Keeping arsenic out of rice

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As a postdoc exploring rice paddies in Cambodia in 2011, Angelia Seyfferth was struck by the towering mounds of husks piling up outside rice mills. Rice husks, the hard outer layer that encloses each grain, are a byproduct of rice production. "It is often considered a waste product that farmers are trying to get rid of," explains Seyfferth, now a soil biogeochemist at the University of Delaware in Newark. Maybe, she thought at the time, she could use a key nutrient in these discarded husks to help address a global health problem: arsenic contamination in the rice itself.

Arsenic, a pollutant stemming from industrial processes and pesticides, also naturally occurs in soil and groundwater in regions across the globe. In its inorganic form, it's highly toxic, with chronic exposure raising the risk for a host of health conditions, including diabetes, cardiovascular diseases, and cancers (1). Drinking water is often a major exposure route.

But in the early 2000s, researchers discovered that rice, a staple food for more than half the global population, can also contain arsenic (2). In 2012, a *Consumer Reports* analysis raised public awareness of the issue by showing that nearly all of 65 types of rice and rice products tested contained arsenic—many of them at concerning levels (3). In 2020, a team of researchers in the United Kingdom found that of 55 samples of commercial rice sold in the UK, more than half exceeded the European Commission's limit for inorganic arsenic levels suitable for infant food or direct feeding to infants (4).

Although the US Food and Drug Administration (FDA) has recommended that industry lower arsenic

Working as a postdoc in Cambodia in 2011, soil biogeochemist Angelia Seyfferth wondered whether the towering mounds of husks piling up outside rice mills could help mitigate arsenic contamination in rice. Image credit: Angelia Seyfferth.

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As a graduate student at the University of California, Davis, plant scientist Daniela Carrijo grew rice in paddies with different moisture levels to find growing conditions that minimize both arsenic and another toxin, cadmium. Image credit: Daniela Carrijo.

levels in rice-based infant cereals, and levels are indeed dropping (5), concerns about arsenic in rice across the globe persist. The contaminant not only affects food safety but also quantity, as arsenic can diminish a rice farmer's yield (6). And the problem may only worsen with climate change—recent research suggests that arsenic uptake by rice plants will increase under higher temperatures (7, 8).

So researchers are working on ways to prevent arsenic from getting into rice in the first place. Seyfferth is developing techniques that could help rice growers use silicon, a nutrient in husks, to outcompete arsenic for entry into the plant. Other approaches include manipulating paddy water and soil or pinpointing genes that could stop arsenic from reaching the grain. Solutions, however, are not straightforward—techniques that decrease arsenic sometimes increase cadmium, another deadly toxin. And the genes that would make rice more arsenic resistant remain elusive.

The Silicon Solution

Rice is susceptible to arsenic contamination, in part, because farmers traditionally grow the plants in standing water. In the anaerobic conditions of a flooded paddy, arsenate, an oxidized form of inorganic arsenic, gets reduced to arsenite, another inorganic form that more readily moves from soil into water where the plant can soak it up. In some regions, crops are irrigated with groundwater already contaminated with arsenic, compounding the problem.

Compared with other plants, rice is also especially prone to arsenic uptake. In 2008, an international team of researchers revealed why: Arsenite enters rice roots through the same pathway that takes in the chemical element silicon (9). Silicon, an abundant metalloid, is nontoxic when ingested. Although beneficial for plants in general, silicon is particularly key for rice, which takes in large amounts for structural support and resistance to pests. "It's a major transport pathway," explains Fang-Jie Zhao of Nanjing Agricultural University in Nanjing, China, an environmental scientist and plant physiologist, who co-led the study while at Rothamsted Research in Harpenden, United Kingdom, along with Jian Feng Ma of Okayama University in Japan.

"Because the arsenite looks chemically similar [to silicon], it gets taken up through that pathway as well," adds Seyfferth. Inspired by these findings, Seyfferth, Zhao, and others began looking for a silicon solution. Numerous studies suggested that silicon added to soil can outcompete arsenite for access to the pathway, while also suppressing key genes governing the pathway, thereby limiting arsenite's entry (10). In her postdoctoral research at Stanford University in Palo Alto, CA, for example, Seyfferth demonstrated that adding silica gel to arsenic-contaminated soil could lower arsenic levels in rice grain by as much as 40 percent (11).

Some farmers were already using silicon fertilizer to increase yield, but the fertilizers are expensive. "Farmers don't very often use the fertilizer because it's a cost," notes Zhao. Rice husks, however, are extremely high in silicon, low in arsenic, and, as Seyfferth witnessed, quite abundant. She decided to put them to use. In 2016, Seyfferth showed that adding rice husks to potted rice plants resulted in grains with 25 to 50 percent less inorganic arsenic (12).

Mills, though, often burn husks to help fuel the machinery. So Seyfferth also tried applying these charred husks to rice plants and showed that they, too, reduce inorganic arsenic in the grain when in flooded pots, although only by as much as about 20 percent (13). To fine-tune the technique, she experimented with charring at different temperatures and reported last December that husks burned at 450 °C released more silicon into soil than those burned at higher temperatures (14).

Now Seyfferth is investigating how husk fertilizer affects the movement and form of arsenic within the rice plant. "It's really important to know exactly where it's going," she says. "That has direct implications for human health." A rice grain consists of the white endosperm coated with a layer of bran. Typically, rice bran contains higher levels of inorganic arsenic than the endosperm. For this reason, brown rice tends to be higher in inorganic arsenic than white rice, which is polished to remove the bran. But in recent work, not yet published, Seyfferth used X-ray fluorescence imaging to show that rice husk fertilization not only decreases inorganic arsenic levels in the white endosperm but nearly eliminates arsenic altogether from the bran.

The reason, she says, is that the husks encourage microorganisms to transform inorganic arsenic into an organic, less toxic form known as dimethylarsenic acid (DMA). Once inside the plant, DMA preferentially moves to the endosperm rather than the bran. "Say you are a grower who is producing rice bran for a company," says Seyfferth. "If you amend the soil with rice husk, you can essentially create this bran product that is nearly devoid of arsenic."

Water, Soil, and Data

Simply modifying rice farming practices could also lower the amount of arsenic that gets into the grain.

For instance, rice plants don't actually require flooding to grow. Indeed, Seyfferth found that experimental pots left unflooded had low arsenic levels; both fresh and charred husks reduce them even further (13). But there's a catch: Drying the paddies can lower yield, while also resulting in heightened levels of cadmium, another toxin. "Cadmium and arsenic are opposite to each other in terms of biogeochemistry," says Zhao. "If we flood the paddy soil, we reduce cadmium availability." Removing both toxins will be a challenge, however.

Plant scientist Daniela Carrijo of Oregon State University in Corvallis is among those searching for growing conditions that minimize both toxins. As a graduate student at the University of California, Davis, she experimented with draining paddies to different moisture levels at different intervals during the growing season. Although not common in California, this "alternate wetting and drying" strategy is already practiced by rice growers in many regions to conserve water.

In one study, she found that letting soil moisture drop to 35% volumetric water content twice during the growing season could halve the inorganic arsenic in the final grain compared with continuously flooding paddies, and without impacting yield (15). The drying also resulted in the grain's cadmium concentration increasing by about 2.5 times. But this outcome is acceptable in California, says Carrijo, because the baseline cadmium levels are so low—regions with high cadmium levels would need different approaches.

One such alternative: simply inverting the soil. In a 2019 study, geochemist Lex van Geen of Columbia University's Lamont-Doherty Earth Observatory in Palisades, NY, and colleagues experimented with inverting soil on farms in the Faridpur district in south-central Bangladesh. The deeper soil—which is less contaminated by the surface irrigation—was placed on top. In the growing season immediately after the inversion, they saw no effect, possibly because the disruption to the soil structure offset any benefit. But in the following season, yield increased in inverted plots by 15 to 30 percent compared with unmanipulated plots (16). Van Geen says that several growers in the region, inspired by this research, have inverted soil on portions of their fields. Unfortunately, this solution is only temporary because irrigation water will continue to deposit more arsenic.

Providing farmers more information could help, van Geen says. Recently, he developed an inexpensive soil arsenic test kit for growers (17). His hope is that data about where soils are contaminated, in combination with a heightened awareness of how arsenic diminishes yield, will encourage growers to plant different crops or use rivers or ponds as irrigation sources, rather than groundwater, wherever arsenic is highest.

Searching for a Genetic Fix

Looking for more lasting solutions, some researchers have turned to rice genetics to understand why certain rice varieties, such as basmati, tend to accumulate less arsenic (18). "Usually we find up to four- or fivefold variation in grain arsenic content between different modern rice cultivars," says Zhao. "But the genetic reasons underpinning that variation are still not very well understood."

Researchers are probing rice cultivars, landraces, and the model plant *Arabidopsis* for the genes that make some plants less prone to arsenic uptake so breeders could then select for these genes to make more resistant cultivars.

But despite more than a decade of work, researchers haven't yet revealed the genes that govern arsenic movement and storage within the plant, causing one cultivar to resist arsenic while another sucks it up. One reason it's so challenging to map genetic contributions to arsenic uptake, says Zhao, is that environmental factors play such a major role. Moreover, it's possible that numerous genes play a part, making it difficult to tease out the subtle impact of any one.

"Rice husk is a material that would be available to rice farmers all over the world."

—Angelia Seyfferth

Still, he and others are making progress. In March, Zhao and colleagues revealed a genetic mutation that indirectly reduces arsenic accumulation in rice grain by about a third. It does so by setting off a series of molecular interactions that ultimately increase levels of peptides known as phytochelatins, which bind to arsenic, limiting its movement into the grain (19). Zhao and colleagues are now exploring whether they can harness this mutation to breed low-arsenic rice.

And through a quantitative trait loci (QTL) analysis published in January, United States Department of Agriculture (USDA) researchers identified seven genomic regions associated with variation in inorganic arsenic in rice grain (20). Within these regions, they identified a handful of candidate genes, including one that codes for a protein known to help move nutrients, metals, and other materials across cell membranes. The team is now testing how combinations of candidate genes affect inorganic arsenic levels in the grain, because their research suggests that the effect is likely cumulative. "Specifically, we want to identify the candidate genes that result in low [inorganic arsenic] accumulation and combine these together (i.e., pyramid or stack them) in one rice cultivar," says study author Jinyoung Barnaby, a plant physiologist at the USDA ARS Dale Bumpers National Rice Research Center in Stuttgart, AR.

A Growing Threat

Even as these research efforts advance, the need for actionable solutions grows. Carrijo fears that climate change-induced droughts may cause more growers to irrigate with arsenic-contaminated groundwater, rather than surface water sources like rivers.

Moreover, Seyfferth and colleagues at the University of Washington in Seattle recently reported that warmer temperatures increase mobilization of arsenic

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from soil into water, making it more available to rice plants (7). They also found that higher rates of transpiration play a secondary role, with plants in warmer growth chambers sucking up more of the arsenic-laden water.

A 2019 study by researchers in Germany and California examining the compounding effects of soil arsenic and climate change on rice production found that doubling atmospheric CO_2 and increasing temperature by 5 °C nearly doubled the inorganic arsenic concentration in the grain, an effect primarily attributed to the temperature increase (8).

Faced with a warmer future, Seyfferth is trying to convince growers that husks could be part of an immediate fix. "Rice husk," she says, "is a material that would be available to rice farmers all over the world."

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