USDA NIFA Workshop on Toxic Elements in Food: Identification of Critical Knowledge Gaps to Ensure a Safe Food Supply

April 4-5, 2022

Workshop Coordinators

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EXECUTIVE SUMMARY

Summary paragraph: There is great interest in reducing exposure to toxic elements in food, particularly for women who are pregnant and/or lactating, infants, and young children up to the age of 5. This report summarizes a USDA/NIFA sponsored workshop that brought together leading scientists, educators, practitioners, and key stakeholders to: 1) identify research, education, and extension needs and opportunities; and 2) advance our understanding of key issues and opportunities, including mitigation of toxic element (arsenic, cadmium, mercury, chromium, lead, and others) contamination in the US food supply to ensure food safety. The workshop embraced a 'One Health Systems' approach and is part of the Closer to Zero (C2Z) initiative, which includes FDA, USDA and other Federal agencies. Discussion outcomes were designed to facilitate an avoidance of unintended consequences, such as eliminating foods that have significant nutritional benefits or reducing the presence of one toxic element while increasing another. The report provides a summary of key findings and critical knowledge gaps related to toxic element exposure in food, as well as efforts to ensure food safety, and provides important recommendations for the USDA to consider. Thirty-five subject matter experts and federal personnel addressed three thematic areas:

1. Soil biogeochemistry, soil amendments, and microbiome interactions with toxic elements;
2. Plant uptake and accumulation of toxic elements; and
3. Multidisciplinary concerns- food processing, detection/sensors, nutritional status-metal interference/ traditional knowledge

Background: Metalloid arsenic (As) and heavy metals such as cadmium (Cd), mercury (Hg), chromium (Cr), lead (Pb), etc., contamination is widely recognized as a significant global health problem. These toxic elements cause cancer and damage most human organs. Recent Congressional Reports have highlighted the significance and severity of this problem in many food commodities and reported that the toxic heavy metals also cause permanent decreases in IQ, inhibit or delay infant neurological development and long-term brain function, increase risk of antisocial behavior in children, and diminish future economic productivity. Historical contamination of soils with Arsenic (As) and toxic metals is a known problem, and efforts made at reducing more recent inputs have been successful. However, toxic elemental uptake by crop plants from soil plays an important role in the transfer of these toxic elements into the food chain. To minimize the contamination there is a need for greater understanding of the interactions and complexity of these toxic elements in soil and the mechanisms in crops for uptake, tolerance, and accumulation in plant tissues. Additionally, approaches such as soil amendments with biochar and engineered nanomaterials as well as agronomic practices are equally important to achieve the intended outcome of minimizing the toxic elements in food crops.

CRITICAL FINDINGS:

Soil biogeochemistry, soil amendments, and microbiome interactions with toxic elements:

- Critical knowledge gaps exist in understanding the interactions in multi-metal exposure scenarios in the environment under realistic conditions and on the effects of a changing climate on metal biogeochemistry.
- Multi-scale studies at the molecular to intermediate to field levels that address kinetic and residence time effects on contaminant availability to better understand this complex problem.
- Knowledge gaps exist between biotic and abiotically-driven mobilization mechanisms of metals as they move through the rhizosphere to the plant.
- Increased funding timelines - short duration funding (< 3 years) does not enable evaluation of the effect of weathering and the subsequent changes in bioavailability over realistic exposure times.

Plant uptake and accumulation of toxic elements:

- Although we have partial understanding of the governing processes controlling toxic metal accumulation in food, many critical knowledge gaps exist along the farm to fork to human continuum.

- There is a lack of understanding of the potentially overlapping mechanisms of toxic metal and nutrient uptake, making development of plants with uncoupled pathways difficult.
- The potential of genetic approaches to develop new varieties with reduced metal distribution to edible plant tissues remains untapped.
- Interdisciplinary research to address the complexity of toxic elements in soil and food crops; expertise in soil science, plant physiology, plant breeding and microbiology is needed.
- Public awareness of risk and levels of safe exposure, is incomplete, particularly for toxic elements in fruits and vegetables in urban agriculture.

Multidisciplinary concerns:

- The diversity of agricultural products and practices and the complexity of food supplies and sources, including imported food testing, necessitate a set of diverse solutions to address food safety problems.
- Maximum metal levels should be based on risk assessment studies (CODEX; Codex Alimentarius | Food safety and quality | Food and Agriculture Organization of the United Nations (fao.org)).
- There are several processing concerns that need further investigation, such as nutrient value vs. safety, e.g., brown rice vs polished rice, par-boiled rice, as well as cooking practices which vary culturally.
- More robust public education and outreach is needed to enable understanding (and acceptance) of technologies such as CRISPR/Cas9- genome editing to generate crops with reduced toxic metal uptake.
- Industry, government, and academia could potentially work together on this complex issue; sufficient funding currently does not exist to address the problem at a systems level.
- The Closer to Zero approach makes sense, but it may not be tenable unless best practices are put in place. A central theme must be a focus on what is both safe and achievable.
- Economic incentives are needed for faster innovation in the processing industry.
- Clearer mandates are needed by governing authorities regarding ingredient and final product testing.

RECOMMENDATIONS:

- A "Center-like" funding mechanism similar to those of NIH, NSF, DOE is needed to address toxic metal exposure in food; anything short of that will yield siloed research programs that will fail to provide sufficient transdisciplinary understanding to avoid and mitigate toxic metal contamination of food.
- Sufficient funding focused on understanding the complex interactions of soil type and toxic elements, redundant or independent mechanisms of toxic metal and nutrient uptake to enable development of plants with uncoupled pathways allowing plant breeders to develop cultivars with lower levels of toxic metals without affecting required nutrients.
- Funding on genetic approaches to develop new varieties with reduced metal distribution to edible plant tissues.
- Funding for extension and outreach activities to increase public awareness of the true risk of metal exposure in food and to support free or low-cost soil testing in Urban communities.
- National and international regulatory systems must be strengthened with common global science-based standards.

"This report does not constitute an official endorsement or approval by USDA NIFA."

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Full Report

USDA NIFA Workshop on Toxic Elements in Food: Identification of Critical Knowledge Gaps to Ensure a Safe Food Supply

Workshop Coordinators:

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Purpose and Goal of the Workshop

A virtual workshop entitled "Toxic Elements in Food: Identification of Critical Knowledge Gaps to Ensure a Safe Food Supply" was held on April 4-5, 2022. This workshop was sponsored by the U.S. Department of Agriculture's National Institute of Food and Agriculture (USDA/NIFA). The goal of this virtual workshop was to bring national and international researchers on toxic elements (metal(loid)s (arsenic, cadmium, mercury, chromium, lead, others) in the U.S. food supply from production to retail. The purpose of the workshop was to identify the critical knowledge gaps pertaining to toxic elements in food to make recommendations that will ensure a safe food supply.

Thirsty five expert scientists and federal personnel (Appendix A) addressed three thematic areas:

1. Soil biogeochemistry, soil amendments, and microbiome interactions with toxic elements;
2. Plant uptake and accumulation of toxic elements; and
3. Multidisciplinary concerns- Food Processing, detection/sensors, nutritional status-metal interference/ traditional knowledge.

The workshop was not designed to cover issues related to toxic metals in drinking water and seafood; rather, to focus on characterization of complex processes in soil-metal interactions, rhizosphere processes, mechanistic understanding of toxic metal uptake, transport, and accumulation in plants, and processed foods.

Background on Toxic Elements in the Environment and in Food

Metalloid arsenic (As) and heavy metals such as cadmium (Cd), mercury (Hg), chromium (Cr), lead (Pb) etc., contamination is widely recognized as a global health problem. Recent Congressional reports have highlighted the significance and severity of this problem in many food commodities (1,2). These congressional reports highlight that commercial baby foods may be tainted with significantly higher levels of toxic heavy metals (including As, Cd, Hg, and Pb) than the allowed levels under existing regulations for other products. These toxic elements can cause significant negative health consequences, including cancer and damage to most human organs (3-5). Toxic heavy metal exposure is also linked to permanent decreases in IQ, inhibited infant neurological development and long-term brain function, increased risk of antisocial behavior in children, and diminished future economic productivity (references?).

Levels of As and toxic metals in many soils have significantly increased due to the use of pesticides fertilizers, wood preservatives containing these elements, and excessive irrigation with contaminated groundwater (6-8). High levels of As, Hg, Cd, Cr and other toxic elements in soil and drinking water have been reported globally; importantly, As contamination in Bangladesh, India, China, Chile and the USA is more widespread. It has been estimated that more than 200 million people in 70 countries are affected by As in drinking water (9), with the situation being most dire in Bangladesh and the West Bengals State of India (10,11)). Normal levels of As in soil are about 1-2 mg/kg (10); levels several-fold above this are considered unacceptable and can directly lead to negative health impacts. Toxic elements in soils, sediments, and water supplies are major sources of food chain contamination and can endanger human health (13,14). As these toxic elements are non-biodegradable, they accumulate in soil over time. Numerous studies have shown that crops grown on contaminated soilcan accumulate high levels of As and other toxic metals in roots, shoots, and seeds (15-19). Rice is well known to accumulate high levels of As and Cd in edible grains. Thus, toxic elemental uptake by crop plants plays an important role in the transfer of these xenobiotics into the food chain (20-22). In addition, at higher levels, these metals(loids) are phytotoxic and can negatively affect plant growth and development and lead to a significant loss of crop yield (23,24).

Soil geochemistry and rhizosphere (the plant root zone) activities play critical roles in the solubility and the bioavailability of these toxic elements in the soil. Once bioavailable, these toxic elements are co-transported from soil to the roots and subsequently translocated to the aboveground tissues via specific ion transporters that transport essential elements. For example, Cd is co-transported via Zn and Fe transporters. Similarly, As in the form of arsenate (AsV) is co-transported via high affinity phosphate transporters and As in the form of arsenite (AsIII) under reducing condition is co-transported via Si transporters, such as members of NIP subfamily of aquaporins.

The toxic metal content of foods is also influenced by other numerous factors ranging from environmental conditions during growth to post-harvest handling, processing, preparation and cooking techniques. Often it is found that the finished food products have higher levels of toxic metals than the original ingredients used. The US Congressional Reports highlighted that several baby food companies are adding ingredients, such as vitamin/mineral pre-mix that may contain unacceptable levels of toxic heavy metals (1,2). Also, some of the processing techniques such as dehydration and lyophilization could further increase the total contents of toxic metals in processed foods.

There is an urgent need to understand the interactions and complexity of toxic element fate in soil. Simultaneously, to minimize the contamination of these toxic elements in foods, there is a great need for understanding the mechanisms of uptake, tolerance, and accumulation in plant tissues. Additionally, approaches such as soil amendments with biochar and engineered nanomaterials, as well as agronomic practices, are equally important to achieve the intended outcomes of minimizing toxic elements in food crops. Notably, it has been reported that current ingredient testing is likely inadequate; S Congressional Reports (1,2) strongly recommended that the FDA require food processing industries to test not only the ingredients but also the finished products for toxic heavy metals.

Workshop Background:
Dr. Jason White and Dr. Om Parkash Dhankher are the PD and Co-PD on a USDA-NIFA sponsored grant entitled *"Nanoscale sulfur for plant nutrition, disease suppression, and food safety"* (USDA NIFA AFRI 2020-67022-32416). Under this grant, one of the objectives is to explore the use of nanoscale sulfur (NS) for preventing heavy metal uptake into plants to promote food safety. During the Year 1 program review at the grantees' annual meeting, data was presented showing the strong impact of NS at increasing arsenic (As) tolerance and decreasing As accumulation in rice. Specifically, the results showed that the soil amendment with NS increased rice seed yield by 26% and caused 54% less As accumulation in rice grains (25). In December 2021 NIFA awarded the PDs a supplemental grant to explore knowledge gaps via a workshop.

Approach:
As discussed above, crops grown on contaminated soils can accumulate high levels of As and other toxic metals in roots, shoots, and seeds. Further, certain technologies used for processing of food can also increase the metal concentration in products such as baby food and other grains and vegetable-based processed foods. The toxic metal interactions in soils and mechanisms of transport and accumulation in plants are highly complex processes and critical knowledge gaps exist. Based on collective understanding and knowledge of toxic metals contamination in soils and subsequent uptake, transport and accumulation in edible plant tissues, the PDs established the following three thematic areas to investigate gaps along the soil-to-plant-to-fork continuum.

1. Soil biogeochemistry, soil amendments, and microbiome interactions with toxic elements
2. Plant uptake and accumulation of toxic elements
3. Multidisciplinary concerns- food processing, detection/sensors, nutritional status-metal interference/ traditional knowledge

Based on these three thematic areas, the PDs invited experts as workshop participants that are conducting research in their respective fields related to toxic metals contamination. A complete list of expert workshop participants, as well as observers from Federal agencies, is provided in **Appendix A**. Instead of requesting research presentations from the invited experts on their research, the PDs focused more on interactive and robust discussion related to the problem of toxic elements in foods to effectively outline and design solutions for filling the critical knowledge gaps. To facilitate discussion, we designed a set of questions (see list of questions below) for each theme. A draft of these questions was shared with all invited experts prior to the workshop for their comments and suggestions. After soliciting this expert input, the final list of questions was again circulated to the participants and federal agencies observers prior to the workshop, as well as the students/postdoctoral associates that were to facilitate the event.

Discussion Questions:

Theme 1: Soil biogeochemistry, soil amendments, and microbiome interactions with toxic elements

1. How does soil biogeochemistry affect the bioavailability and uptake of toxic elements in food crops? Do we have a comprehensive understanding of these processes? What remains unknown? This may be specific to element and crop, for example, arsenic in paddy fields vs arsenic in upland rice or in other crops.
2. How can we understand the important correlations between toxic element speciation and their fate and transport in the environment? Do we have the appropriate and effective methods/techniques for determining metal concentration and speciation in soil across molecular, microscopic, macroscopic, and field scales? What are the advantages and disadvantages of different characterization techniques?
3. What practical strategies/solution are available to decrease the As and other toxic elements bioavailability in soils at varied spatial and temporal scales?
4. What is the impact of the soil microbiome on toxic element toxicity, bioavailability, and uptake? Does toxic element speciation and availability alter the metabolism of soil microbiome?
5. Given the likely increase in urban agriculture, what contamination routes are likely to be of concern? Will aerial deposition be a significant route relative to soil contamination? If so, what controls the bioavailability of aerially deposited metal contaminants?

Theme 2: Plant uptake and accumulation of toxic elements

1. What are the major pathways and mechanisms of uptake, transport and accumulation for various metals and metalloids in plants and food crop? What remains unknown? What are the methods/techniques for characterizing?
2. Do we have sufficient understanding of the epigenetic regulation of toxic elements in plants? Which factor(s) have the biggest impact on toxic metal susceptibility/tolerance?
3. How can the impact of toxic metals on crop productivity/yields/quality be minimized?
4. How do we maintain a balance between preventing the negative impact of toxic metals and the beneficial impacts of nutrient elements, i.e., the balance between food safety vs. nutritional security?
5. What practical strategies could be utilized for preventing uptake and accumulation of toxic metals in food crops? What agricultural strategies/practices could limit toxic elements in food crops?
6. Do we have sufficient understanding of how endophytes and rhizosphere microbiomes impact toxic element uptake and accumulation in plants?
7. Is toxic metal contamination of animal feed an important exposure route for humans?

Theme 3: Multidisciplinary concerns - food processing, detection/sensors, nutritional status-metal interference/ traditional knowledge

1. What are the biggest challenges and opportunities for preventing toxic metals contamination in food crops?
2. What are the main sources of toxic metals in soil and waters that will impact agriculture, including both historical and ongoing sources?
3. What concentration of toxic metals are commonly found in food crops? What are the minimum levels accepted for safe consumption?
4. What are the processing practices to limit the bioavailable and total amounts of toxic metals in food products?
5. Which crops, animal meat, dairy, and seafood products contribute most to dietary exposure of toxic metals?
6. What is the impact of toxic metals on crop productivity/yields and quality? How will this be impacted by a changing climate and the need to produce more under greater marginal conditions.
7. Is toxic metal contamination of animal feed an important exposure route for humans?
8. Do countries have appropriate regulatory oversight to monitor toxic metal contaminants in imported and exported foods?

Discussion questions to be addressed by all groups/themes

1. How can communities be made aware of potential exposure to toxic elements and opportunities for prevention?
2. How and what traditional knowledge strategies would help to minimize exposure to toxic elements in foods?
3. Are there resources to encourage technological innovations in food production, processing and distribution to ensure safe food?
4. Does sufficient data exist to establish regulatory limits for toxic metals in food? What data is missing and how do we get it?
5. How can we inform the regulatory process in a way that maximizes food safety but also minimizes negative impacts on agriculture and growers?
6. Does the increase in toxic metal increase the human bioavailability of that metal? Is there enough evidence? How does metal-nutrient interactions affect bioavailability of both essential and non-essential elements?

Workshop structure and agenda:

The structure of this online virtual workshop included two days, each with 11:00am-4:00pm sessions. On day one, there was an opening plenary session, followed by several breakout discussion sessions based on the three themes and ended with a closing report out session for reporting the key outcomes and discussions for each day (**see workshop Agenda Appendix B**). The welcome remarks were made by Dr. White and Prof. Dhankher, followed by opening remarks from Dr. Shoushan 'Steve' Zeng (Director, Food Safety Division USDA-NIFA) and Dr. Conrad Choiniere, (Director, Office of Analytics and Outreach (OAO) and The FDA's Center for Food Safety and Nutrition (CFSAN)).

The breakout sessions were facilitated by pre-identified theme facilitators and each had assigned graduate student/post-doctoral associate scribes to capture session content. Breakout sessions were also recorded to facilitate information capture. Following the opening remarks and introductions, Theme Facilitators for each thematic area made brief presentations to outline the current research knowledge and potential knowledge gaps on each thematic area. During the Opening Plenary Technical session, experts for each theme were invited to present the current state of knowledge across the three areas. The workshop organizers felt this was important to establish the baseline understanding in each area before spending time discussing the critical knowledge gaps. For theme 1, Dr. Olena Vatamaniuk (Cornell University) made a technical presentation on the mechanisms of cadmium (Cd) uptake, transport, detoxification, and accumulation in food crops. In addition, Dr.

Om Parkash Dhankher (UMass Amherst) presented an overview of arsenic (As), mercury (Hg) and lead (Pb) accumulation and transport in plants. For theme 2, Dr. Ganga Hettiarachchi (Kansas State University) gave a presentation on the role of soil chemistry in mediating the bioavailability of toxic elements. For theme 3, Dr. Michael Strano (Massachusetts Institute of Technology) presented an overview of developing sensors for metal detection and Dr. Steve Linscombe (US Rice Board) gave a presentation on toxic element issues in the food processing industry, as well as on the lack of international standards of tolerable Upper Intake Levels in food, vegetables, and processed food. After the opening/plenary session, experts and participants were sent to three breakout sessions for the detailed exploration of each theme. On Day 2, the breakout sessions were reconvened and were then followed by the report out session where Theme Facilitators reported and presented the key findings, critical knowledge gaps and recommendations. The concluding remarks and message of gratitude were made by Dr. Jason white, Prof. Om Parkash Dhankher and Dr. Mark Carter. Following this workshop, Drs. White and Dhankher presented the key outcomes and discussed the report at the USDA C2Z Public Meeting on April 27, 2022.

Key Findings and Recommendations-

Theme 1: Soil biogeochemistry, soil amendments, and microbiome interactions with toxic elements

The key findings from this group were broad and highly complex, which is largely a function of the difficulty in trying to understand complex processes in a highly complex media (i.e., soil). Although there is a fair level of understanding of the fate of select elements in soil, there is poor understanding as system complexity increases, whether that be by introducing soil type, climate change impacts or multi-contamination scenarios, to name a few. The topic of novel soil amendments received much attention, as did the topic of urban agriculture. Outreach and education will be needed under these potential exposure scenarios. The specific key findings are as follows:

- Soil biogeochemistry is highly complex (e.g., soil type vs toxic element interactions, climate change, soil amendments, crop-specific growing season, etc.).
- Critical knowledge gaps exist around the interaction of multi-contaminant exposure scenarios in the environment under realistic conditions, soil element response to seasonal and temporal changes, and the effects of a changing climate on metal biogeochemistry.
- Multi-scale studies are needed: molecular to intermediate to field scale and kinetic and residence time effects on contaminant availability.
- There is a need for the development of novel and non-destructive detection and speciation techniques that allow *in situ* measurements.
- Field scale crop and metal-specific research is needed to demonstrate the value of practical strategies/solutions.
- More practical, cost-effective, deployable, and sustainable soil amendments and agronomical approaches are needed to limit toxic elements in food.
- Access to speciation facilities needs to be increased.
- The use of a simplified spatial or temporal scale approaches should be considered to understand system complexity.
- There is a knowledge gap between biotic and abiotic-driven mobilization mechanisms of metals in the rhizosphere, especially under different moisture regimes. The change in metal bioavailability from bulk soil through the rhizosphere to the plants are not known.
- Longitudinal studies with longer funding times would allow for experiments that evaluate the effect of weathering and the subsequent changes in bioavailability.
- Educate growers on the use of site-specific cropping systems (select right crop for right location/time). This is important as landscape topography in relation to hydrology can influence metal accumulation.
- The importance of soil testing should be emphasized; there should be USDA or other agency programs to support free or low- cost soil testing.

- In the area of Urban agriculture, public education on toxic elements in food crops should emphasize the concept of metal bioavailability and not necessarily total concentration/content.

Theme 2: Plant uptake and accumulation of toxic elements

The key findings of this group were nearly as broad and complex as Theme 1, although there was consensus that the existing current knowledge in plant-based systems is more developed for some toxic elements, e.g., As in rice, a critical knowledge gaps exist for other elements in many food crops. There was great interest in developing strategies to decouple nutrient and contaminant uptake, and a general recognition that advanced physiological and molecular mechanistic studies would be a necessary pre-cursor to the work. However, there was clear consensus that this entire issue of food chain contamination with toxic metals is in fact a transdisciplinary problem and that approaching one aspect of the system (i.e., crop species) without including other aspects (i.e., soil) would result in failure. Other major areas of concern included the impacts of a dynamic climate and the potential need for economic incentives, as well as the importance of public awareness in urban settings. The specific key findings are as follows:

- The genetics of metal transport and accumulation pathways for toxic elements in plants are not well understood, with some exceptions such as As in rice and Cd in wheat. Little is known about Pb and Hg in food crops.
- Use genetic approaches to develop new varieties with low levels of uptake.
- More researchers are needed on genome editing (CRISPR-Cas) and/or genetic engineering approaches for knockdown/overexpression of genes to block toxic metal accumulation.
- Crop cultivars with high tolerance and low accumulation in vegetative tissues and seeds are needed. QTL mapping and integration of low toxic element accumulation traits into high yield cultivars should be explored by breeding Marker Assisted Selection (MAS).
- Toxic metal accumulation in plants is species-specific. Species to species variation and mechanisms need to be investigated.
- Redundant or independent mechanisms of toxic metal and nutrient uptake needs to be understood to enable development of plants with uncoupled pathways. Plant breeders may need to analyze all metal and nutritional data in their cycles of selection and include these features in the selection index.
- Interdisciplinary research is needed to address the complexity of toxic elements in soil and food crops. Soil scientists, plant physiologist, breeders, and microbiologists need to work together to address this complex issue.
- Dedicated Centers with collaborative and multi-disciplinary research (e.g., plant production, climate smart, nutrition, etc.) are needed to address the toxic metals in food and environment.
- Most of the studies are done in model plants such as Arabidopsis and known genes are from model plant species; not much is known about the genes in the QTL's in other crops. However, there are key mechanisms for which the genes remain unknown and model systems can accelerate their discovery but that must be translated to crop species.
- There is a lack of sufficient modeling to describe nutrient allocation within the plant; this limits the ability to develop strategies for reducing heavy metal uptake and accumulation in plants.
- Metal speciation is an important aspect of metal toxicity and accumulation. *In planta* studies evaluating the speciation (kinetics and magnitude) of heavy metals needs to be done.
- There is a need for understanding how climate change stresses (high temperature, drought, salinity) impact the interactions of toxic metals in soil, rhizosphere processes, and accumulation into plants and edible tissues.
- The role of endophytic microbes and the rhizosphere microbiome should be explored.
- Strong public awareness, particularly for toxic elements in fruits and vegetables, is needed through Cooperative Extension Services. Soil testing for community gardens.
- Economic incentives are needed for faster innovation in the food processing industry.
- Clearer mandates are needed by regulatory authorities - ingredients are tested but not the end products.

- ➢ There is a lack of centralized database for the metals in food in the public domain. Regulatory limits should be set based on the available levels and speciation of toxic elements in foods to humans and not based on total amount of a particular element.

Theme 3: Multidisciplinary concerns- Food Processing, detection/sensors, Nutritional status-metal interference/ traditional knowledge

Theme 3 findings were among the broadest of the workshop. There was a consensus that given the complexity of current food systems, solutions would be many and could be applied at many places along the production to retail chain. There were significant concerns expressed over the lack of universal and science-based regulatory standards, as well as a recognition that proposed solutions must be tenable and achievable. The specific key findings are as follows:

- ➢ Diversity of agricultural products and practices and complexity of food supplies and sources necessitates a set of diverse solutions to address food safety problems. Imported foods testing is too limited.
- ➢ Regulatory systems vary internationally; common global science-based standards are needed. Maximum levels should be based on risk assessment studies (CODEX; Codex Alimentarius | Food safety and quality | Food and Agriculture Organization of the United Nations (fao.org)).
- ➢ There are several processing concerns- nutrient value vs safety, e.g., brown rice vs polished rice, par-boiled rice, cooking practices vary culturally.
- ➢ Engage in public education to ensure the public understand and accept technologies such as CRISPR/Cas9- genome editing to generate crops with reduced toxic metal uptake.
- ➢ Industry, government, and academia should work together on this complex issue; sufficient funding currently does not exist to address the problem at a systems level.
- ➢ More thorough understanding of the absorption of toxic metals from food as impacted by other factors (nutrition, health).
- ➢ The C2Z approach makes sense but it may not be tenable unless best practices are put in place. What is achievable must be a central theme.

Recommendations and Conclusions

There is currently only a partial understanding of the governing processes controlling toxic metal accumulation in food, and several critical knowledge gaps exist along the farm to fork to human continuum. It is also evident that many of these knowledge gaps are transdisciplinary in nature and as such, will require a systems level strategy to effectively address this problem. The PIs offer the following recommendations:

- A "Center-like" funding mechanism similar to NIH, NSF, DOE programs is needed to address toxic metal exposure in food; anything short of that will yield siloed research programs that fail to provide sufficient transdisciplinary understanding to avoid and mitigate toxic metal contamination of food.
- There is a need of sufficient funding focused on understanding the complex interactions of soil type and toxic elements, redundant or independent mechanisms of toxic metal and nutrient uptake to enable development of plants with uncoupled pathways; this will allow plant breeders to develop cultivars with lower levels of toxic metals without affecting required nutrients.
- There is a need of funding on genetic approaches to develop new varieties with reduced metal distribution to edible plant tissues.
- Funding is also needed for the extension and outreach services to increase public awareness over the true risk of metal exposure in food as well as to support free or low- cost soil testing.
- Regulatory systems at the national and international levels must be strengthened, and common global science-based standards are needed.

Acknowledgements
The funding for this workshop from the USDA NIFA AFRI program via grant # USDA NIFA AFRI 2020-67022-32416 is acknowledged. We are also highly thankful to all the invited subject matter experts, scribes, ZOOM helpers, and observers for their enthusiastic participation, contributions, and help in running this workshop.

Disclaimer:
The above findings and recommendations are the thoughts of the PIs and the workshop SMEs. This report does not constitute an official endorsement or approval by USDA NIFA.

Appendices A: Full list of Attendees

Subject Matter Experts:

Theme 1: Plant uptake and accumulation of toxic elements

1. Angelia Seyfferth, Department of Plant and Soil Sciences, University of Delaware; Email: angelias@udel.edu
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Theme 2: Soil- bioavailability/soil amendments/microbiology, wastewater use irrigation

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Theme 3: Food Processing, detection/sensors, Nutritional status-metal interference/ traditional knowledge

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Appendix B: Workshop Agenda

April 4, 2022

11:00am Welcome and introduction- Om Parkash Dhankher and Jason White
11:20-11:30 Objectives and overview for the Workshop- Jason White, Om Parkash Dhankher
11:30- 11:45 Opening Remarks- USDA and FDA (Dr. Shoushan 'Steve' Zeng- USDA; Conrad Choiniere- FDA)
11:45-1:00 Plenary Technical Session: State of Current Knowledge and Panel Discussion

Session Moderators: Jason White (CAES), and Jorge Gardea-Torresdey (UTEP)

Presenters and topics

- Plants- Olena Vatamaniuk (Cornell) and Om Parkash Dhankher (UMass)
- Soils- Ganga Hettiarachchi (KSU)
- Sensors- Michael Strano (MIT)
- Food processing- Steve Linscombe (US Rice)

1:00-1:30 Lunch break
1:30- 3:00 Breakout Discussion Sessions (assignments on page 4)

1. Plant uptake and accumulation of toxic elements
Discussion facilitators- Julian Schroeder (UCSD) and Olena Vatamaniuk (Cornell)
Scribes: Ahmed Ali and Sudhir Sharma (Graduate student, UMass Amherst)

2. Soil biogeochemistry/soil amendments/microbiology
Discussion facilitators- Yuji Arai (Uni. Illinois) and Jorge Gardea-Torresdey (UTEP)
Scribes: Yi Wang (Postdoc CAES) and Gurpal Singh (Graduate student UMass)

3. Multidisciplinary concerns- Food Processing, detection/sensors, Nutritional status-metal interference/ traditional knowledge
Discussion facilitators- Shelley Minter (Uni. Utah) and Steve Linscombe (US Rice)
Scribes: Jaya Borgatta (Postdoc CAES) and Josphat Kiunga (Graduate student UMass)

April 5, 2022

11:00- 11:15 Recap from day 1- Jason White and Om Parkash Dhankher
11:15- 1:00 Breakout sessions

1. Plant uptake and accumulation of toxic elements
Discussion facilitators- Olena Vatamaniuk and Julian Schroeder
Scribes: Ahmed Ali and Sudhir Sharma

2. Soil biogeochemistry/soil amendments/microbiology
Discussion facilitators- Yuji Arai and Jason White
Scribes- Yi Wang and Gurpal Singh

3. Multidisciplinary concerns- Food Processing, detection/sensors, Nutritional status-metal interference/ traditional knowledge
Discussion facilitator- Charles Santerre (Clemson Uni) and Steve Linscombe
Scribes: Jaya Borgatta and Josphat Kiunga

1:00- 1:30 Lunch break
1:30- 2:45 Theme facilitators report out and discussion (25 minutes per theme)
2:45- 3:00 Concluding remarks (Jason White, Om Parkash Dhankher; Mark Carter - USDA); report logistics and time frame

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