

Assessing Soil Conditions Through Plant Accumulation of Toxic Substances

Research reveals how absorption of soil toxins by plants can indicate soil health, guiding effective management and remediation strategies.

Plants can serve as the direct indicators of soil environmental conditions because they readily absorb and accumulate toxic substances from the soil. By studying the mechanisms through which plants accumulate chemical or toxic substances, we may prevent crops from taking up these harmful substances. Additionally, analysis of plants may be used to evaluate the effectiveness of soil remediation. Here, we present the research findings from 2024 conducted at the NSRRC, which focused on how plants accumulate toxic substances from the soil and how this process can be used to assess the effectiveness of soil

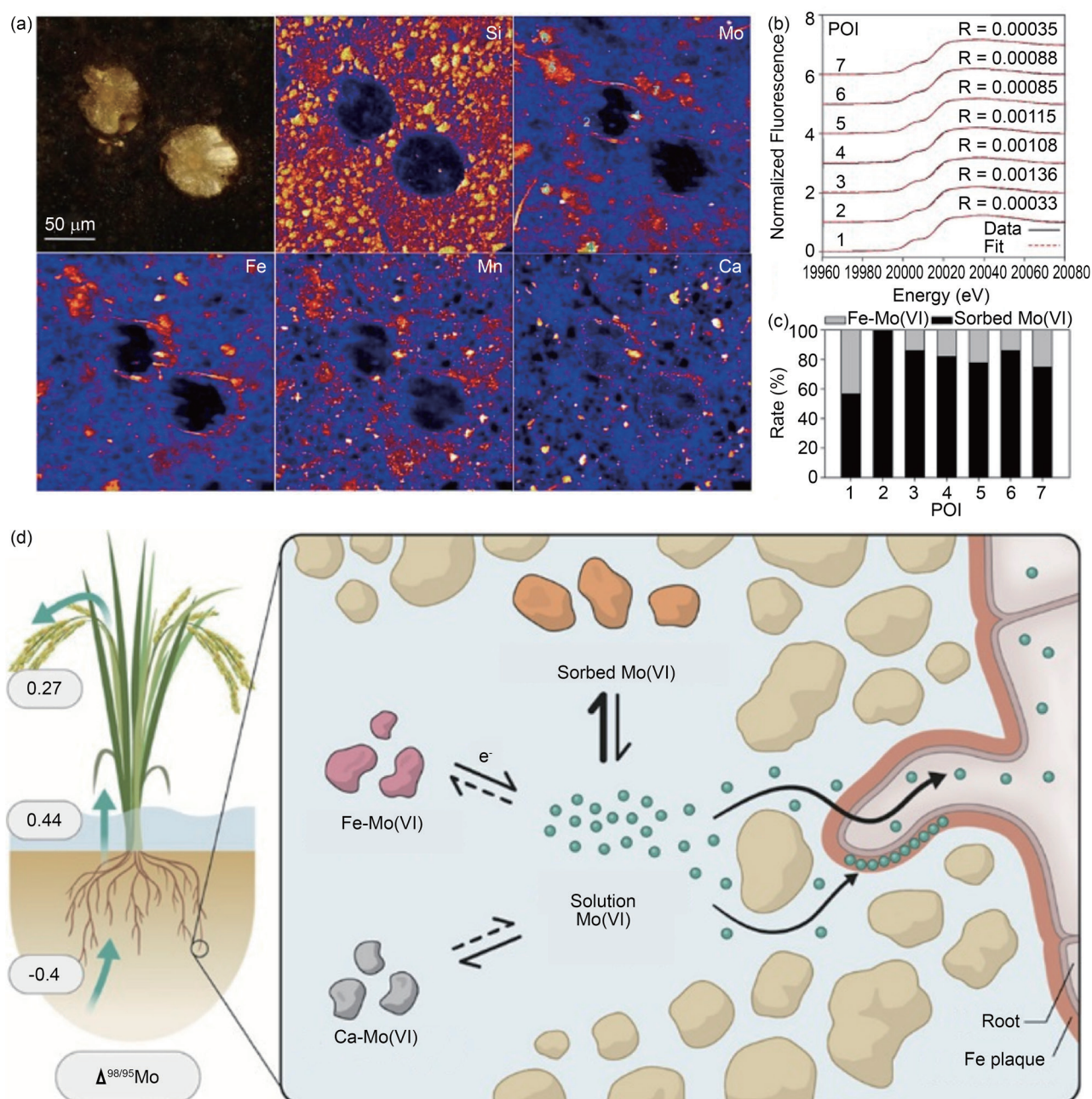


Fig. 1: (a) Microscopic view of rice roots, and spatial distributions of Si, Mo, Fe, Mn, and Ca; (b) μ -XANES spectra and (c) linear combination fits of the points of interest (POIs) indicated in (a). (d) Mechanism of rice uptake of soil molybdenum. [Reproduced from Ref. 1]

modification. With these discoveries, we aim to deepen our understanding of the interactions between plants and soil and to develop more effective soil management and remediation strategies.

Chemical Speciation and Uptake of Molybdenum by Rice

Molybdenum (Mo), a vital micronutrient for organisms, facilitates the metabolism of nitrogen, carbon, and sulfur and is crucial in enzyme catalysis. Although generally present in low concentrations in the Earth's crust, Mo levels can be elevated near industrial areas, potentially contaminating soil and accumulating in crops. This poses the health risks, including livestock poisoning and, in humans, conditions such as infertility and gout-like symptoms.

Rice, a major Mo dietary source for humans, often grows in submerged conditions that enhance Mo solubility and availability. This availability is further influenced by continuous flooding, which contrasts with the reduced Mo uptake seen in alternating wet–dry cycles. Key factors include soil redox processes driven by microbial activity and the dissolution of iron hydroxides, which affect the mobility of Mo compounds.

Shan-Li Wang (National Taiwan University) and his co-workers utilized X-ray absorption near edge structure (XANES) at **TPS 44A** and **TLS 16A1** and other microanalytical techniques to investigate how soil conditions affect Mo chemical forms and uptake in rice (**Fig. 1**). Their findings highlight the strong associations between Mo and Fe in the rice rhizosphere, which are facilitated by Fe plaques on root surfaces. This association promotes Mo dissolution/desorption, which is crucial for root absorption and subsequent transport to plant shoots, though only minimal amounts reach the grains.

The study reveals that Mo can accumulate significantly in rice without apparent toxicity, even in contaminated soils, raising concerns about Mo levels in consumed rice. Advanced studies in soil solution chemistry and Mo speciation provide the deeper insights into the complex dynamics of Mo availability and uptake, influencing the future research directions, particularly in Mo isotope fractionation. This study provides further understanding of the mechanisms affecting Mo's behavior in soil and its broader environmental and health impacts.

Physiology and Molecular Basis of Thallium Toxicity and Accumulation in *Arabidopsis thaliana*

Thallium (Tl) is a heavy metal with extensive applications across several industries, including chemical, pharmaceutical, optical, electronics, energy, and aerospace, as well as in superconducting materials and high-energy physics. Despite its limited annual production—approximately 10 tons globally—industrial processes inadvertently release an estimated 2,000 to 5,000 tons into the environment each year. This can significantly elevate Tl concentrations in contaminated soils, with well above the typical background level of less than 1 mg/kg found in most uncontaminated soils. Recognized for its extreme toxicity, Tl has been classified as a priority pollutant, which necessitates thorough research into its environmental impact, exposure routes, and toxicity.

Tl is particularly concerning because of its ability to be readily absorbed by plants, where it can disrupt potassium (K)-dependent biological processes and accumulate in the edible parts of plants, such as the roots and leaves. This accumulation poses the significant risks of food chain contamination. The model plant *Arabidopsis thaliana* (hereafter *Arabidopsis*), which is known for its fully sequenced genome, provides an excellent subject for mutagenesis studies aimed at understanding the physiological and molecular impacts of Tl. These studies are crucial for developing strategies to mitigate Tl toxicity and accumulation in plants.

Kuo-Chen Yeh (Academia Sinica) and his co-workers utilized the NSRRC **TPS 23A** X-ray nanoprobe beamline to perform X-ray fluorescence (XRF) analyses on *Arabidopsis* (**Fig. 2(a)**). These studies reveal that different concentrations of Tl not only inhibit growth and cause leaf chlorosis but also result in Tl accumulation in both roots and shoots, illustrating the plant's transport capabilities and the mechanisms of Tl toxicity.

Further investigations showed that Tl absorption occurs primarily through the roots, moving to the stems with increasing concentrations in the growth media. At peak levels, Tl concentrations reached 1,775 mg/kg in roots and 1,219 mg/kg in shoots. The plant demonstrated a significant transfer factor from roots to aerial parts, but this accumulation adversely affects the growth of both. The similarity in the distribution patterns of Tl and K within *Arabidopsis* suggests that they might share transport proteins or channels.

In addition to physiological studies, genetic and transcriptomic analyses aim to identify mutants with altered responses to TI and to explore the genes involved in its uptake and transport. Early transcriptional response studies have identified several TI-responsive genes associated with oxidative stress, antioxidant defense, K channel activity, and photosynthesis. These findings are integral to understanding TI's behavior in plants and the potential mechanisms of bioaccumulation (Fig. 2(b)), paving the way for future research and mitigation strategies.

Lemongrass and Sage Fertilized with Humic Acid Accumulate Toxins in Soil Treated with Heavy Oil Fly Ash

Saudi Arabia relies on over 40 million tons of heavy oil annually

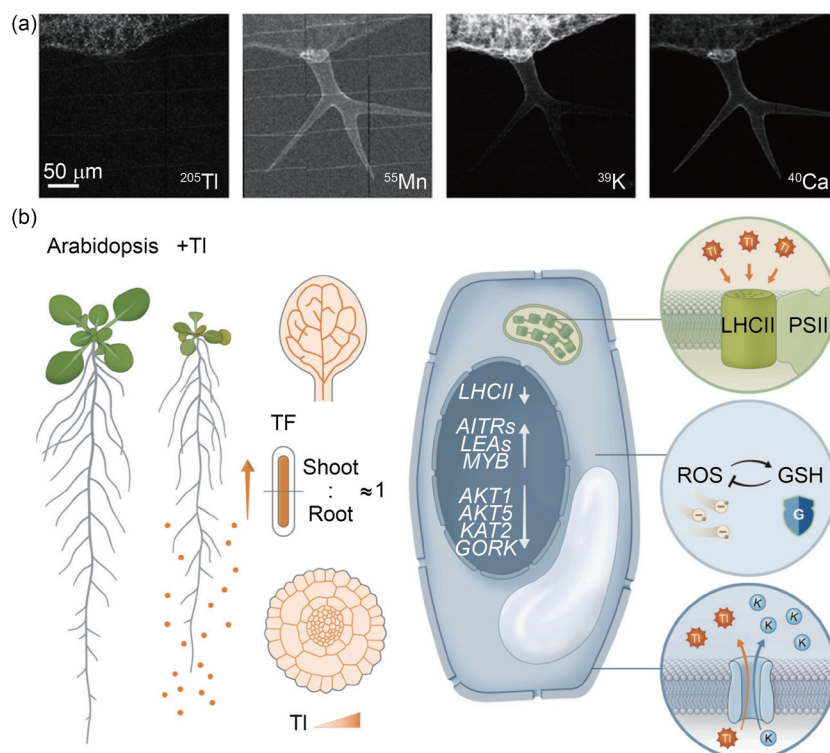


Fig. 2: (a) Synchrotron μ-XRF images of TI, Mn, K, and Ca distribution in TI-treated leaves. The elemental signal is shown in white. (b) A schematic representation of the uptake, toxicity, and accumulation of TI in Arabidopsis plants. [Reproduced from Ref. 2]

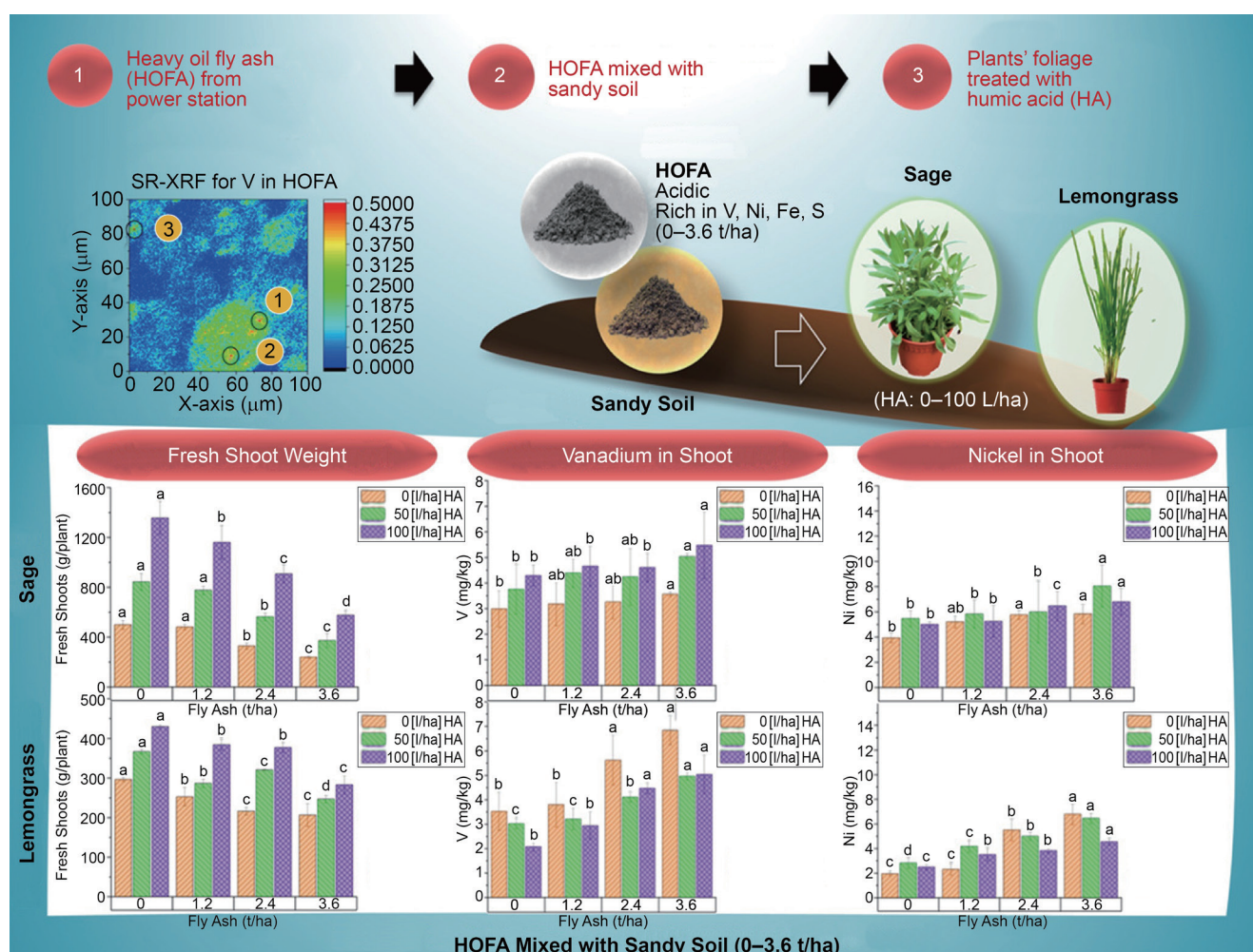


Fig. 3: Evaluating the effect of soil amendment with HOFA using sage and lemongrass as indicators. [Reproduced from Ref. 3]

for electricity and desalination, which contribute to 70% of its energy output, and it consumes about 320 million barrels of oil each year. This process results in the production of roughly 250,000 tons of heavy oil fly ash (HOFA) annually, with the individual facilities like the Rabigh power plant generating around 10,000 tons. Predominantly, HOFA is disposed of in landfills, a method that increases the risk of air, surface water, and groundwater pollution due to its content of unburned carbon and toxic inorganic compounds like vanadium and nickel.

Efforts to manage and mitigate HOFA's environmental risks are crucial. It has found uses in construction as a stabilizing material in cement, concrete blocks, asphalt mixtures, and in synthesizing glass ceramics. Additionally, HOFA serves economical roles in recovering valuable metals and as a water treatment adsorbent. However, its application in agriculture as a soil amendment is less explored because of the high levels of toxic elements it contains, which can harm soil quality and plant growth.

Samir Gamil Mohammad Al-Solaimani (King Abdulaziz University, Saudi Arabia) and his co-workers conducted research using the NSRRC **TPS 23A** beamline, including XRF imaging and XANES analysis. These techniques aided in assessing the impact of varying HOFA doses on sandy soils' nutrient and toxic element profiles and explored the effects of humic acid on plant growth and elemental uptake (**Fig. 3**).

Results indicated a significant presence of vanadium, nickel, iron, and sulfur in HOFA, with lower levels of chromium and manganese and minimal silicon. Notably, about 17.3% of vanadium exhibited high mobility, potentially increasing the environmental risks. Experiments demonstrated that low HOFA doses (1.2 to 3.6 tons per hectare) slightly affected soil pH, electrical conductivity, and element content, while higher doses adversely impacted plant growth. Treatment with humic acid significantly improved plant resilience to HOFA-induced stress.

Among the species tested, common sage showed the superior capability in accumulating elements compared to lemongrass, though both remained below critical toxicity thresholds. The findings suggest that controlled application of HOFA could enhance nutrient levels in low-fertility soils without severely altering their properties, particularly when combined with humic acid. Common sage also displayed potential for phytoremediation in HOFA-treated soils containing nickel and vanadium. These insights confirm the potential of HOFA as a resource for improving soil health in arid environments and offer new strategies for its disposal that are relevant both within Saudi Arabia and globally.

These studies underscore the critical role of plants in monitoring and improving soil health, providing the valuable data that can inform soil management strategies and mitigate pollution. The findings from the NSRRC in 2024 emphasize the complex dynamics of substance accumulation in plants and offer new insights into effective environmental management practices. (Reported by Chun-Chieh Wang)

*This report features the work of Shan-Li Wang and his collaborators published in Sci. Total Environ. **949**, 175141 (2024); the work of Kuo-Chen Yeh and his collaborators published in Ecotox. Environ. Safe. **276**, 116290 (2024); and the work of Samir Gamil Al-Solaimani and his collaborators published in Sci. Total Environ. **945**, 173998 (2024).*

TPS 23A X-ray Nanoprobe

TPS 44A Quick-scanning X-ray Absorption Spectroscopy

TLS 16A1 Tender X-ray Absorption, Diffraction

- Quick-scanning XAS, XRF, XANES
- Environmental and Earth Sciences, Physics, Materials Science, Chemistry

References

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