainless steel pot)			0.080	
	6:1 (stainless steel pot)			0.078	
Xinfeng 2	1.8:1 (steamer)	Deionized water	0.058	0.050	Liu et al. (2018)
	1.8:1 (pressure cooker)			0.050	
	1.8:1 (microwave oven)			0.049	
T-You 15	1.8:1 (steamer)	Deionized water	0.122	0.104	
	1.8:1 (pressure cooker)			0.107	
	1.8:1 (microwave oven)			0.104	

whether water soluble and thermosensitive compounds in cooked rice are affected as a function of a continual stream of percolating water. Moreover, designing and technological improvements are required to devise systems which facilitate the use of a continual stream of percolating water at household levels.

4.2. Introduction of rainwater harvesting systems

One of the major problems for elevated As levels in cooked rice in As endemic areas, as discussed in Section 2, is the use of As-contaminated water for cooking rice. Therefore, As free water sources can be adapted for washing and cooking rice. Rainwater is one of the best alternatives to be used for the preparation of rice in As endemic areas around the world. Rainwater harvesting units set up at the household level can collect rainwater during the rainy season and store it for long-term use. The first flush mode of the rainwater harvesting system may prevents debris (i.e. dead plant materials and bird feces) entering into the storage tank. Filters with different mesh sizes, placed in the water intake line, may also prevent debris entering into the storage tank. However, water quality assessment should be performed to assess whether water quality parameters meet guidelines for safe drinking purposes. If needed, water purification steps (i.e. chlorination and filtration) can also be introduced before using collected rainwater. The water quality of rainwater is dependent on the proximity of contaminant sources, meteorological conditions in a particular area, and roofing materials (Gwenzi et al. 2015; Kahinda et al. 2007). Potential risks (i.e. development of pathogens) associated with rainwater could be minimized by boiling the water for a certain time (~5–20 min) (WHO 2008). Engineering/technological interventions, proper housekeeping practices, and public education also lead to minimization of rainwater contamination and subsequently safeguard public health.

So far, only one study has reported the effects of rainwater on As content in cooked rice. O'Neill et al. (2013) demonstrated that in Prey Veng, Cambodia, As concentration in rice cooked in rainwater was significantly lower than that of raw rice. In that study, total As concentration in cooked rice was below the limit of detection (LOD). Studies revealed that total As content in cooked rice tends to be less than that of raw rice if the cooking water meets the WHO limit of $< 10\ \mu g\ L^{-1}$. The rain water used by O'Neill et al. (2013) contained a zero level of As. Therefore, governments and respective policy makers could initiate the introduction of rainwater harvesting systems, in particular for As endemic areas. The collected rainwater could eventually be used as safe drinking water and cooking water for communities. Rainwater harvesting is also a sustainable and economically feasible option for the global As dilemma. However, regular water quality monitoring for collected rainwater will also be required for the protection of public health.

5. Concluding remarks

Studies related to post-harvesting techniques and modification of cooking methods have been considered to evaluate the decrease of As content in cooked rice. Polishing of raw rice grains leads to a reduction in As content in cooked rice. Sequential washing of raw rice, cooking rice in As free excess water or in percolating cooking water have all remarkably decreased As content in cooked rice. Access to As free water sources such as rainwater harvesting systems is one of the most practical approaches to reduce the As content in cooked rice in As endemic areas. Most of the mitigation measures (i.e. sequential washing of raw rice and cooking rice in excess water) can be implemented at almost zero additional cost. However, use of the stream of percolating cooking water for cooking rice is still being investigated at the laboratory scale. Initial setup cost and low maintain cost will be involved for rainwater harvesting systems.

The key knowledge gaps regarding As removal from cooked rice remain unanswered and should be the focus of future studies. It will be worth studying the effect of long-term storage conditions for rice grains (i.e. storage of rice grains at varying temperature and humidity conditions) to examine whether long-term storage conditions affect As content in raw rice grains. There is a lack of information regarding the changes in As speciation in cooked rice during the different stages of cooking. It is important to investigate how As speciation changes over time, with respect to the mechanisms involved, during the cooking of rice. Optimum parameters (i.e. degree of polishing, number of washing steps, and rice: water ratio for cooking) need to be set for different rice varieties to decrease As content and to maintain required nutrient levels in cooked rice. Carefully designed cooking vessels may be able to effectively decrease As content in cooked rice. The effect of rainwater on reduced As concentration in cooked rice at different rainwater: rice cooking ratios also needs to be investigated in detail. Development of sequential analytical steps of the digestive process (i.e. to simulate the mouth, stomach, and intestines) would provide detailed information regarding the bioaccessibility of As species. Future research assessing As exposure in humans should also assess the As intake from gruel, if any, for a realistic representation of the As exposure scenario in As endemic areas around the world.

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