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Improved Rice (*Oryza sativa*) Water Utilization to Reduce Arsenic Accumulation and Aquifer Overdraft

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Abstract

Arsenic contamination of water, soil and food is a global concern. Rice (*Oryza sativa*) is uniquely involved because rice is a major staple food and its culture in anaerobic soil promotes arsenic accumulation. This manuscript attempts to apprise our current understanding of arsenic in rice in terms of: (i) the severity of the arsenic problem, (ii) the various irrigation technologies being advanced to mitigate arsenic rice accumulation, and (iii) the potential for emerging water conserving irrigation systems to reduce aquifer overdraft. The leading contenders to mitigate arsenic accumulation include (i) plant breeding, (ii) irrigation technologies, (iii) soil amendments that restrict arsenic bioavailability, and (iv) groundwater purification. Recent research involving (i) wetting and drying irrigation and (ii) furrow irrigation typically conserve water and inhibit arsenic accumulation. In Missouri, furrow irrigation generally reduced rice seed arsenic concentrations to less than 0.05 $mg \cdot kg^{-1}$. Plant breeding to both limit arsenic accumulation and tolerate increased temperatures show promise, yet detailed research needs to be expanded.

Keywords

Arsenic, Alternate Wetting Drying, Furrow Irrigation, Climate Change, *Oryza sativa*

1. Introduction: Arsenic and Its Health Effects, Occurrence in Water and Soil

Arsenic is an element in the Periodic Table with an atomic number of 33 and an electronic ground configuration of [Ar] $3d^{10}\ 4s^2\ 4p^3$ (Lee, 1991). In reducing environments, As^0 and As^{3+} (arsenite) exist, whereas in more oxidizing environments

As^{5+} (arsenate) predominately exists (Aide, 2016a; Kabata-Pendias, 2011). Important oxyanions include AsO_4^{3-}, $HAsO_4^{2-}$, $H_2AsO_4^-$ (Lee, 1991; Aide, 2016a).

Arsenic is an insistent human carcinogen, with strong evidence for initiating skin, lung, and bladder cancers (United States Environmental Protection Agency, 2025). Other documented health issues include cardiovascular diseases, pulmonary diseases, diabetes, and child health concerns (United States Environmental Protection Agency, 2025). Inorganic arsenic is perceived as more toxic than mono- and dimethyl-arsenic, however, increasing attention has focused on the toxicity of trimethylated arsenite United States Environmental Protection Agency, 2025).

The United States Environmental Protection Agency has established the arsenic maximum contaminant level for drinking water at 10 $\mu g \cdot kg^{-1}$, which is the same value as specified by the World Health Organization (Kabata-Pendias, 2011; United States Environmental Protection Agency, 2025). The United States Environmental Protection Agency inorganic arsenic reference dose is 0.6 $\mu g \cdot kg^{-1} \cdot day^{-1}$ (United States Environmental Protection Agency, 2025). In the United States, there are no maximum contaminant levels for food inorganic arsenic, except for selected infant products (apple juice, infant rice cereal). For international rice shipments, Codex Alimentarius Commission (United Nations Food Standards Body) has established polished rice arsenic maximum contaminant level at 0.2 $mg \cdot kg^{-1}$ (United States Environmental Protection Agency, 2025).

The Earth's crust has an average arsenic concentration of 1.8 $mg \cdot kg^{-1}$, with argillaceous sediments having arsenic concentrations rising to 13 $mg \cdot kg^{-1}$ (Kabata-Pendias, 2011). In the United States soil concentrations range from less than 0.1 to 93 $mg \cdot kg^{-1}$, with a geometric mean of 5.8 $mg \cdot kg^{-1}$ (Kabata-Pendias, 2011). Aide et al. (2013) surveyed 22 soil profiles for arsenic concentrations across the Southeastern Missouri. Typically soil arsenic concentrations were within the limits for geogenic accumulation, with Ap horizons exhibiting 2 to 12 $mg \cdot kg^{-1}$, and argillic horizons exhibiting 10 to 30 $mg \cdot kg^{-1}$.

The purpose of this manuscript is to document recent progress in understanding arsenic accumulation in rice and the development of protocols for limiting rice arsenic uptake. Specifically, this manuscript reports on (i) emerging rice irrigation protocols to both limit aquifer overdraft and alter the soil's oxidation-reduction status to limit arsenic bioavailability.

2. Methods for Selecting Manuscripts for Inclusion

A literature search was conducted across multiple databases, including Agricola, Biological and Agricultural Index Plus, Google Scholar, PubMed, Science Direct, emphasizing articles published after 2005. Some citations were from recent textbooks (Lee, 1991; Kabata-Pendias, 2011). Search topics included arsenic health effects, geological and soil concentrations, groundwater studies, aquifer depletion, and irrigation studies (alternate wetting and drying, furrow irrigation comparisons with continuous flood). Many open access journals provided additional reference and citation lists. Many excellent manuscripts were not included because the manuscript concepts and conclusions were similar to the cited manuscripts.

3. Arsenic Concentrations in Groundwater as a Contaminant Source

Groundwater irrigation is a major arsenic source in selected locations in Argentina, Bangladesh, Cambodia, Chile, China, India, Pakistan, United States, and Vietnam (United States Environmental Protection Agency, 2025). Welch et al. (2000) reviewed arsenic in groundwater across the United States. At a broad regional scale, arsenic concentrations exceeding 10 μg·L^{-1} appear to be more frequently observed in the western United States. Recent investigations of ground water in New England, Michigan, Minnesota, South Dakota, Oklahoma, and Wisconsin suggest that some arsenic groundwater concentrations exceed 10 μg·L^{-1}. Arsenic desorption from iron oxides appears to be a common cause for groundwater arsenic concentrations exceeding 10 μg·L^{-1} (Welch et al., 2000). Other germane and pertinent literature sources concerning arsenic in groundwater are in **Table 1**.

Table 1. Pertinent literature source on arsenic in groundwater.

Source	Description
Vicky-Singh et al., 2010	Well water from Ganges Plains ranges from 5.0 to 17.3 μg·L^{-1}.
Ivy et al., 2023	In Bangladesh, drinking arsenic contaminated groundwater is the primary arsenic exposure
Huq & Naidu, 2005	In Bangladesh, crops receiving arsenic contaminated water have accumulated arsenic levels that exceed the maximum allowable daily limit of 0.2 mg·kg^{-1} dry weight
Phuong et al., 2008	Along the Red River, Vietnam, arsenic contents greater than 35 mg·kg^{-1} were recorded for soils because of irrigation water.
Huang et al., 2016	Groundwater in the Mekong Delta is influenced by arsenic-rich clayey alluvium transferred from the Tibet Highlands.

In a review, Horie (2019) noted that rice-producing nations most susceptible to global change include Thailand-Myanmar, east-central China, northern and southeastern India. Horie further noted that with projected temperature increases, trends will likely include: (i) increased rice biomass with nitrogen management, (ii) increased panicle density because of optimum tillering, and (iii) increased spikelet sterility. Wichelns (2016) projected that climate change will likely manifest as changes in the timing and intensity of rainfall and with increased minimum and maximum daily temperatures.

4. Emerging Rice Irrigation Practices the Conserve Water and Limit Arsenic Accumulation in Rice

Soil oxidation-reduction conditions may be classified as oxic, suboxic, and anoxic. Microbial activity is highly influenced by the soil's oxidation-reduction status, which influences the favorability of soil reactions. In oxic soil conditions, (i) Mn- and Fe-oxyhydroxides are stable and are adsorption substrates for arsenic, thus reducing arsenic's bioavailability, and (ii) arsenate is the predominant arsenic species which has fewer root aquaporins (plasma membrane intrinsic proteins) for plant accumulation. In anoxic soil conditions, microbial populations support arsenic mobility and bioavailability by establishing microbial pathways that reduce arsenate to arsenite and degrade Mn- and Fe-oxyhydroxides, fostering plant accumulation.

Alternate wetting and drying is an emerging, water conserving, producer profitable, and ecofriendly irrigation system. Ishfaq et al. (2020) noted that alternate wetting and drying frequently maintains yield production goals. Typically, irrigation water is applied a few days after the disappearance of the ponded water, thus the term wetting and drying. Depending on soil type, weather, and crop growth stage, the number of days of non-flooded soil between irrigations can vary from 1 to more than 10 days. A full flood is usually maintained at panicle initiation and at anthesis. Furrow irrigation provides water to graded land, where tillage induced beds or channels permit the parallel flow of water across the field. Other germane and pertinent literature sources concerning water conservation and limiting arsenic accumulation in rice are in **Table 2**.

Table 2. Irrigation advances to support water conservation and limiting arsenic accumulation.

Allen & Sander, 2019	Alternate wetting and drying irrigation is emerging as an irrigation strategy to reduce methane emissions and water applications
Atwill et al., 2018	Compared to continuous flooding, alternate wetting and drying can increase rice yields and nitrogen use efficiencies.
Yang et al., 2017	In China, reduced irrigation applications may be accomplished without yield reductions
Carrijo et al., 2016	In California, comparisons of alternate wetting and drying irrigation with continuous flood demonstrated that alternate wetting and drying irrigation decreased yields by nearly 6%; however, field trials using mild or less intensive alternate wetting and drying irrigation showed rice yields that were comparable to traditional yields.
Carrijo et al., 2018	Alternate wetting and drying irrigation considered mild produced yields comparable to continuous flooding, whereas more severe alternate wetting and drying irrigation conditions did reduce arsenic accumulation.
Carrijo et al., 2019	continuously flooded irrigation increased arsenic grain accumulation, and (ii) severe soil drying reduced arsenic grain accumulation,
Li et al., 2019	In California, reported that different intervals of alternate wetting and drying irrigation influence the degree of arsenic accumulation.
Henry & Clark, 2021	In Arkansas, evaluated (i) continuously irrigated and (ii) furrow-irrigated rice systems. Rice yields were highest for the continuous irrigation treatment and lowest for the longest (14-day) irrigation withdrawal treatment. The shortest (3-day) irrigation withdrawal treatment showed promise to maintain yields.
LaHue et al., 2016	Alternate wetting and drying decreased rice grain total arsenic concentrations more than 59% and grain yields were not affected.
Aide & DeGuzman, 2020	Irrigation technologies may reduce methane emissions and rice arsenic accumulation.

Aide et al. (2016b) compared furrow irrigated rice with delayed flood irrigated rice, showing that furrow irrigated rice reduced arsenic concentrations in paddy (rough) rice, brown rice, and polished rice. Furrow irrigation produced arsenic concentrations at or below 0.1 $mg \cdot kg^{-1}$, whereas the delayed flood irrigation showed arsenic concentrations from 0.22 to 0.28 $mg \cdot kg^{-1}$.

In 2015 and in Missouri, Aide and Goldschmidt (2017) evaluated 12 rice cultivars having furrow irrigation and delayed flood irrigation, eight furrow irrigated cultivars exhibited rough rice seed arsenic concentrations smaller than 0.05 $mg \cdot kg^{-1}$ and all furrow irrigated cultivars had arsenic concentrations less than 0.17 $mg \cdot kg^{-1}$ (**Table 3**). All varieties sampled from the delayed flood irrigation system averaged 0.25 mg kg^{-1} and no cultivars has arsenic concentrations below the detection limit. Subsequently, in a second-year trial in 2016, Aide and Goldschmidt (2017) showed that for 20 cultivars cultured under furrow irrigation, 17 cultivars exhibited arsenic levels less than 0.05 $mg \cdot kg^{-1}$, whereas all cultivars cultured under delayed flood exhibited detectable arsenic concentrations, which averaged 0.37 $mg \cdot kg^{-1}$.

If rice producers limit arsenic concentrations to 0.05 $mg \cdot kg^{-1}$ then Mid-South rice may easily flow through international channels. The processing of rice for baby foods will be a potential market and consumer confidence will expand. The result is a greater market share for rice producers.

Table 3. Seed (Rough) arsenic concentrations (mg As/kg) for 12 rice cultivars. Source: Aide and Goldschmidt, 2017.

Cultivar	Furrow Irrigated	Delayed Flood
#1	0.06	0.20
#2	<0.05	0.21
#3	<0.05	0.18
#4	<0.05	0.26
#5	<0.05	0.30
#6	<0.05	0.24
#7	<0.05	0.38
#8	<0.05	0.20
#9	<0.05	0.34
#10	0.06	0.20
#11	0.13	0.13
#12	0.17	0.30
Mean	<0.05	0.25

Farrow et al. (2024) demonstrated that intermittent flooding significantly reduced grain arsenic accumulation, while intermittent irrigation may increase grain cadmium accumulation.

Aerobic soil conditions lead to reduced arsenic bioavailability because of enhanced soil adsorption and reduced translocation of arsenic from the roots to culm and culm to seed (Shehzad et al., 2022). In Missouri, furrow irrigation is gaining producer acceptance, with the perceived advantages including: (i) water conservation, (ii) reduced labor and energy usage, (iii) less reliance on airplane applications, and (iv) reduced levee construction. Disadvantages include: (i) the requirement of land grading, (ii) possible delays in maturity, (iii) greater difficulties in weed control and nitrogen management, (iv) potentially lower yields because of water stress, and (v) need for producer education (Aide et al., 2016; Aide & Goldschmidt, 2017).

Rokonuzzaman et al. (2022) stressed that limiting rice arsenic accumulation requires (i) groundwater purification, (ii) arsenic-resistant rice varieties, and (iii) implementing alternate wetting and drying or aerobic rice cultivation. In a major review of sustainable rice irrigation, Arouna et al. (2023) documented that understanding and utilizing rice crop water requirements conserve water resources and improve rice productivity.

In Missouri, Aide (2018, 2019a) performed unique furrow and delayed flow irrigation field trials, where the plot length was 1,200 meters. The plots were furrow and delayed flood irrigated and the furrow irrigated plots were partitioned into upper, middle, and lower (tail water) sections. Each plot had three varieties. The furrow irrigated upper and middle plots produced rough rice with arsenic less than 0.1 $mg \cdot kg^{-1}$, whereas the tailwater section and the delayed flood irrigation system exhibited arsenic concentrations from 0.14 to 0.24 $mg \cdot kg^{-1}$.

Leavitt et al. (2025) found that the most effective and broadly applicable practices to inhibit arsenic accumulation were (i) irrigation methods with aerobic periods such as alternate wetting and drying and (ii) the application of silicon-rich amendments. Devi et al. (2024) in an extensive review, supported the premise that aerobic irrigation systems limit arsenic accumulation

5. Aquifer Depletion in the Mississippi River Embayment

Aquifer depletion is a global concern and groundwater conservation requires irrigation systems to limit aquifer overdraft. In response, the shift to furrow irrigation and alternate wetting and drying systems supports both water conservation and reducing rice arsenic accumulation. Aide (2019b) noted that rice production and nations having regional diminished water availability require emerging irrigation research to ensure continuance of rice production and to support water sustainability. The mid-South region of the United States has focused on furrow irrigation to reduce excessive groundwater depletion. The State of Mississippi Delta Region receives over 50 inches of rain annually; however, the rainfall distributions are such that the growing season typically receives limited precipitation. Thus, irrigation using groundwater resources is extensive because the region depends on irrigation to sustain agricultural production. Because of groundwater withdrawal, the Mississippi River Valley alluvial aquifer, in some regions, shows negative rates of recharge and declining water levels. On average, in the Mississippi Delta region, the aquifer depletion rate is accelerating (Aide, 2019b). Other germane and pertinent literature sources concerning aquifer overdraft are in **Table 4**.

Table 4. Important studies in Mid-South USA on aquifer overdraft.

Reba et al., 2017	Decline of the Mississippi River Valley Alluvial Aquifer partially attributed to irrigation. Research is focusing on continued innovation in irrigation, producing on-farm reservoirs, on-farm reservoir-tailwater recovery systems.
Arkansas Department of Agriculture, 2022	In Arkansas, the Grand Prairie and Cache River regions annually produce severe cones of depression.
Massey et al., 2017	Over 12 years showed rice irrigation rates were 9,200 $m^3 \cdot ha^{-1}$.
Atwill et al., 2020	Alternative irrigation rice strategies could reduce Mississippi River Valley Alluvial Aquifer withdrawal without having an adverse effect on yield and profitability.

6. Conclusion: Emerging Technologies and Land Management Options to Mitigate Arsenic Accumulation

Agribusiness, producers, governments, and consumers all acknowledge that arsenic-groundwater and foods are undesirable. Research is focusing on four discrete technologies to reduce arsenic risk: (i) plant breeding, (ii) irrigation, (iii) groundwater monitoring, and (iv) soil amendments. Plant breeding is focusing on improving heat tolerance to avoid spikelet sterility and limiting arsenic root to culm and culm to seed transference. Irrigation technologies are focusing on providing episodes of soil oxidation to limit arsenic bioavailability, while maintaining rice yields. Both alternate wetting-drying irrigation and furrow irrigation are promising. Groundwater is a natural resource that may have naturally occurring arsenic levels that are unacceptable, thus water treatment is a potential area for research. The application of soil amendments may limit root arsenic uptake (Devi et al., 2024). The soil chemistry of each individual amendment needs to be fully understood and commercialization of the products is required.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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