Received: 22 August 2026 | Revised: 28 October 2026 | Accepted: 16 November 2026

https://doi.org/10.56946/jspae.v5i2.1127
Volume 5 (2): 93–107

Journal of Soil, Plant and Environment

Review Article

Sustaining Arsenic Control from Soil to Rice Grain under Wetting and Drying

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Abstract

Soil amendments can reduce arsenic mobility in paddy soils, but their long-term value depends on whether chemical retention translates into sustained protection of rice plants and harvested grain. This critical review examines how wetting, drying, and reflooding influence amendment performance through interactions among soil minerals, microorganisms, and roots. We distinguish three outcomes: persistent restriction of arsenic mobility in soil, reduced plant uptake and physiological injury, and lower inorganic arsenic concentrations in grain. Evidence from mineral investigations, rhizosphere experiments, amendment trials, and field irrigation studies shows that these outcomes do not necessarily coincide. Iron-associated retention can persist for years under some conditions, whereas redox transitions, amendment aging, organic matter interactions, and microbial transformations may alter treatment effectiveness. Root oxygen release, iron plaque formation, silicon availability, and internal arsenic transport further complicate the relationship between soil measurements and grain composition. Consequently, lower extractable soil arsenic or improved crop growth alone cannot establish lasting grain protection. We propose an evaluation framework linking soil and porewater speciation, root exposure, plant performance, and grain composition across water transitions and cropping seasons. The framework emphasizes matched amendment and irrigation controls, sampling during drainage and reflooding, and distinguishing changes in grain arsenic concentration from changes in total accumulation. Potential effects on yield, nutrition, and other contaminants should also be assessed. Future studies must test whether observed benefits persist across soils, cultivars, water regimes, and successive harvests, and whether measurements improve prediction beyond soil indicators. Such evidence would support reliable, context-specific recommendations for arsenic management in rice.

Keywords: Soil amendments; Redox cycling; Rhizosphere processes; Iron plaque; Amendment aging; Grain speciation.

1. Introduction

Controlling arsenic in rice requires more than reducing its mobility in soil. Concentrations and chemical species of arsenic in harvested grain vary across production regions [1], while cultivar and growing environment jointly influence grain accumulation [2]. Total soil arsenic alone is therefore insufficient to judge the likely benefit of an intervention. A more informative assessment follows arsenic from soil reservoirs and porewater to root exposure, plant uptake, internal redistribution, and grain deposition [3]. Soil amendments may affect several of these steps, but a reduction in one measured pool does not necessarily predict a reduction in another. Previous reviews have addressed agronomic approaches to lowering grain arsenic [4], its transformation in paddy soil–rice systems [5], engineered remediation materials [6], and the extent to which agricultural remediation has been tested under realistic conditions [7]. Recent syntheses have also examined iron-mediated redox transformations [8] and abiotic immobilization in flooded paddies [9]. Although these reviews establish the importance of soil mineral reactions and management, a specific evidence gap remains: how reliably a measured amendment effect survives changes in water regime and whether that persistence translates into lower rice exposure and grain arsenic. This review evaluates the duration and environmental history of each treatment, the arsenic pool actually measured, and the plant or grain outcome demonstrated. Its purpose is to test the strength of the connection between soil retention and crop protection, not to propose a new universal immobilization mechanism or rank all amendments.

The need to assess durability is reinforced by changing climatic and management conditions. Field-based experiments combined with modelling showed that concurrent increases in atmospheric CO_2 and temperature raised inorganic arsenic concentrations in rice grain under the conditions studied [10]. A rhizobox investigation found that alternate wetting and drying (AWD) reduced porewater arsenic exposure and grain

arsenic under both present-day and severe future-climate treatments [11]. These findings do not establish either a universal climate response or a guarantee of protection under AWD. Rather, they indicate that amendment performance must be assessed under the water and environmental conditions experienced by the crop, including transitions that may alter arsenic release and retention. Water management also presents competing food-safety outcomes. A quantitative synthesis found that soil drying generally reduced grain arsenic while tending to increase cadmium, with responses influenced by drying intensity and timing [12]. Irrigation studies have documented differences among soils [13] and among grain total arsenic, inorganic arsenic, and dimethylarsinic acid [14]. Thus, lower total arsenic cannot automatically be taken to mean lower inorganic arsenic or an improvement in all contaminant endpoints. To isolate an amendment effect, amended and unamended treatments should first be compared under the same measured water regime. Differences among water regimes can then be examined separately, ideally through a factorial design with matched controls.

Three related outcomes are distinguished throughout this review. Chemical persistence refers to continued restriction of arsenic mobility over a stated period and environmental history. Plant protection refers to changes in arsenic uptake, physiological injury, nutrition, and growth. Grain protection refers to a reduction in arsenic concentration in a specified harvested rice product, with inorganic arsenic reported separately. A relative decline in grain concentration does not, by itself, demonstrate compliance with food standards or establish dietary safety. These distinctions prevent short-term soil responses, improved biomass, and lower grain exposure from being treated as equivalent evidence of success. The distinction between external immobilization and plant-mediated mitigation is equally important. Arsenite transport through rice silicon transporters [15], sequestration that limits its movement into grain [16], and responses to silicon-releasing amendments [17] act at different stages of the soil–plant pathway. Their existence does not mean that every soil amendment modifies these processes. Nevertheless, they help explain why similar changes in soil arsenic may yield different grain outcomes across cultivars or soils. The central question is therefore when amendment-associated reductions in arsenic exposure and accumulation remain effective through repeated drainage and reflooding, and how rhizosphere microorganisms and rice roots modify that outcome. Figure 1 summarizes the connected pathways and the distinct endpoints that require measurement.

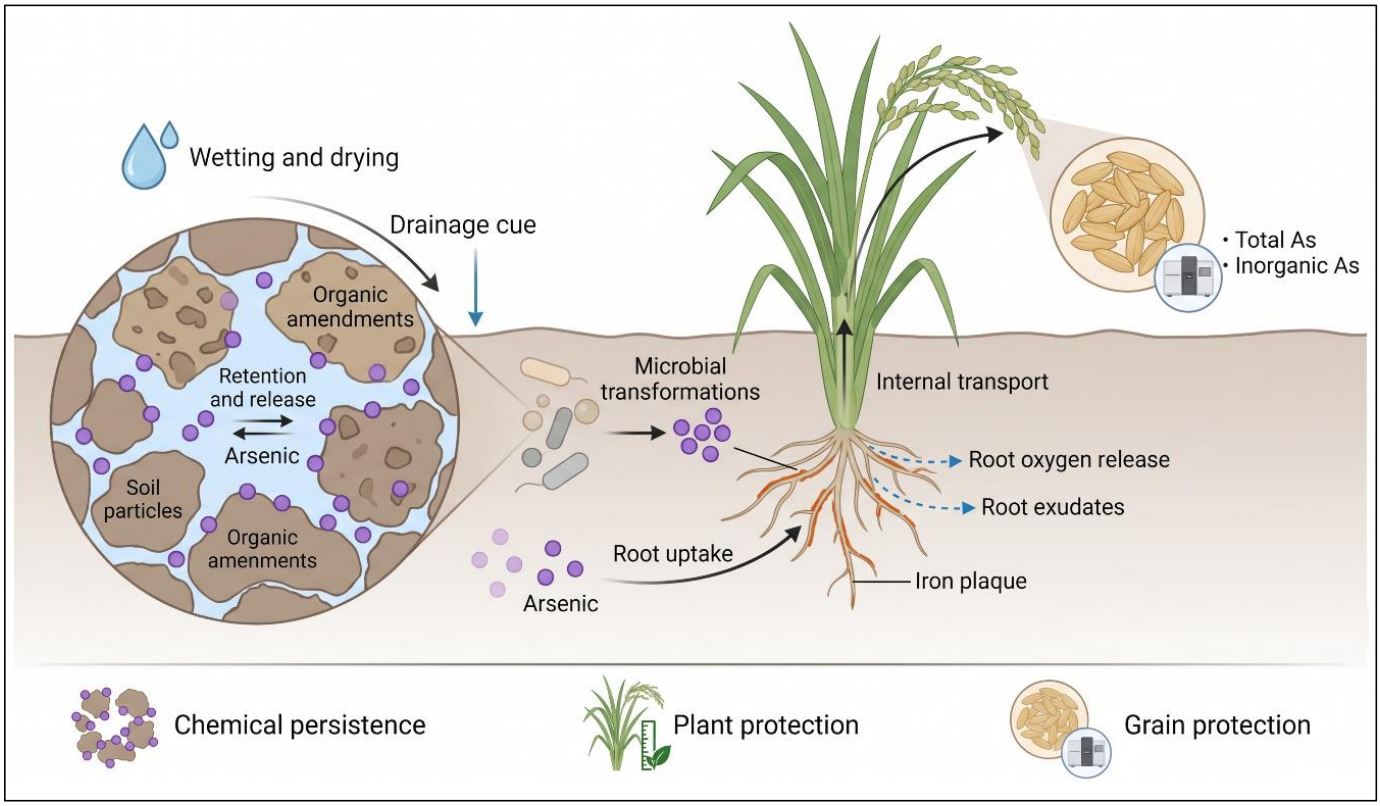


Figure 1. Connected soil–root–grain pathways of arsenic control. The conceptual diagram links amendment characteristics and soil conditions with microbial transformations, rhizosphere exposure, root uptake, internal transport, and harvested grain composition. Root oxygen release and exudation are shown as potential feedbacks on local chemistry. Chemical persistence, plant protection, and grain protection are presented as related but distinct evaluation endpoints, with nutrient acquisition, yield, and cadmium included as accompanying outcomes. Arrows indicate plausible processes supported by the literature discussed in this review; they do not imply that all pathways operate equally or in the same direction under every soil and water regime. The figure was created using BioRender: Scientific Image and Illustration Software (Toronto, Canada; app.biorender.com).

2. Literature Search and Evidence Assessment

A targeted critical-review approach was used to assess the linkage between amendment performance, changing soil conditions, and rice outcomes. Google Scholar, Web of Science, PubMed, publisher websites, and reference lists of relevant articles were consulted through November 16, 2026. Search combinations included rice and arsenic with soil amendment, iron, biochar, material aging, AWD, redox cycling, rhizosphere, iron plaque, microbial transformation, speciation, uptake, and grain. An illustrative Boolean combination was arsenic AND rice AND (biochar OR iron OR soil amendment) AND (aging OR wetting and drying OR redox). Additional mechanism-focused searches included iron plaque, arsenic transporters, microbial methylation, and thiolated arsenic. Publication metadata were checked against article titles and digital object identifiers when accessible. Studies were selected for their relevance to amendment chemistry, water- or redox-dependent arsenic transformations, rhizosphere processes, rice uptake, and grain composition, rather than by a fixed publication-year cutoff. Foundational reports were retained where necessary to interpret mechanisms or analytical methods. Studies in non-rice soils were used only to examine material aging or geochemical retention, with limits to extrapolation clearly identified. Where full text was accessible, conclusions were considered in the context of the reported methods and conditions; when only an abstract could be assessed, interpretation was restricted accordingly. The review is selective rather than systematic: it does not claim exhaustive retrieval, a formal risk-of-bias score, or a pooled quantitative treatment effect.

Evidence was assessed by experimental setting, soil characteristics, amendment composition and dose, water management, treatment duration, arsenic species or operational fraction measured, and crop endpoint. Laboratory incubations provide information about chemical behavior but cannot alone demonstrate plant or grain protection. Pot experiments connect soil treatment with crop response but may not establish long-term field persistence. Repeated sampling within one growing season was distinguished from measurements across successive crops, and related publications were not assumed to represent independent replication. Microbial community composition and gene abundance were treated as associations or indicators of functional potential unless supported by measured transformation processes. These differences in design, analytical endpoints, and grain processing preclude a defensible pooled ranking. Table 1 later contrasts selected studies, while Table 2 presents diagnostic comparisons proposed for future work rather than a complete evidence inventory.

3. Soil Processes Controlling Arsenic Immobilization

3.1. Chemical and mineral controls

Flooding and drainage change the mineral and redox environments that control arsenic mobility in paddy soils. Field observations have linked flooded conditions to reductive dissolution of iron-bearing phases and release of associated arsenic, followed by renewed retention when non-flooded conditions favour iron oxidation [18]. These processes may recur within a season, so a single concentration measurement cannot establish sustained immobilization. Amendment performance should be interpreted relative to the preceding drainage–reflooding sequence, with sampling timed to capture both potential release and re-immobilization. Arsenic oxidation state is important but does not, by itself, predict mineral retention. Comparisons of arsenite and arsenate sorption onto different iron oxides show that mineral identity and solution chemistry influence their relative adsorption [19]. Consequently, promoting arsenite oxidation should not automatically be equated with permanent immobilization. Assessment of an iron-based amendment requires information about its reactive mineral phases, their evolution under relevant redox conditions, and the surrounding chemistry that controls competitive sorption and dissolution.

In rice grown on a soil with relatively high background arsenic, iron-material additions increased soil iron-oxide pools and reduced soil-solution arsenic and grain accumulation under the experimental conditions [20]. This links a soil chemical response to a crop endpoint, but does not establish that newly formed or added reactive phases will withstand later reducing episodes. Comparisons intended to test durability should characterize the amendment-derived iron phases before and after water transitions while maintaining the same soil, cultivar, and measured irrigation regime across amendment treatments. A water-regime label is not a sufficient description of the conditions experienced by arsenic-bearing minerals. In a two-year field comparison, the AWD treatment reflooded when the perched water table reached 15 cm below the surface, yet the 0–15 cm soil layer remained saturated; stronger drying treatments controlled by volumetric water content produced actual drying of that layer [21]. Accordingly, studies should report water-table depth, soil moisture or water potential, sampling depth, and the timing and frequency of reflooding. Transfer of results between soils should be based on measured hydrological conditions rather than a shared AWD designation.

Nutrient and organic-matter interactions further complicate material performance. Phosphate can compete with arsenic for reactive sorption sites, with the outcome depending on variable-charge soil properties [22]. Organic constituents can either modify arsenic binding or alter iron transformations and solution chemistry [23]. It is therefore misleading to assume that inorganic amendments are uniformly stabilizing or organic amendments uniformly mobilizing. The relevant comparison is the net effect of the amendment within a defined soil matrix and water history. A controlled paddy-soil incubation illustrates this matrix dependence. Biochar-supported zero-valent iron reduced the concentration of 0.05 M ammonium-sulfate-extractable arsenic by 64.2% in the original soil and by 5.1% in soil subjected to hydrogen-peroxide removal of much of its organic matter, each relative to its corresponding untreated control [23]. The treatment used arsenic-spiked soil and a 30-day incubation; organic-matter removal also altered pH, fulvic

carbon, and organomineral interactions [23]. These results demonstrate that the chemical effectiveness of this material depends on the soil matrix. They do not isolate the effect of natural aging, establish a field persistence rate, or demonstrate reduced arsenic in harvested rice.

Sulfur cycling can support retention while also changing dissolved arsenic speciation. In a flooded, contaminated floodplain soil, microbial sulfate reduction promoted iron-sulfide formation and solid-phase arsenic retention, including an arsenic-sulfide-like component associated with mackinawite [24]. Dissolved thiolated arsenic species have independently been detected in paddy porewater [25]. Because these findings concern different arsenic phases and soil settings, they do not support a general claim that sulfate reduction always lowers root exposure. Evaluation of sulfur-bearing materials under drainage and reflooding should measure dissolved arsenic species alongside solid-phase transformations, rather than inferring immobilization from sulfide formation alone. The analytical endpoint determines what can be claimed about persistence. Sequential extraction separates operationally defined soil arsenic fractions and is useful for tracking changes following treatment [26], but an extraction fraction is neither a direct mineral identification nor a measurement of porewater concentration or root uptake. More robust interpretation combines fractionation with porewater speciation and, where feasible, spectroscopic characterization of the solid phase. Reports of prolonged immobilization should identify the pool that remained restricted, the conditions at sampling, and the duration observed. Changes in extractable and dissolved arsenic should be presented as complementary, not interchangeable, evidence.

3.2. Microbial processes and amendment persistence

Water management alters both microbial communities and the arsenic chemistry of the rice rhizosphere. A field study documented differences in rhizosphere communities between intermittently and continuously flooded rice [27], while a related investigation considered arsenic speciation and iron-reducing bacteria in contrasting rhizosphere compartments [28]. The reports address complementary measurements and should not be interpreted as independent confirmation of the same causal process without examining their experimental relationship. They also show why bulk soil alone may not represent the chemical and microbial conditions experienced at the root surface. Microorganisms can influence arsenic mobility in opposing directions. Experiments have linked iron-reducing bacteria to increased arsenic mobilization in the rice rhizosphere [29], while microbial arsenic methylation provides an additional route for changing the chemical species present near roots [30]. The net effect depends on the transformations occurring, their rates, and the species that reach the plant. Changes in microbial abundance or community composition should therefore not be described as improved arsenic control unless supported by evidence of altered arsenic chemistry and exposure.

Long-term manure application provides an example of interacting biological and chemical effects. Changes in rice-rhizosphere bacterial communities and arsenic-related genes accompanied changes in grain arsenic speciation [31]. These associations suggest possible microbial contributions but do not, on their own, establish that a particular taxon or gene caused the grain response. Organic additions can also change available carbon, nutrient supply, and redox conditions. Functional gene abundance should therefore be distinguished from directly measured rates of arsenic transformation, and microbial explanations should be evaluated alongside these alternative pathways. Aging adds a further time dependence that is not necessarily monotonic. During an incubation of arsenic- and lead-contaminated mining soil, selected biochars initially increased arsenic mobility before subsequent changes in retention over the incubation period [32]. In a separate two-year field study of polluted soils, biochars sorbed trace elements but did not consistently lower the $CaCl_2$ -extractable pools in the surrounding soils [33]. These studies show that material surface changes and whole-soil extractability need not move together. Neither involved a demonstrated rice-grain endpoint, so their relevance to sustained protection under paddy wetting and drying remains a hypothesis to test.

Long-term stabilization is nevertheless possible under particular conditions. Reactive iron phases were found to contribute to arsenic retention in contaminated soils sampled 2–15 years after zero-valent iron treatment [34]. This observation cautions against treating aging as inevitable failure, but the studied soils were not equivalent to repeatedly flooded and drained rice fields. The unresolved question is whether iron-associated retention can persist through comparable redox cycles and continue to reduce root exposure and grain accumulation. Long elapsed time in one soil environment is not a substitute for evidence across different environmental histories. Persistence should consequently be evaluated against two distinct dimensions: time since application and the sequence of conditions experienced during that time. A useful experiment would compare aged and fresh material under the same soil and water conditions, then test whether either continues to retain arsenic after a defined reducing event and subsequent re-oxidation. Measurements of mineral transformations, dissolved arsenic species, and plant uptake could distinguish survival of the original amendment from formation of new reactive phases or temporary suppression of arsenic release. These are competing explanations requiring direct testing, not assumptions that can be assigned to every material.

4. Roots as Active Controls on Arsenic Availability

4.1. Root modification of the rhizosphere

Rice roots actively modify the rhizosphere in which arsenic and soil amendments interact. In hydroponic experiments, radial oxygen loss (ROL) and external aeration affected iron (Fe) plaque formation and arsenic accumulation, with responses varying among rice genotypes and root positions [35]. Oxygen released from roots can promote Fe (II) oxidation and precipitation near the root surface, creating reactive mineral surfaces whose abundance and properties depend on local conditions [35]. Because oxygen release is

spatially heterogeneous, plaque measurements from whole-root samples should not be assumed to represent young root tips, lateral-root junctions, and older root segments equally. Soil-based experiments have also linked root oxidation to arsenic redistribution and sequestration at the rice root surface [36]. These observations indicate reciprocal controls: soil redox conditions influence the arsenic presented to roots, while root activity modifies the immediate chemical environment in which arsenic may be retained or released. An unplanted soil incubation is consequently informative about amendment chemistry but cannot reproduce root-driven oxygen gradients or all rhizosphere reactions. Evidence from mixed forest plantations also demonstrates that belowground interactions can regulate rhizosphere phosphorus mobilization and plant biomass. Comparisons of planted and unplanted soil can reveal a plant-associated effect, although they cannot by themselves distinguish oxygen release from exudation, nutrient uptake, and microbial responses.

Carbon inputs add a further source of ambiguity. Iron-reducing bacteria have been implicated in enhanced arsenic mobilization in the rice rhizosphere [29], but plant exudates and amendment-derived organic carbon may supply different substrates and change microbial activity in different ways. To test their respective contributions, studies should combine measurements of exudate composition and dissolved organic carbon with Fe reduction and arsenic-speciation measurements. An association between bulk carbon content and dissolved arsenic would not identify which carbon source, microorganism, or reaction was responsible. Rice genotype influences whether a change at the soil–root interface leads to lower grain arsenic. A multi-site study documented substantial variation in grain arsenic among cultivars and growing environments [37], while multi-environment screening showed that stable low accumulation of arsenic and cadmium cannot be inferred from performance in a single setting [38]. Therefore, an amendment response obtained with one cultivar should not be generalized without considering differences in root architecture, oxygen release, uptake, and development. Contrasting cultivars tested under matched soil and irrigation conditions would help determine whether a proposed root-mediated mechanism is transferable. Crop development should be recorded alongside the drainage and reflooding schedule. Sampling at tillering, booting, heading, and grain filling could help establish whether differences between cultivars arise from contrasting exposure histories or stage-dependent root behavior. Such measurements may improve interpretation, but their capacity to predict harvested-grain arsenic remains a hypothesis requiring evaluation against established genotype-by-environment effects [37,38].

4.2. Iron plaque and the soil–root interface

Iron plaque offers reactive surfaces at the soil–root interface, but its distribution is uneven. Root imaging and arsenic-speciation measurements show that arsenic is not confined to plaque and that recently formed roots or root regions may carry relatively little Fe coating [39]. As a result, a whole-root extraction combines segments with different ages, mineral coatings, and exposure histories. Increased plaque-associated arsenic may indicate more effective surface retention, greater external arsenic supply, or both. Assessing protection requires paired measurements of porewater arsenic, plaque-associated arsenic, and arsenic within root tissues, with the operational separation of these pools stated explicitly. The mineral composition of plaque is as important as its quantity. A method that preserved intact plaque revealed silicon-associated changes in Fe mineral composition together with differences in shoot arsenic [40]. This supports the view that plaque mass alone cannot predict arsenic retention or plant uptake. A treatment may alter reactive mineral phases, competing solutes, or the stability of arsenic-bearing plaque without producing a proportional change in plaque Fe. Mineral characterization, where feasible, should accompany quantitative plaque measurements before a protective mechanism is assigned.

Plaque-related Fe deposition also changes with crop development. In a pot experiment, removable vinyl films positioned adjacent to rice roots captured rhizosphere Fe deposition over time [41]. Deposition increased during vegetative growth, reached a maximum around booting, and subsequently declined; a similar temporal pattern was observed in the ratoon crop [41]. Silicon influenced the timing of deposition, but its effects on the amount of Fe recovered from harvested roots were not equivalent [41]. Importantly, films sample deposition in the root-influenced soil and cannot be treated as a direct measure of the plaque mass adhering to roots. Studies should distinguish deposition rate, accumulated Fe on sampling surfaces, root-associated plaque extracted at harvest, mineral composition, and plaque-associated arsenic. Recent experiments with goethite-modified biochar examined how irrigation-dependent Fe redox behavior and plaque dynamics relate to arsenic and cadmium movement in rice [42]. These findings strengthen the case for evaluating an amendment together with the water regime under which it is used. Nevertheless, covariation among soil chemistry, plaque abundance, and tissue concentrations does not isolate a single causal pathway. A stronger test would separately quantify arsenic retained by the amendment, arsenic associated with root-surface Fe, and arsenic taken up into the root and shoot.

The protective role of plaque must therefore be treated as conditional rather than universal. Plaque may limit arsenic entry in some settings, but its net effect depends on external exposure, root distribution, competing nutrients, mineral stability, and internal transport. Evidence that rice husk amendments change silicon availability while irrigation determines important grain arsenic and cadmium responses [43] reinforces the need to measure nutrient acquisition and co-contaminants alongside arsenic. A rise in plaque Fe alone is not sufficient evidence of lower grain arsenic. Methods should state whether reported root arsenic includes surface-associated material, how roots were washed, and whether plaque was chemically extracted or imaged before internal tissue analysis. Standardized preparation and complementary imaging can improve comparability, but agreement among analytical pools does not by itself establish causation. Figure 2 illustrates how water transitions, developmental stage, plaque observations, and grain endpoints could be aligned to test whether apparent soil retention is maintained through the crop cycle.

5. From Root Exposure to Rice Performance and Grain Composition

5.1. Uptake and physiological responses

Arsenic uptake depends on the chemical species reaching the root. Experiments on rice seedlings demonstrated distinct uptake kinetics for different arsenic species [44]. In rice, the silicon influx transporter Lsi1 permits arsenite entry, while the efflux transporter Lsi2 contributes to its movement across root tissues toward the xylem; mutation of Lsi2 substantially reduced arsenic accumulation in shoots and grain in the experimental material studied [15]. An amendment that changes dissolved arsenic speciation or plant-available silicon may therefore affect uptake without producing a corresponding decrease in total dissolved arsenic. Demonstrating this pathway in an amended soil requires species-resolved exposure and uptake measurements. Plant metabolism and internal transport add further controls between root exposure and grain accumulation. OsHAC1;1 and OsHAC1;2 catalyze arsenate reduction and influence arsenic accumulation in rice [45], whereas the ABC transporter OsABCC1 limits grain arsenic by sequestration in vacuoles of node phloem companion cells [16]. Manipulating plant transport has also been shown to reduce grain arsenic in engineered rice [46]. These studies identify established plant functions, not evidence that a soil amendment activates them. Changes in transcript abundance following amendment application should be described as associations unless transporter activity, species-specific fluxes, or suitable genetic comparisons establish the proposed mechanism.

A plant may also tolerate arsenic without excluding it. Comparative rice studies have identified biochemical and molecular responses associated with contrasting arsenic tolerance [47], but greater growth does not necessarily imply lower arsenic uptake or reduced transfer to grain. Tissue concentration is influenced by both the arsenic mass present and the biomass in which that mass is distributed. Consequently, a fall in concentration may reflect reduced acquisition, redistribution, or biomass dilution. Evaluations of plant protection should report tissue arsenic concentration together with biomass, estimated arsenic content where feasible, and indicators of injury, avoiding any inference of exclusion from growth alone. Silicon-rich amendments illustrate the need to integrate nutrient supply with contaminant exposure.

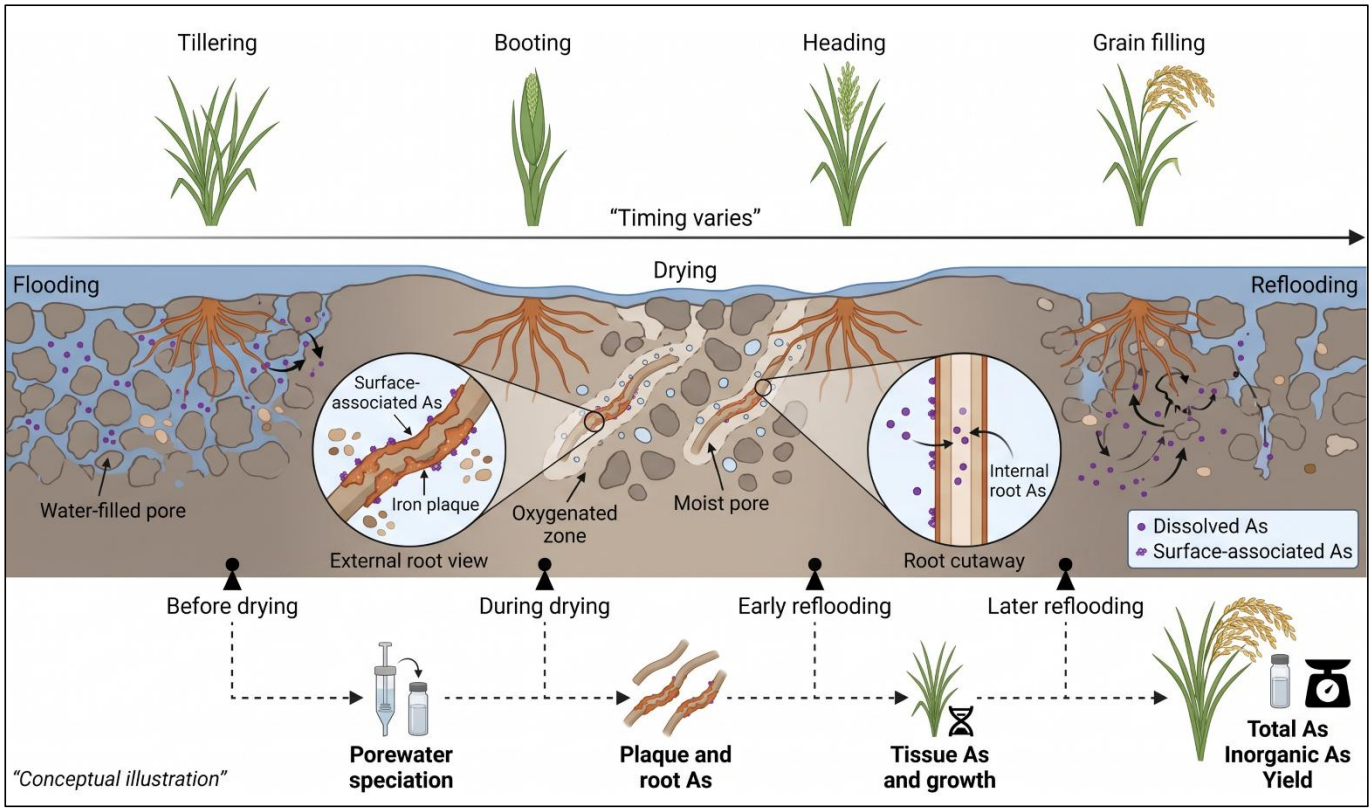


Figure 2. Coordinating arsenic measurements with water transitions and rice development. The proposed timeline aligns flooding, drainage, and reflooding with crop stage, porewater arsenic speciation, rhizosphere Fe deposition, root-associated plaque, tissue arsenic, and harvested grain composition. Reported stage-dependent plaque formation provides a mechanistic basis for temporal sampling [41], but any trajectories drawn in the figure are schematic rather than measured treatment responses. Deposition on sampling films and plaque extracted from roots are distinct endpoints. The diagram identifies measurements needed to test whether changes in soil retention coincide with root exposure and eventual grain accumulation; comparable season-average exposure is not assumed to imply equivalent grain outcomes. The figure was created using BioRender: Scientific Image and Illustration Software (Toronto, Canada; app.biorender.com).

A pot comparison of rice husk, husk ash, and calcium silicate reported different responses in arsenic-related yield loss and grain arsenic, associated in part with differences in silicon and nutrient release [17]. A rice-paddy mesocosm experiment linked residue amendments with changes in plant silicon, arsenic uptake, plaque mineralogy, and grain speciation [48]. Materials with similar total silicon content should therefore not be assumed to provide equivalent plant-available silicon or arsenic protection. The timing of release and the surrounding soil chemistry are relevant to both mechanisms. Organic residues also deliver carbon that can alter arsenic cycling independently of their silicon content. In unplanted flooded soils, fresh rice straw, husk, and corresponding ashes caused different porewater responses; fresh straw promoted greater mobilization of dissolved Fe and arsenic in the tested conditions [49]. Because this study did not include growing rice, it does not establish whether these changes increased plant uptake or grain arsenic. Its relevance is to show why silicon supply and readily decomposable carbon should be assessed jointly, then tested in planted soils under the intended irrigation regime.

5.2. Grain accumulation and agronomic outcomes

Root or shoot arsenic concentrations cannot directly predict the chemical composition of harvested grain. Excised-panicle experiments showed species-dependent unloading into rice grain, including relatively efficient movement of dimethylarsinic acid (DMA) [50]. Experiments introducing arsenic species through flag leaves separately demonstrated differences in phloem transport during grain filling [51]. These controlled studies identify distinct transport processes, but their transfer rates should not be imposed as universal coefficients for field-grown plants. They instead support tracking the species available for internal redistribution when interpreting differences between root exposure and grain composition. Arsenic speciation complicates any simple classification of organic arsenic as harmless. Silicon addition reduced grain DMA and mitigated straighthead disorder under controlled conditions [52], while subsequent experiments identified dimethylmonothioarsenate (DMMTA) as an important contributor to rice straighthead injury [53]. Thiolated arsenic species have been identified in rice products [54], and DMMTA has been reported in grain samples from multiple regions [55]. These findings do not make all organic species equally toxic; they show that the inorganic-versus-organic classification alone is inadequate for interpreting potential hazards. Grain inorganic arsenic remains a central food-safety endpoint, but other identified species should be reported separately rather than grouped as uniformly detoxified arsenic. Analytical preparation is critical: nitric acid extraction can transform monothioarsenate to arsenite and dimethylated thioarsenates to DMA, changing the species subsequently measured [54]. Methods should therefore report extraction chemistry, recovery, and species-preservation checks, without implying that routine inorganic arsenic results are necessarily invalid.

The severity and timing of drying influence the grain endpoint against which amendments are evaluated. Aerobic rice cultivation reduced arsenic accumulation in an experimental comparison [56]. In a two-season field study, the two stronger alternate-wetting-and-drying treatments reduced total arsenic in polished grain by 56–68% relative to continuous flooding, whereas milder drying did not achieve a comparable statistically significant reduction [21]. A separate experiment varying the timing and severity of a single drying event showed that lower total grain arsenic did not always correspond to lower inorganic arsenic [57]. These values describe water-management responses, not amendment effects. Reporting actual soil moisture dynamics, the harvested product, and species-specific grain concentrations is essential before applying such evidence to amendment decisions. Grain quality and production outcomes should be assessed alongside arsenic. Multi-location irrigation experiments have jointly examined water use, greenhouse gas emissions, yield, and grain arsenic, identifying trade-offs across water-management practices [58]. On-farm studies of midseason drainage reported an average reduction in grain arsenic of approximately one-fifth without a corresponding increase in grain cadmium or a clear yield penalty under the conditions tested [59]. Other irrigation comparisons have assessed nutrient elements, yield components, and starch-related grain quality [60]. Because these studies differ in water regimes, grain processing, and analytical endpoints, their results should not be combined into a single amendment-effect estimate or treated as interchangeable indicators of food safety.

A minimum grain-reporting set should distinguish brown from polished rice, total arsenic from inorganic arsenic, and dry-mass from fresh-mass concentrations, as illustrated by irrigation studies that considered both arsenic and cadmium [13,14]. Grain dry mass and yield should accompany concentration so that total arsenic mass in harvested grain can be estimated when appropriate. Concentration describes exposure per unit product, whereas total arsenic mass helps distinguish reduced transfer from biomass or yield dilution. Cadmium, silicon, and nutritionally important elements should be reported where they are relevant to the proposed amendment mechanism. These are analytical recommendations, not additional regulatory limits. Absence of visible injury is not evidence of grain protection. Controlled studies demonstrate that arsenic species can have different consequences for vegetative and reproductive development [52,53]. Each treatment claim should therefore identify its endpoint: root growth, vegetative biomass, reproductive fertility, grain yield, total grain arsenic, or inorganic grain arsenic. Evidence for biochemical tolerance [47] and evidence for reproductive injury from methylated species [52,53] answer different questions and should not be collapsed into one general measure of arsenic resistance.

Exposure timing offers a testable explanation for otherwise inconsistent amendment responses. Two treatments with comparable season-average porewater arsenic might lead to different grain outcomes if exposure peaks occur at different developmental stages or involve different arsenic species. Drying-timing experiments [57] and evidence of species-dependent grain transport [51] make this plausible, but they do not validate a universal developmental weighting rule. A discriminating experiment would impose different exposure sequences while measuring porewater species,

developmental stage, tissue arsenic content, biomass, and final grain composition. Changes in nutrition, root damage, and yield dilution would need to be assessed as competing explanations.

6. What Evidence Demonstrates Sustained Protection?

6.1. What existing experiments establish

Table 1 contrasts long-term soil stabilization, laboratory aging, planted pot trials, and field management experiments. These evidence types are not interchangeable: persistence of a chemical fraction in soil does not demonstrate sustained reductions in rice grain, while a grain response in one season does not establish durability across repeated wetting and drying. The comparisons below focus on what each study actually measured and on the limits of its treatment history, setting, and crop endpoint. The distinction is clear in a laboratory comparison of Fe- and Al-based amendments. Both decreased soluble or leachable arsenic in initial tests, but Fe-associated retention became less stable under reducing conditions, when Fe reduction promoted remobilization [61]. This supports challenging amendments with environmental conditions relevant to their intended use. It does not establish a rice-grain advantage for the Al treatment, because crop performance and harvested grain were not evaluated [61]. Any agronomic recommendation would require assessment of plant growth, nutrient balance, and grain composition under realistic water management.

Iron-impregnated biochar has also been tested under simulated irrigation and accelerated aging, with arsenic retention varying among soils and organic-additive conditions [62]. Measurements of culturable bacteria provide a biological indicator, but do not establish microbial arsenic-transformation rates or a causal explanation for retention [62]. These screening results are useful for identifying candidate materials and settings. They cannot be converted into a stated number of successful field seasons without calibration, nor do they establish rice uptake or grain protection. Subsequent testing should retain matched water conditions while adding a planted crop and a harvested-grain endpoint. Rice pot studies show why growth, soil chemistry, and grain results must be considered separately. In a two-year continuous-cropping experiment, bamboo biochar applied at 3% or 5% by mass increased dissolved Fe and arsenic and improved some growth variables, but did not significantly lower grain arsenic [63]. A separate study compared fresh and six-month naturally aged chitosan-functionalized biochar in a subsequent greenhouse rice crop, predominantly under flooding [64]. Fresh and aged chitosan-functionalized treatments reduced grain arsenic concentrations by 43.1% and 32.8%, respectively, relative to the unamended control [64]. However, differences among the tested biochar treatments in grain arsenic were not statistically significant [64]; the numerical contrast should not be presented as proof that aging weakened grain protection. Pre-aging followed by one crop also does not demonstrate persistence over repeated flooded–dry cycles or cropping seasons.

Table 1. Selected studies relevant to persistence of arsenic retention and protection of rice grain.

Study	Treatment and setting	Reported finding	Evidence boundary
Kumpiene et al. [34]	Fe treatment; soil sampled 2–15 years later	Reactive Fe phases contributed to As retention	No rice crop or grain endpoint
Lai and Basta [61]	Fe or Al; laboratory redox tests	Fe-associated As remobilized during reduction	No planted rice or harvest
Li et al. [64]	Fresh and six-month aged functionalized biochar; one rice crop	Both reduced grain As; numerical difference not significant across biochar treatments	Pre-aging is not repeated-season AWD
Song et al. [63]	Bamboo biochar; two-year rice-pot trial	Growth responses and grain As reduction did not coincide	Pot evidence; grain As was not significantly reduced
Vicente et al. [65]	Single biochar dose; three field years and irrigation treatments	Added biochar benefit for grain As disappeared by year three	Material age confounded with calendar year
Wen et al. [68]	Fe-modified biochar; rice pots under different water regimes	Brown-rice As decreased while Cd and Pb increased	Co-contaminants require concurrent assessment
Chen et al. [69]	Layered double hydroxides; alternating wet–dry soil–rice test	Grain Cd, total As, and inorganic As were reduced	Field-season persistence not established
Alvarenga et al. [70]	Compost and sprinkler irrigation; three-year field experiment	Arsenic benefit largely reflected irrigation	Independent compost effect on As unclear

Note: The entries are selected contrasts, not a quantitative ranking. Duration refers to the observation period or material history reported by the original study; it does not necessarily indicate repeated successful harvests. Grain arsenic refers to total arsenic unless inorganic arsenic is specified.

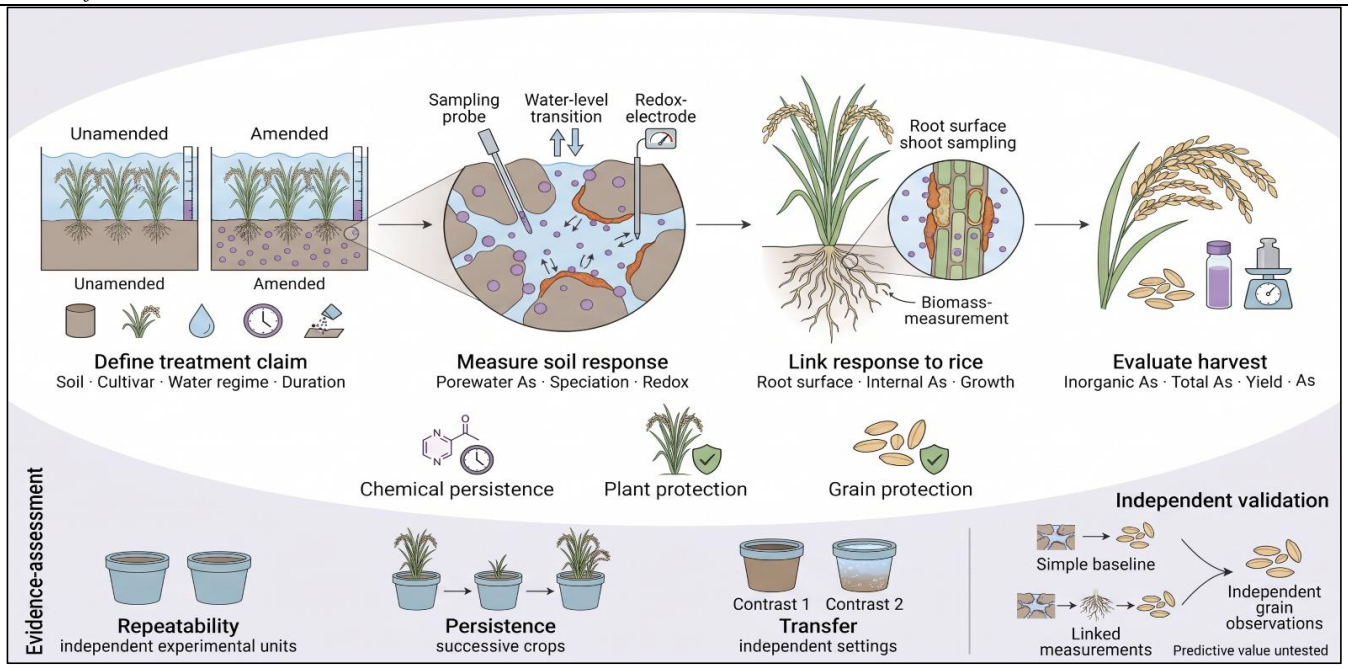


Figure 3. Proposed evidence framework for sustained arsenic protection in soil–rice systems. The sequence begins with a defined treatment claim, including soil, cultivar, amendment dose, water regime, and observation period. It then connects arsenic speciation and retention across drainage–reflooding transitions with root-surface and internal tissue measurements, plant performance, and harvested-grain composition. Experimental repeatability, persistence through cropping seasons, and transfer to independent settings are distinct evaluation levels. Chemical persistence, plant protection, and grain protection may have different degrees of support. The diagram presents proposed comparisons rather than a validated causal or predictive model. The figure was created using BioRender: Scientific Image and Illustration Software (Toronto, Canada; app.biorender.com).

Longer field trials are especially informative. A three-year Mediterranean rice trial combined a single biochar application with continuous flooding or alternate wetting and drying at two intensities [65]. The additional reduction in grain arsenic attributable to biochar was reported during the first two years but was no longer evident by the third year [65]. This is direct evidence of diminishing treatment contribution in that setting, not a basis for claiming that all amended soils lose effectiveness over time. Because material age, calendar year, and seasonal conditions changed together, an age-specific causal effect would require comparison of fresh and previously applied material within a common season. Modified materials can improve arsenic outcomes but can alter other contaminant pathways. A pot study reported lower arsenic accumulation after applying ferromanganese oxide-impregnated biochar and examined associated plant and plaque responses [66]. A field comparison found different effects of carbide slag, lodestone, and biochar on arsenic and cadmium availability and plant accumulation [67]. In another rice-pot study, a Fe-modified biochar reduced arsenic in brown rice while increasing cadmium and lead relative to the corresponding control [68]. Such results argue against selecting amendments from arsenic data alone. Grain cadmium and other relevant contaminants should be monitored with arsenic, especially when water management changes.

Magnesium–iron layered double hydroxides have more recently been studied under alternating wet–dry conditions. The reported experiment coupled soil chemical measurements and microbial responses with reduced cadmium, total arsenic, and inorganic arsenic concentrations in rice grain [69]. This integrates more of the soil-to-crop pathway than a laboratory sorption test. However, microbial associations should not be described as direct transformation mechanisms without process-specific evidence, and protection during an imposed sequence should not be conflated with persistence through multiple field seasons. Factorial water-management comparisons are essential for identifying the source of an observed benefit. In a three-year field study, changes in rice-grain arsenic were mainly associated with sprinkler irrigation, whereas compost effects on arsenic were not clearly established; compost had a more apparent role in cadmium responses [70]. A separate pot experiment found that rice husk amendments increased porewater and plant silicon, while irrigation treatment was a major determinant of grain arsenic and cadmium [43]. In that study, some husk-amended treatments under alternate wetting and drying had higher inorganic grain arsenic than the unamended treatment [43]. These cases show that a nutrient benefit cannot be substituted for a contaminant endpoint. Amended and unamended treatments should be compared under matched water regimes before any additional benefit is attributed to an amendment.

6.2. A proposed framework for evaluating persistence

Sustained protection should be evaluated using

connected evidence rather than a single success indicator. The first step is to define the claim and its boundary: lower extractable arsenic after an incubation is not equivalent to lower inorganic arsenic in grain over several cropping seasons. A defensible conclusion should specify soil properties, rice cultivar, amendment identity and dose, irrigation and redox history, application or reapplication schedule, analytical endpoint, and observed duration. Chemical persistence may result from newly formed reactive phases even if the original amendment changes structurally. Conversely, recovery of the amendment itself does not demonstrate that arsenic exposure or grain concentrations remain low. The framework proposed here is an approach to organizing evidence, not a validated prediction system. The second step is to assess the chemical response across relevant environmental transitions. Sampling should bracket drainage, the drying phase, reflooding, and any subsequent arsenic release or retention events. Redox potential should be reported with electrode depth and reference-electrode convention, together with soil moisture, pH, dissolved Fe, and arsenic speciation. A favorable redox range observed in one study [43] should not be generalized as a threshold for all rice soils. Such thresholds would require independent tests across contrasting mineralogy, organic matter, soil pH, and exposure histories.

Time since application must be separated from the effects of repeated amendment delivery. Following a single application through several harvests evaluates persistence of the original intervention; reapplication evaluates a continuing management strategy. Both designs can be agronomically useful, but the costs and conclusions differ. Reports should state when materials were added, whether they were replaced, and whether any recovery in performance occurred before or after replenishment. A successful reapplication cannot establish uninterrupted protection from the first dose. The third step connects changing soil exposure with plant processes. Developmental variation in Fe deposition [41] and species-dependent transport into grain [50,51] justify sampling at informative crop stages. Experiments should distinguish arsenic associated with root surfaces from internal root arsenic, monitor plant biomass and tissue arsenic content, and align root measurements with porewater chemistry and water transitions. If a grain response is attributed to a specific transporter or plaque-mediated barrier, direct functional evidence or a discriminating experimental contrast is needed; final root-to-grain concentration ratios alone are insufficient.

The fourth step evaluates harvest endpoints across time. Grain processing, arsenic speciation, yield, cadmium, and relevant nutrients should be reported for each measured season. A decline in the additional benefit of an amendment should be acknowledged even if the amended treatment remains better than its control. Conversely, aging should not be treated as failure when measured crop protection persists. This separation allows chemical persistence, plant protection, and grain protection to receive different evidence judgments within the same experiment. The independence of evidence matters as much as the number of observations. Repeated porewater samples from one pot improve temporal resolution but do not provide new experimental replicates. Several harvests at one site can demonstrate local durability but cannot establish performance across soils, cultivars, or climates. Interpretation should therefore distinguish treatment replication, repeated-season persistence, and independent-site reproducibility, with uncertainty retained wherever these have not been tested.

Finally, predictive value requires external validation. The proposed sequence of soil, root, and grain measurements could be used to predict inorganic grain arsenic prospectively, then evaluated in a different season or field. It should be compared with simpler baselines, such as initial extractable soil arsenic, water management, or measured soil properties alone. If the added transition-resolved and root observations do not improve predictive performance, their incremental predictive benefit would not be supported for the tested conditions. Prediction errors, uncertainty, and unfavorable cases should be reported. Figure 3 summarizes this proposed evaluation sequence and makes clear that its usefulness remains to be demonstrated.

7. Management implications and research priorities

Amendment choice should begin with the actual soil–rice production system, not a generalized ranking of materials. Iron amendments have reduced soil-solution arsenic and grain accumulation under specific experimental conditions [20], while biochar-supported Fe behavior depends on the surrounding soil matrix [23]. Studies should therefore report feedstock, synthesis or modification method, application rate, initial soil pH and mineralogy, and water-management history. Silicon-rich residues can change both nutrient supply and biogeochemistry through accompanying carbon inputs [49], and sulfur application has been associated with water-dependent arsenic responses [71]. These findings support initial screening under the intended irrigation regime, followed by planted tests before field recommendations are made. Materials tested under continuous flooding should also be challenged by the drying depth, frequency, and timing expected in practice, including subsequent reflooding. Nitrate addition has been investigated as a modifier of arsenic redox transformations and transfer in flooded soil–rice seedling systems [72]. Nanoscale sulfur has separately been tested for its influence on arsenic stress and accumulation in rice through more advanced growth stages [73]. Their different crop stages and outcomes do not justify direct comparison of effectiveness or unrestricted field application. Agronomic evaluation must consider rates, nutrient and contaminant trade-offs, environmental persistence, and harvested-grain composition.

The proposed diagnostic comparisons in Table 2 focus on uncertainties most relevant to sustained protection. They ask whether an initial amendment benefit survives successive drainage–reflooding sequences, whether transient porewater arsenic peaks overlap periods of active uptake, and when soil-mineral retention and root-associated Fe reinforce or counteract one another.

Table 2. Proposed diagnostic comparisons for testing sustained arsenic protection in soil–rice systems.

Diagnostic test	Measurements	Key comparison	Interpretation boundary
Retention after reflooding	Porewater As species, dissolved Fe, pH, moisture, redox	Amended versus unamended, with matched water history	Post-drainage retention does not prove post-reflooding retention
Root contribution	Root-surface and internal As; plaque distribution, composition or formation	Planted versus unplanted; distinct tissue and plaque pools	Plant effects do not identify a single root mechanism
Exposure timing	Time-resolved As species, crop stage, tissue As, grain composition	Contrasting sequences at comparable overall exposure	Control for nutrition, damage and dilution
Persistence of one dose	Application dates, soil response, yield, grain inorganic As	Single dose across seasons; reapplication separately	Repeated dosing tests a management program
Grain concentration versus amount	As concentration, grain dry mass, product type	Concentration and estimated grain As mass together	Lower concentration may reflect dilution
Transfer across settings	Speciation recovery, Cd, nutrients, yield; predictive errors	Independent season, soil, or cultivar with prospective test	Within-study fit does not show transfer

Note: These comparisons are proposed research tests, not a validated scoring system, monitoring standard, or regulatory threshold. Individual studies should select the measurements needed to resolve their specified mechanism and management claim.

Matched controls, recorded water conditions, and repeated measurements are more important than an indiscriminately large factorial experiment. A well-chosen contrast can isolate one mechanism while leaving other mechanisms as explicit limitations. Field validation should distinguish controlled interventions from observational surveys. A 2026 Arkansas study analyzed polished white rice from 103 field-years under production-scale water management [74]. Multiple measured soil-aeration events were associated with lower total and inorganic grain arsenic, whereas the single-aeration category did not show the same significant reduction; grain cadmium remained low in those sampled fields [74]. The survey provides valuable evidence across management settings, but it did not randomize an amendment treatment or measure root arsenic availability, and its regional cadmium results should not be generalized to other soils. For amendment studies, its main lesson is the value of evaluating performance under real-world variation in irrigation and soil conditions.

Persistence should also be expressed in terms relevant to farming. Reports should identify the number of crops evaluated, whether the amendment was reapplied, the water regimes encountered each season, and the consistency of inorganic grain arsenic and yield responses. Reapplication may be a defensible management option, but it should be assessed as a recurring intervention with associated costs rather than evidence for a durable single dose. Transport, incorporation, material availability, monitoring requirements, and potential impacts on other contaminants all need consideration. Existing syntheses of agronomic approaches and field-tested remediation provide context for these practical questions [4,7]. Unfavorable results are essential to defining the limits of an amendment recommendation. Increased dissolved arsenic, better crop growth without lower grain arsenic, or arsenic reduction accompanied by elevated cadmium should be retained in reports rather than excluded as failed treatments. Comparable descriptions of controls, application dates, soil moisture history, grain-processing type, analytical recovery, and detection limits would make future synthesis more informative. Recommendations should state the conditions and duration over which benefit was actually observed and identify the measurements needed to verify that protection in later crops.

8. Conclusions

Sustained arsenic control in rice cannot be demonstrated by soil immobilization alone. Its effectiveness depends on whether arsenic remains less mobile through drainage and reflooding, whether root exposure and plant uptake are reduced, and whether these changes lead to lower arsenic concentrations in harvested grain. These outcomes are connected but not interchangeable. Improved plant growth or lower extractable soil arsenic does not, by itself, establish grain protection. Treatment performance must therefore be evaluated within a clearly defined soil, cultivar, water regime, and period of observation. Amendment aging should be judged by its measured effects on arsenic retention and crop outcomes, rather than assumed to cause either improvement or failure. Grain inorganic arsenic, yield, nutrient status, and cadmium accumulation should be assessed together, while changes in grain concentration should be distinguished from changes in total arsenic accumulation. The framework proposed here connects soil and porewater chemistry, rhizosphere processes, plant responses, and grain composition across water transitions and cropping seasons. Its predictive

value remains to be established. Future studies should use matched amendment and irrigation controls, sample around drainage and reflooding, and test outcomes across independent seasons, soils, and cultivars. Such evidence will help identify the conditions under which amendments provide lasting reductions in grain arsenic without compromising crop performance or creating additional contaminant risks.

Author contributions

Naseeb Ullah: Writing – original draft, reviewing and editing, conceptualization, data curation, figure making, and visualization; Siraj Ud Din: Writing, reviewing and editing, conceptualization, data curation, figure making, visualization, resources, software, formal analysis, and investigation;

Ethical approval

Not applicable.

Conflicts of Interest

The authors report no conflicts of interest.

Acknowledgment

The authors would like to express their sincere appreciation to their respective institutions for providing academic support and facilities during the preparation of this paper.

Data availability statement

Data sharing is not applicable to this article as no new data were generated or analyzed in this review.

Funding

No funding received for conducting this study.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used AI-assisted tools (specifically GPT-5) in order to polish the English language and enhance clarity. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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How to Cite: Ullah, N., & Din, S. U. (2026). Sustaining Arsenic Control from Soil to Rice Grain under Wetting and Drying. Journal of Soil, Plant and Environment, 5(2), 93–107.



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