Nanotechnology and Agriculture: Sustainably Achieving Food Security

Jason C. White, Ph.D.

Director, The Connecticut Agricultural Experiment Station, New Haven CT

Presented at the Northeastern Regional Association of State Agricultural Experiment Station Directors Meeting
March 15, 2022

“Nano” Research at the CAES

1. Applications: Nano-enabled agriculture

USDA
National Institute of Food and Agriculture

The Center for Sustainable Nanotechnology

Nanyang Technological University – Harvard T.H. Chan School of Public Health
Initiative for Sustainable Nanotechnology

- Nano-enabled micro/macronutrient delivery platforms
- Nanoscale micronutrients to modulate crop nutrition for for disease suppression
- Nanoscale materials to enhance stress tolerance, photosynthesis, induce RNA interference

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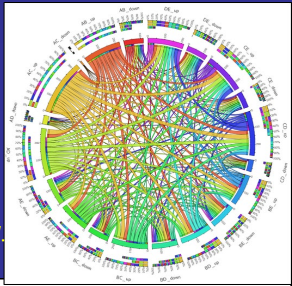
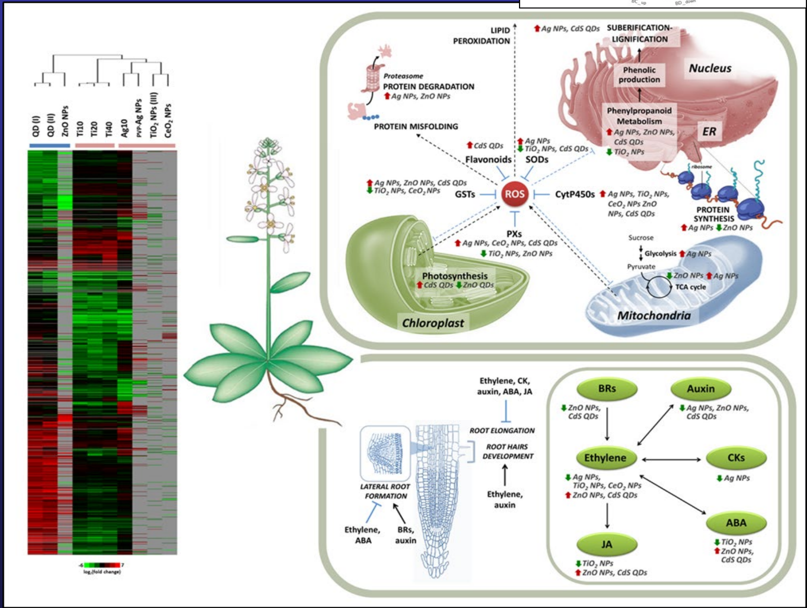
2. Implications: Nanotoxicology

- Fate and effects of nanomaterials (NM) on plants and related biota.
- Investigating the molecular basis of plant response; needed to ensure accurate risk assessment and safe use
- NM trophic transfer and transgenerational impacts in the food chain
- NM Co-contaminant interactions with pesticides, pharmaceuticals, metals



Ruotolo et al. 2018.
Environ. Sci. Technol.
52:2451-2467.



Agriculture: Current Perspective

- ➢ Agricultural productivity has increased dramatically in the last 50 years (irrigation, agrichemicals). However, global agriculture is dominated by a small number of crops in a few countries.
- ➢ The rate of crop yield increase has <u>declined</u> since the 1980s.
- ➢ Poverty and hunger have decreased globally, but 800 million are chronically hungry; 2 billion suffer micronutrient deficiencies.

nature nanotechnology

JUNE 2019 VOL 14 NO 6

www.nature.com/naturenanotechnology

NANOFLUIDICS
Origin of ionic Coulomb blockade

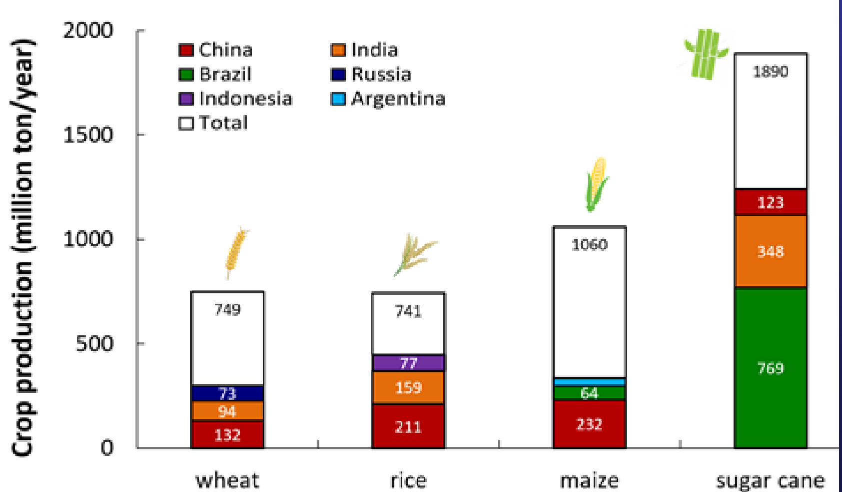
CANCER NANOMEDICINE
Ironing out leukaemia cells

NANOELECTRONICS
An organic performance

Providing an insight into nano-enabled agriculture

- ➢ Agricultural systems in the much of the world have plateaued at 20-80% of yield potential
- ➢ Agrichemical delivery efficiency is often only 1-25% (**<u>Nanotechnology!</u>**)

Kah et al. 2019 *Nature Nano* 14:532-540.



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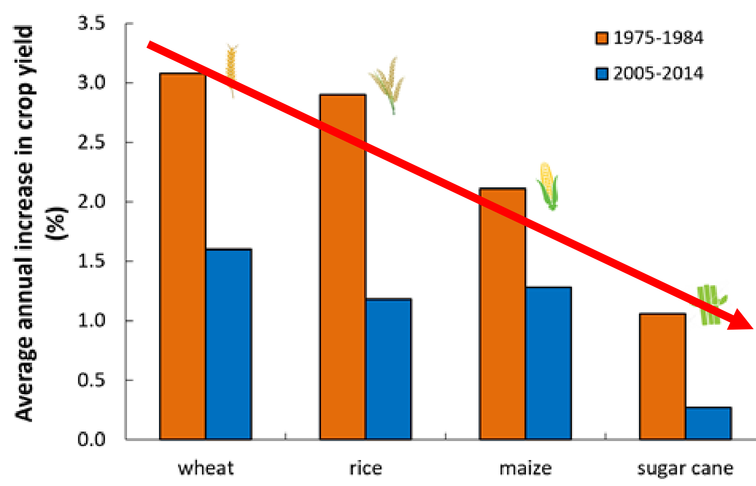


Why Nano-Agriculture? Declining Global Food Security!!!

- Current estimates are that food production will need to increase by 70-100% by 2050 to sustain the population
- Negative pressure from a changing climate and a loss of arable soil
- And then there is COVID…
- Novel strategies and technologies are needed from “farm to fork” (and beyond) to sustainably solve the grand challenge of global food security
- Nanotechnology **can and will** play a significant role in this effort; **particularly with the inefficiencies!!**

INSIGHTS

Science July 2020

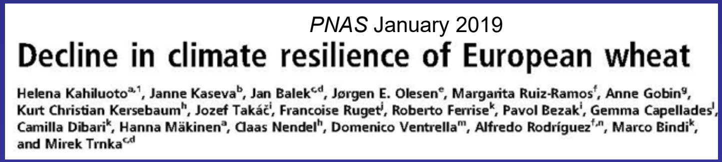
Farm workers using the H-2A temporary agricultural worker visa maintain safe distance on 27 April 2020 in Greenfield, California.

POLICY FORUM

FOOD SECURITY: COVID-19

COVID-19 risks to global food security

Economic fallout and food supply chain disruptions require attention from policy-makers



PNAS January 2019

Decline in climate resilience of European wheat

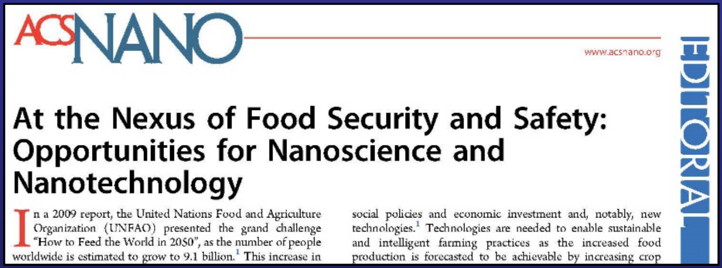
Helena Kahiluoto[a,1], Janne Kaseva[b], Jan Balek[c,d], Jørgen E. Olesen[e], Margarita Ruiz-Ramos[f], Anne Gobin[g], Kurt Christian Kersebaum[h], Jozef Takáč[i], Francoise Ruget[j], Roberto Ferrise[k], Pavol Bezak[i], Gemma Capellades[l], Camilla Dibari[k], Hanna Mäkinen[a], Claas Nendel[h], Domenico Ventrella[m], Alfredo Rodríguez[f,n], Marco Bindi[k], and Mirek Trnka[c,d]

CLIMATE CHANGE

Science Aug. 2018

Increase in crop losses to insect pests in a warming climate

Curtis A. Deutsch[1,2*†], Joshua J. Tewksbury[3,4,5†], Michelle Tigchelaar[6], David S. Battisti[6], Scott C. Merrill[7], Raymond B. Huey[2], Rosamond L. Naylor[8]



ACS NANO

www.acsnano.org

EDITORIAL

At the Nexus of Food Security and Safety: Opportunities for Nanoscience and Nanotechnology

In a 2009 report, the United Nations Food and Agriculture Organization (UNFAO) presented the grand challenge “How to Feed the World in 2050”, as the number of people worldwide is estimated to grow to 9.1 billion.[1] This increase in social policies and economic investment and, notably, new technologies.[1] Technologies are needed to enable sustainable and intelligent farming practices as the increased food production is forecasted to be achievable by increasing crop

PNAS

Opinion: To feed the world in 2050 will require a global revolution

Paul R. Ehrlich[a,1] and John Harte[b,1]

[a]*Department of Biology, Stanford University, Stanford, CA 94305; and* [b]*Energy and Resources Group, University of California, Berkeley, CA 94720*

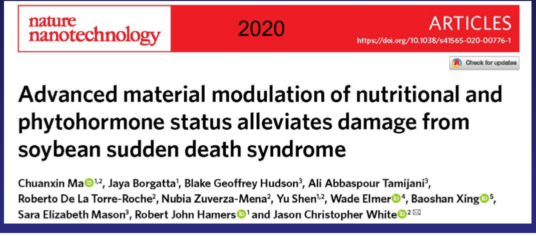
Achieving universal food security is a staggering challenge, especially in a world with an (and especially in combination) impede attempts to achieve progressive and effective policies feed humanity makes the prospects seem slim for making the projected 9.7 billion population food-secure and healthy in 2050, and perhaps billions more beyond that (5).

Major Challenges

Humanity now faces severe biophysical con-

Nanotechnology & Agriculture

- There has been significant interest in using nanotechnology in agriculture to:
  - Increase production rates and yield
  - Increase efficiency of resource utilization
  - Minimize waste production
- Specific applications include:
  - Nano-fertilizers, Nano-pesticides
  - Nano-based treatment of agricultural waste
  - Nanosensors



nature nanotechnology | 2020 | ARTICLES

https://doi.org/10.1038/s41565-020-00776-1

Check for updates

Advanced material modulation of nutritional and phytohormone status alleviates damage from soybean sudden death syndrome

Chuanxin Ma[1,2], Jaya Borgatta[1], Blake Geoffrey Hudson[3], Ali Abbaspour Tamijani[3], Roberto De La Torre-Roche[2], Nubia Zuverza-Mena[2], Yu Shen[1,2], Wade Elmer[4], Baoshan Xing[5], Sara Elizabeth Mason[3], Robert John Hamers[1] and Jason Christopher White[2] ✉

Environmental Science Nano | 2017

TUTORIAL REVIEW | View Article Online | View Journal | View Issue

Check for updates

Cite this: *Environ. Sci.: Nano*, 2017, 4, 757

Nanotechnology for sustainable food production: promising opportunities and scientific challenges

Sónia M. Rodrigues,[a] Philip Demokritou,[b] Nick Dokoozlian,[c] Christine Ogilvie Hendren,[de] Barbara Karn,[f] Meagan S. Mauter,[gh] Omowunmi A. Sadik,[i] Maximilian Safarpour,[j] Jason M. Unrine,[dk] Josh Viers,[l] Paul Welle,[h] Jason C. White,[m] Mark R. Wiesner[dc] and Gregory V. Lowry*[dg]

Environmental Science Nano | 2018

PAPER | View Article Online | View Journal

Check for updates

Cite this: DOI: 10.1039/c8en00038g

Environmental fate of nanopesticides: durability, sorption and photodegradation of nanoformulated clothianidin†

Melanie Kah,*[ab] Helene Walch[a] and Thilo Hofmann*[a]

REVIEW ARTICLE | INSIGHT | nature nanotechnology

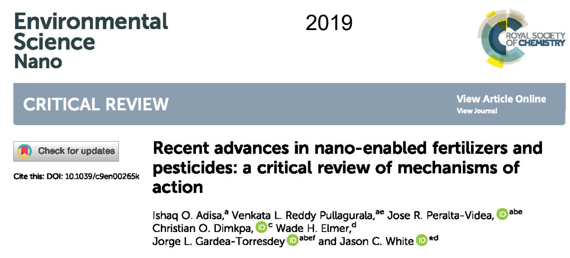
https://doi.org/10.1038/s41565-019-0439-5

Nano-enabled strategies to enhance crop nutrition and protection

2019

Melanie Kah[1*], Nathalie Tufenkji[2] and Jason C. White[3*]

Various nano-enabled strategies are proposed to improve crop production and meet the growing global demands for food, feed and fuel while practising sustainable agriculture. After providing a brief overview of the challenges faced in the sector of crop nutrition and protection, this Review presents the possible applications of nanotechnology in this area. We also consider performance data from patents and unpublished sources so as to define the scope of what can be realistically achieved. In addition to being an industry with a narrow profit margin, agricultural businesses have inherent constraints that must be carefully considered and that include existing (or future) regulations, as well as public perception and acceptance. Directions are also identified to guide future research and establish objectives that promote the responsible and sustainable development of nanotechnology in the agri-business sector.



Environmental Science Nano | 2019

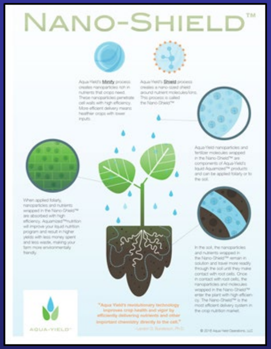
CRITICAL REVIEW | View Article Online | View Journal

Check for updates

Cite this: DOI: 10.1039/c9en00265k

Recent advances in nano-enabled fertilizers and pesticides: a critical review of mechanisms of action

Ishaq O. Adisa,[a] Venkata L. Reddy Pullagurala,[ae] Jose R. Peralta-Videa,[abe] Christian O. Dimkpa,[c] Wade H. Elmer,[d] Jorge L. Gardea-Torresdey[abef] and Jason C. White*[d]



NANOTECHNOLOGY AND AGRICULTURE | 2018

Achieving food security through the very small

Nanotechnology could make agriculture more efficient and more sustainable, but more systematic understanding of the mechanisms involved is necessary to prove the potential of nano-enabled agrochemicals.

Jason C. White and Jorge Gardea-Torresdey

NATURE NANOTECHNOLOGY | VOL 13 | AUGUST 2018 | 621–629 | www.nature.com/naturenanotechnology | 627

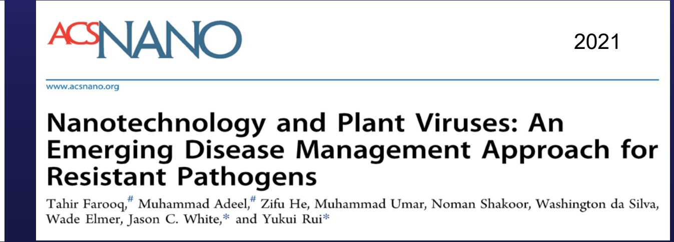
REVIEW ARTICLE | 2020 | nature food

https://doi.org/10.1038/s43016-020-0110-1

Check for updates

Technology readiness and overcoming barriers to sustainably implement nanotechnology-enabled plant agriculture

Thilo Hofmann[1] ✉, Gregory Victor Lowry[2] ✉, Subhasis Ghoshal[3], Nathalie Tufenkji[4], Davide Brambilla[5], John Robert Dutcher[6], Leanne M. Gilbertson[7], Juan Pablo Giraldo[8], Joseph Matthew Kinsella[9], Markita Patricia Landry[10], Wess Lovell[11], Rafik Naccache[12], Mathews Paret[13], Joel Alexander Pedersen[14], Jason Michael Unrine[15], Jason Christopher White[16] and Kevin James Wilkinson[17]



ACS NANO | 2021

www.acsnano.org

Nanotechnology and Plant Viruses: An Emerging Disease Management Approach for Resistant Pathogens

Tahir Farooq,[#] Muhammad Adeel,[#] Zifu He, Muhammad Umar, Noman Shakoor, Washington da Silva, Wade Elmer, Jason C. White,* and Yukui Rui*

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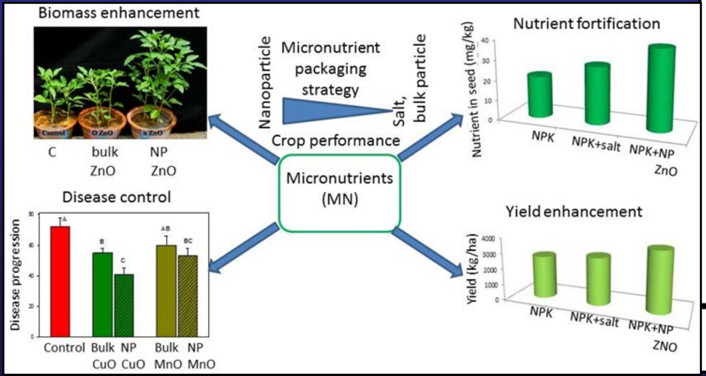
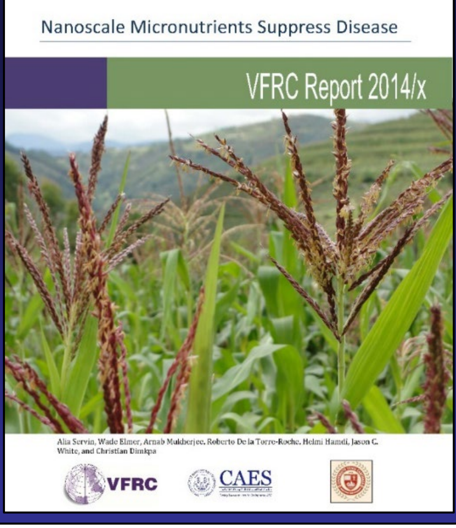
Nanoscale Nutrients and Root Disease

- In 2014, we began working on soil borne diseases; difficult to manage and reduce crop yields by 20%
- Fungal pathogens reduce US annual economic return by $200 million; $600 million on control
- Many micronutrients (Cu, Mn, Zn, Mg, B, Si…) stimulate or are part of plant defense systems
- However, these nutrients have limited availability in soil and limited efficacy when foliarly applied
- What about "nanoscale" nutrients? Will they be more effective at enhancing nutrition/ suppressing disease? **Note- No direct toxicity to the pathogen**

Servin et al. 2015. *J. Nano. Res.* 17:92.





Nanoscale Micronutrients Suppress Disease

VFRC Report 2014/x

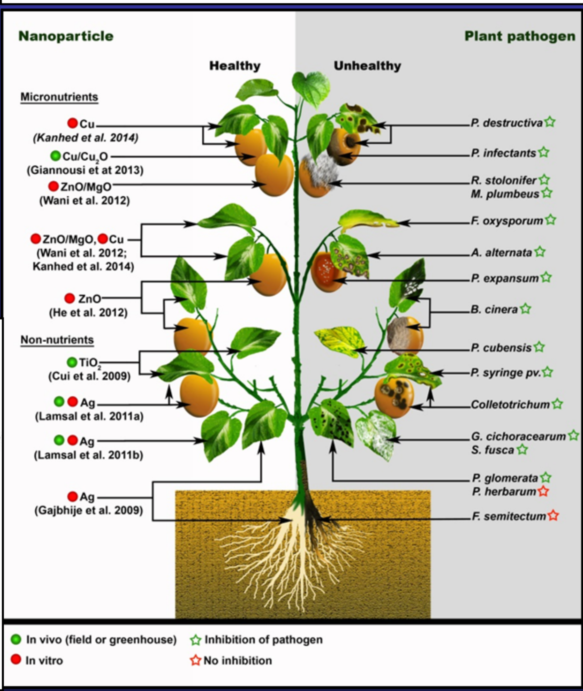
Alia Servin, Wade Elmer, Arnab Mukherjee, Roberto De la Torre-Roche, Helmi Hamdi, Jason C. White, and Christian Dimkpa

J Nanopart Res (2015) 17:92
DOI 10.1007/s11051-015-2907-7

REVIEW

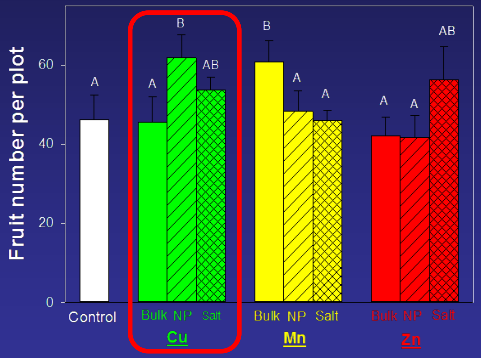
A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield

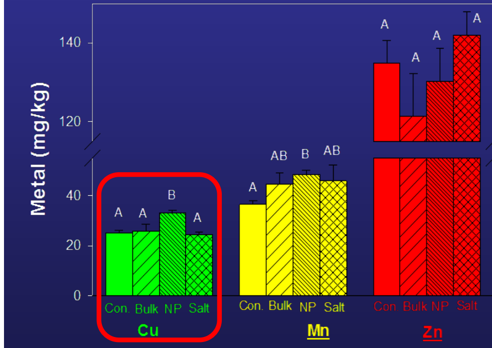
Alia Servin · Wade Elmer · Arnab Mukherjee ·
Roberto De la Torre-Roche · Helmi Hamdi ·
Jason C. White · Prem Bindraban · Christian Dimkpa

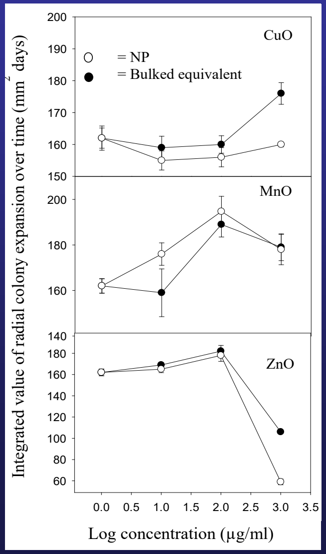


Nanoscale Micronutrients for Disease Suppression

- ➢ 2014-2015- Greenhouse and field trials with eggplant and tomato; commercial NPs
- ➢ Single foliar application of NP (bulk, salt) CuO, MnO, or ZnO (100 mg/L; 1-2 mL treatment) to seedling; transplant to infested soil
- ➢ NP CuO had increased yield, greater disease suppression, and higher Cu root content. NP CuO had no direct toxicity on the pathogen
- ➢ **$44 per acre** for NP CuO suppressed a root pathogen of eggplant, increasing yield from **$17,500/acre** to **$27,650/acre**



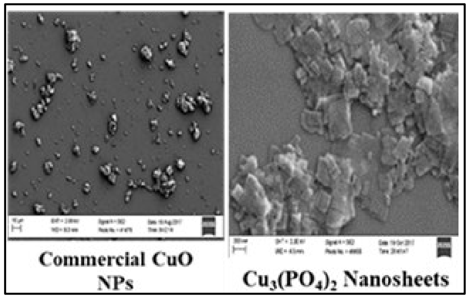




Elmer and White. 2016. *Environ. Sci.: Nano.* 3:1072-1079.

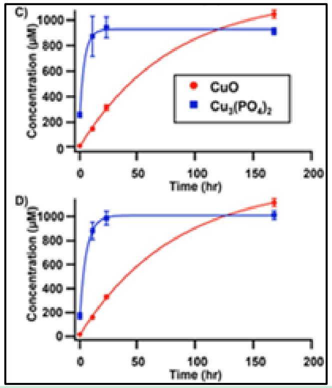
Tuning Particle Properties

- ➢Commercial CuO NPs vs $Cu_3(PO_4)_2$ nanosheets (NS) from the NSF Center for Sustainable Nanotechnology (NSF CCI)
- ➢Differences in morphology and composition lead to differences in dissolution
- ➢Materials were foliar applied to watermelon grown in *Fusarium* infested soils (greenhouse, field)
- ➢$Cu_3(PO_4)_2$ NS promote growth and inhibit disease more effectively than CuO NPs
- ➢In the field, NS suppressed disease and increased yield at **<u>10-fold</u> <u>lower dose</u>**
- ➢Effective management of risk!



Commercial CuO NPs

$Cu_3(PO_4)_2$ Nanosheets



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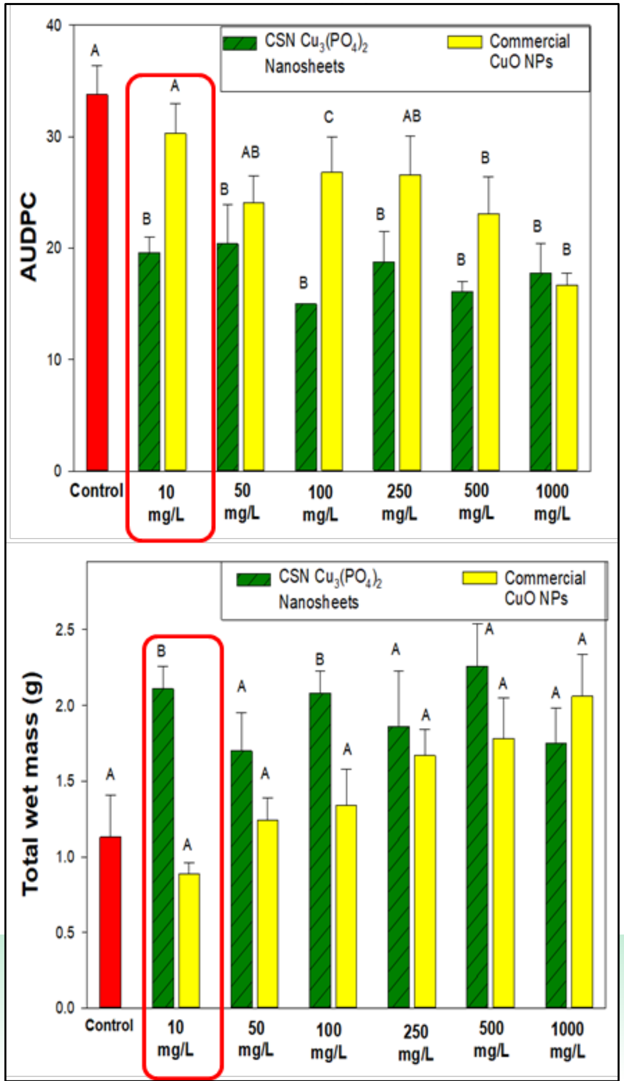
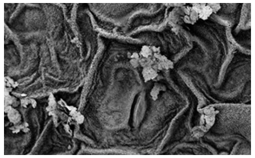
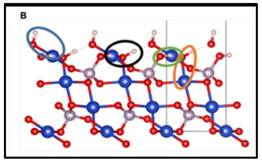
Borgatta et al. 2018. *ACS Sustain. Chem. Eng.* 6:14847-

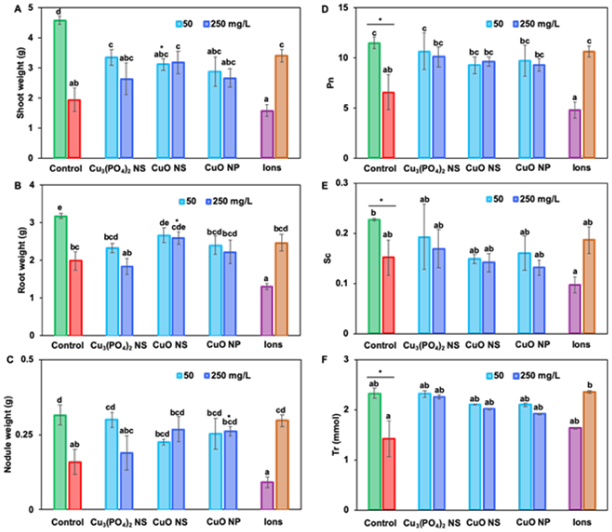


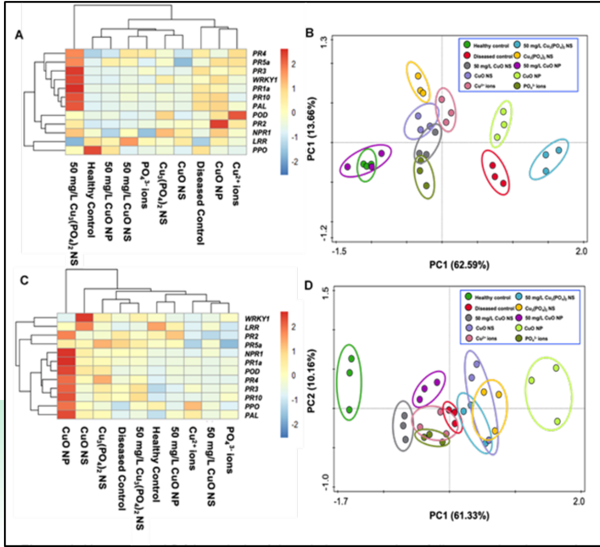
Tuning Particle Properties

- Custom $Cu_3(PO_4)_2$ and CuO nanosheets (NS) and commercial CuO nanoparticles (NPs) were investigated with soybean sudden death syndrome (SDS).
- Infection reduced biomass and photosynthesis by 60-70%; foliar application of nanoscale Cu reversed this damage.
- Disease-induced changes in antioxidant enzyme activity and fatty acid profile were also alleviated by Cu-amendment.
- The transcription of two dozen defense- and health-related genes correlated nanoscale Cu-enhanced innate disease response to reduced pathogenicity and increased growth.
- $Cu_3(PO_4)_2$ NS exhibited greater disease suppression than CuO NPs due to greater leaf surface affinity and Cu dissolution as determined computationally and experimentally.
- The findings highlight the importance and tunability of NM properties such as morphology, composition, and dissolution.





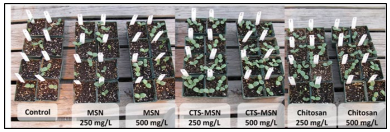


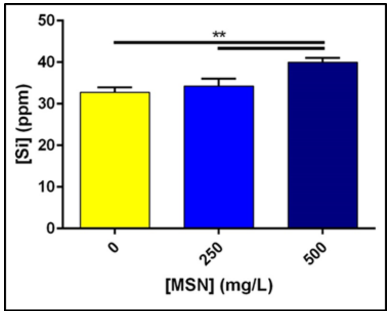


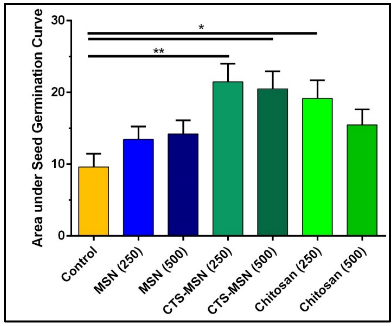
Ma et al. 2020. *Nature Nano* DOI : 10.1038/s41565-020-00776-1

Tuning Particle Properties

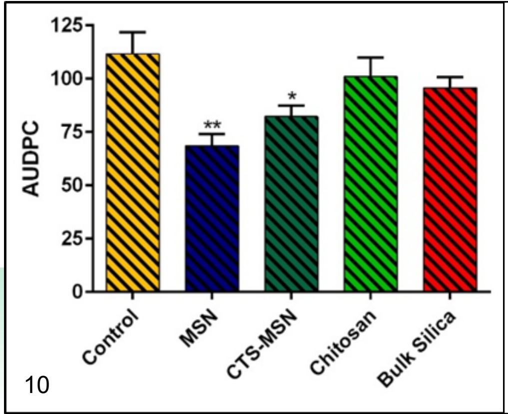
- Si is a non-essential element that helps plant response to biotic/abiotic stress
- The potential of mesoporous silica nanoparticles (MSN) with or without a chitosan coating to suppress *Fusarium* wilt in watermelon was evaluated
- Materials were seed treated or foliar applied (0-500 mg/L) to watermelon grown in *Fusarium* infested soils (greenhouse, field)
- Seed Si content increased by 7-20%; germination was increased and disease was suppressed
- For many genes related to stress (CSD1, PAO, PPO, RAN1, MDHA), treatment with MSNs, CTS-MSNs, or chitosan showed decreased expression.
- The decreased expression suggests alleviation of some of stress of disease

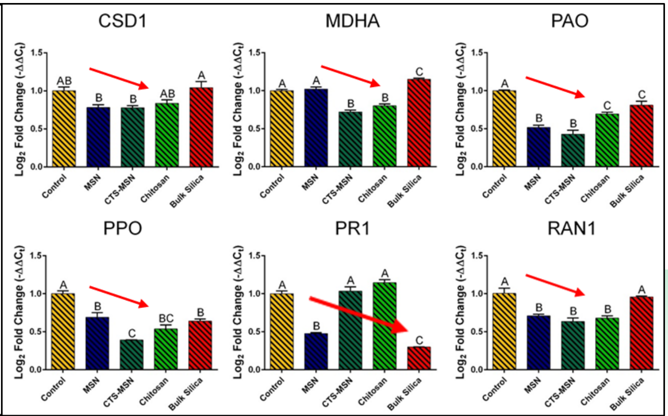






Buchman et al. 2019 *ACS Sus. Chem. Eng.* 7:19649-19659





Tuning Particle Properties

- In the field, the impact of seedling treatment on fruit yield was measured.
- For diseased-infected plants, treatment had no impact.
- For healthy plants, a single application of 1-2 mL of 500 mg/L via seedling dipping led to a 70% increase in watermelon yield
- The cost of this amount of CTS-MSN is approximately $0.02/seedling or $19 per acre of watermelon.
- Assuming an average watermelon yield per acre of <u>31,800</u> pounds (USDA, 2014) and a sale price of $0.40/pound, this $19 could increase yield to <u>54,000</u> pounds
- This equates to an increase from **<u>$11,100 to $18,900 per acre!</u>**

Buchman et al. 2019 *ACS Sus. Chem. Eng.* 7:19649-

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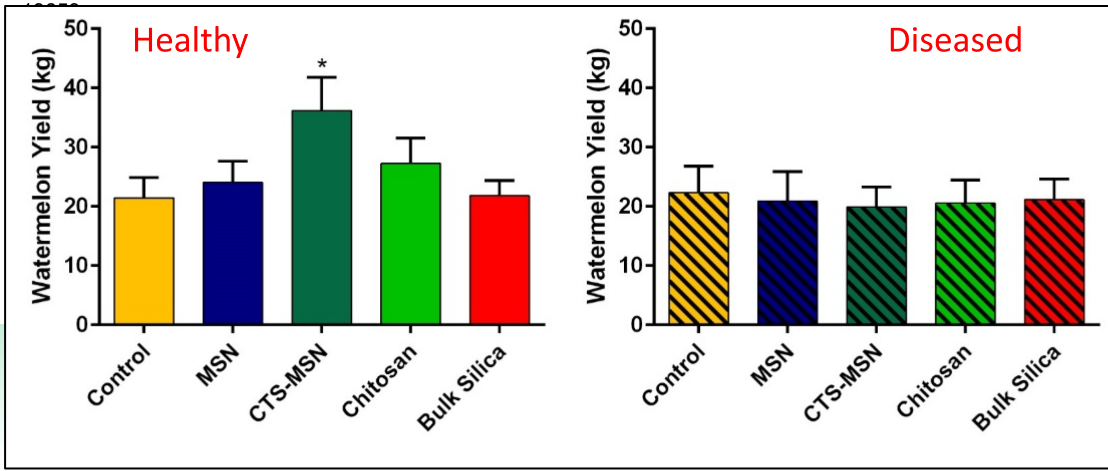


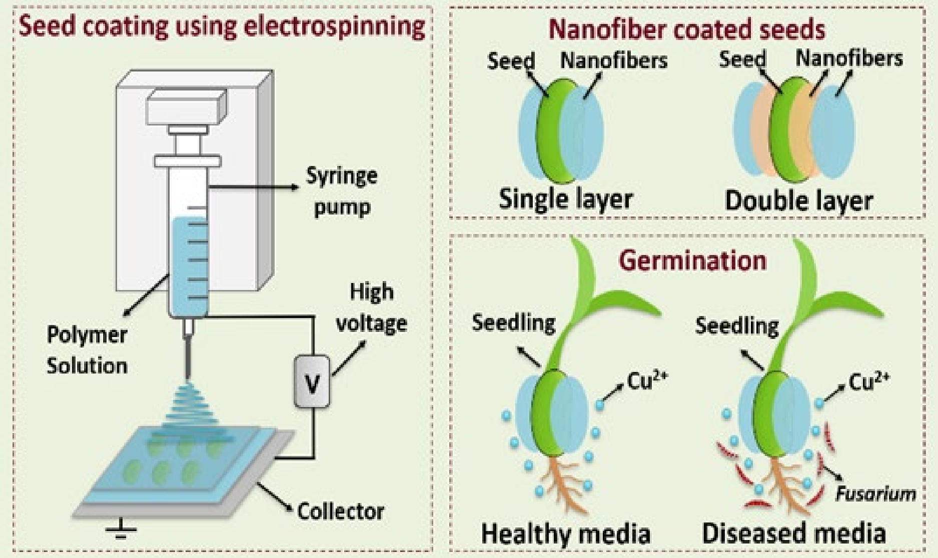
Nanoscale Seed Coatings

- Conducted as part of the Nanyang Technological University-Harvard University T.H. Chan School of Public Health Initiative for Sustainable Nanotechnology

Nanyang Technological University – Harvard T.H. Chan School of Public Health
Initiative for Sustainable Nanotechnology

HARVARD T.H. CHAN SCHOOL OF PUBLIC HEALTH
NANYANG TECHNOLOGICAL UNIVERSITY

- **Seed treatments** have been used to deliver certain critical protective agents that promote seed storage, germination, and seedling growth.
- However, current platforms are limited in terms of efficacy and versatility
- We developed a scalable, biodegradable, sustainable, “green” (non-toxic), biopolymer-based **nanoplatform** using electrospinning which can be used as a seed coating to enhance targeted and precision delivery of agrichemicals (the 3 Rs).
- Tested under healthy and diseased (*Fusarium*) conditions

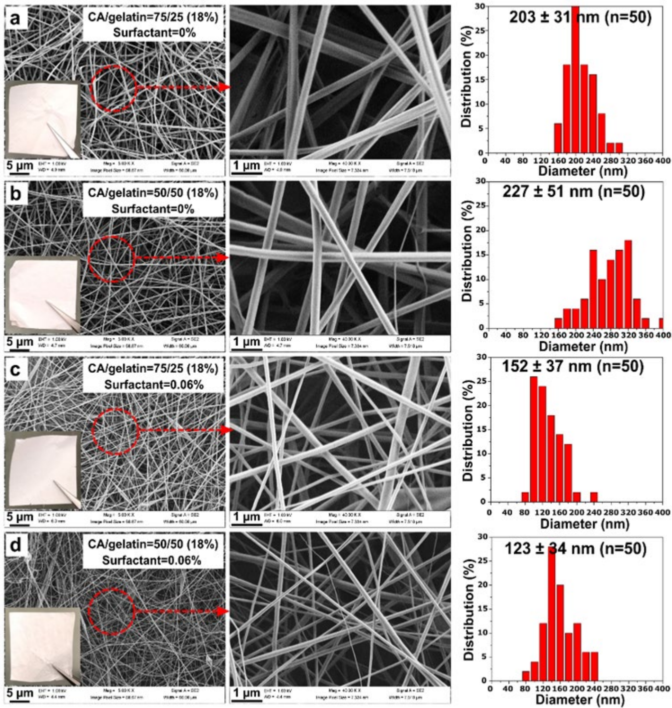


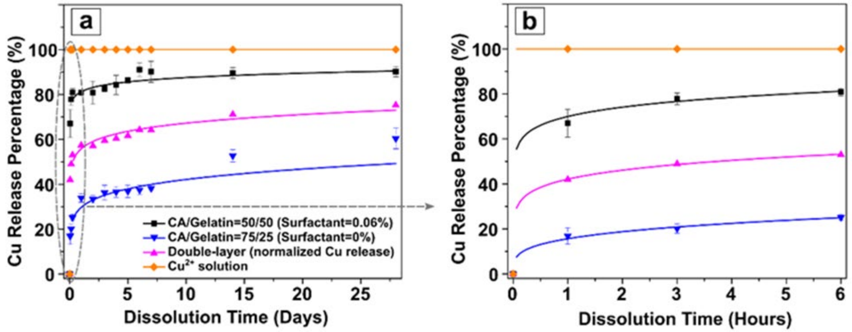
Xu et al. 2020 *ACS Sus. Chem. Eng.* 8, 25, 9537–9548

Electrospun nanofibers

- Cellulose acetate/gelatin-derived electrospun nanofibers were synthesized that are of desired morphology/thickness, mechanical properties, and surface wettability
- The morphology of different electrospun **Cu^{2+} loaded** nanofibers and their diameter distribution (n=50) is shown below.
  - (a-b) CA/gelatin ratio of (a) 75/25 and (b) 50/50, without surfactant;
  - (c-d) CA/gelatin ratio of (c) 75/25 and
  - (d) 50/50, with surfactant
- The insert of the left of each image shows the free-standing electrospun nanofiber membranes
- The Cu^{2+} release kinetics of were measured
- "**Fast**" release is CA/gelatin=50/50, surfactant= 0.06%; "**Slow**" release is CA/gelatin=75/25, surfactant=0%; "**Double-layer**" is "fast" on the outside and slow in the inside

www.ct.gov/caes



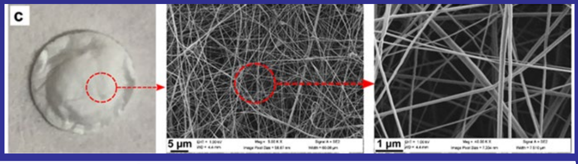


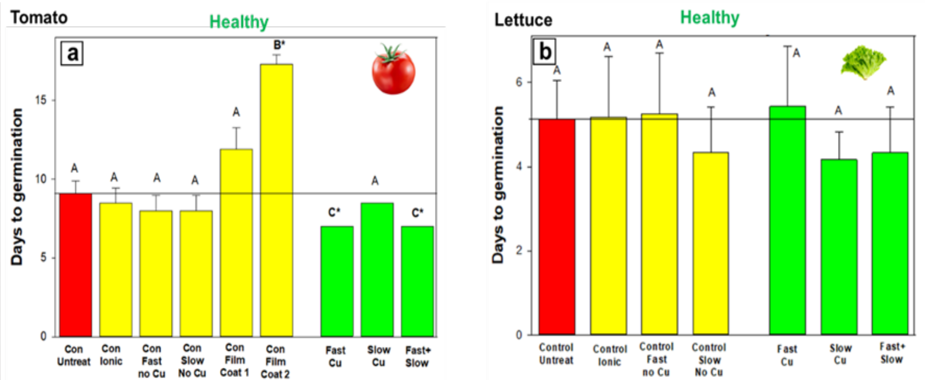
Xu et al. 2020 *ACS Sus. Chem. Eng.* 8, 25, 9537–9548

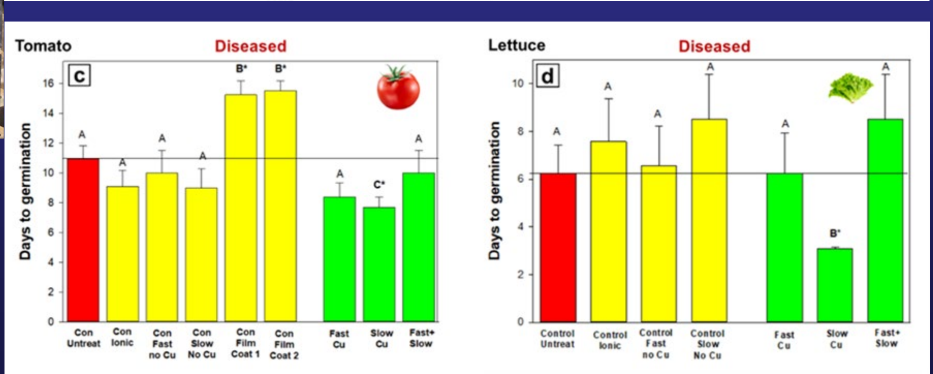
Time to Germination

- ➢ Tomato and lettuce seeds coated with “fast,” “slow,” and “fast + slow” Cu release nanofibers, as well as ionic Cu and Cu-free nanofiber, and traditional film-coated controls were germinated
- ➢ For healthy tomato, the number of days to germination was **decreased** by 22% for the “fast” and “fast + slow” coated seeds (a).
- ➢ For lettuce, there was no effect, although there were trends for reduced time to germination with treatment
- ➢ Fusarium increased the time to germination by 20%.
- ➢ The “slow” release coated seeds significantly reduced the time to germination by 30% for tomato
- ➢ For lettuce, with the “slow” Cu release coating significantly decreasing the germination time by 51% (d).
- ➢ ***The increased rate of germination led to greater biomass at 15 days!***

Xu et al. 2020 *ACS Sus. Chem. Eng.* 8, 25, 9537–9548

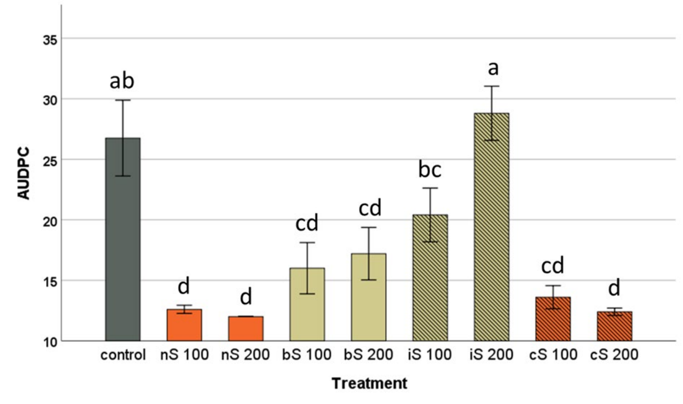


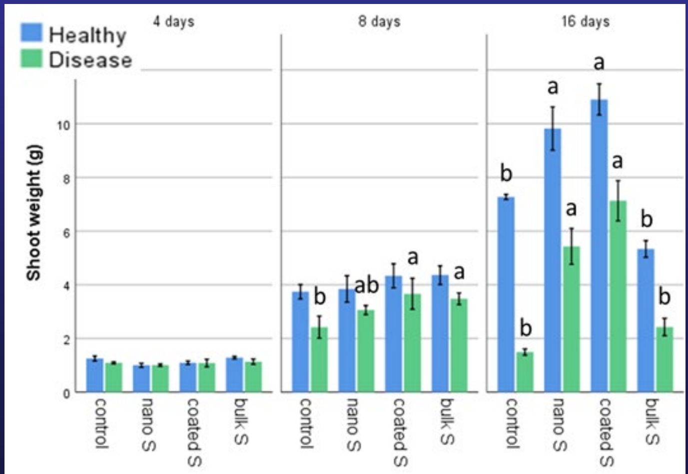




Nanoscale Sulfur and Disease

- In two greenhouse studies and a field experiment, soil was amended with SNPs (pristine and stearic acid coated; 100 and 200 mg/L soil) and tomato was grown in the presence of *Fusarium*
- Measured endpoints include disease progress, biomass, yield, pigment production, tissue nutritional content, leaf metabolomic profile (LC-MS), tissue gene expression analysis (defense and S-related genes), two photon microscopy, and rhizosphere soil microbiome analysis (16s RNA seq)
- Coated and uncoated SNPs suppressed disease and increased biomass after 16 d for healthy and infected plants
- In diseased plants, SNPs also increased shoot S and chlorophyll content, as well as photosynthetic output relative to other treatments
- Bulk S conveyed some limited benefits; ionic did not





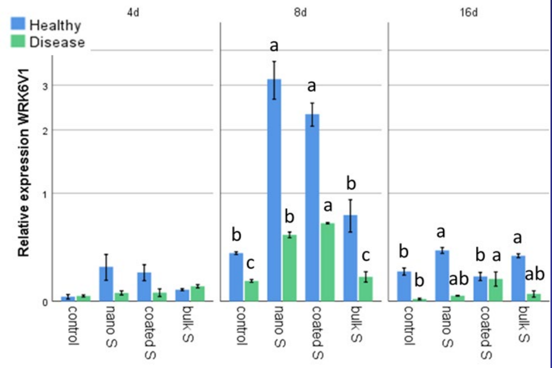
Wang et al. 2022 *Nature Nano*. In review.; Wang et al 2022 *J. Ag. Food Chem*. In prep.

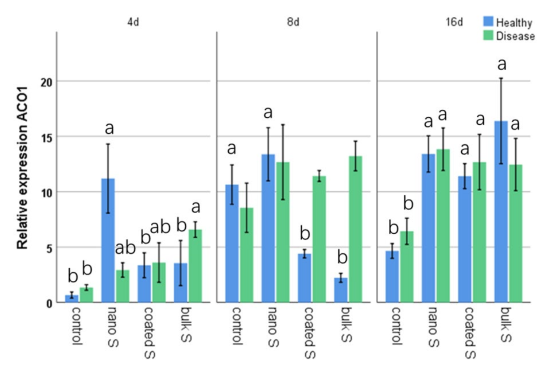
Nanoscale Sulfur and Disease

- Transcriptomic and metabolomic analyses are ongoing…

www.ct.gov/caes

- The expression of WRKY6v1 (defense-related gene) in leaves was upregulated by uncoated and coated SNPs by 6.4-8.7 -fold (8 d) and 2.0-2.2 -fold (16 d) compared to healthy controls. Also increased in diseased plants
- 1-aminocyclopropane-1-carboxylate oxidase 1 (ACO1) is part of plant defense and is also upregulated in a time dependent fashion as a function of both S size and coating
- In the field study, foliar coated SNPs on healthy plants increased early yield per plant by 18%; a **$33** investment per acre led to an increase of **$6,700 per acre**.
- In the diseased plants, foliar coated SNPs increased the yield per plant by 54% (to healthy levels); **$33** investment led to an increase of **$12,200 per acre.**



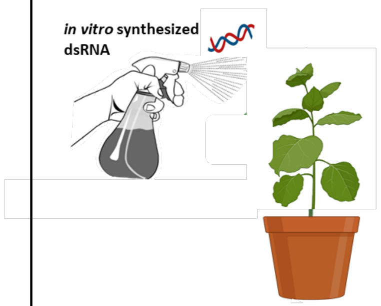


Wang et al. 2022 *Nature Nano*. In review.;
Wang et al 2022 *J. Ag. Food Chem*. In prep.

RNA Interference and Viral Infection

Topically applied double stranded RNA (dsRNA) provides protection against target plant virus

dsRNA application triggers RNAi, a natural host defense mechanism against the virus

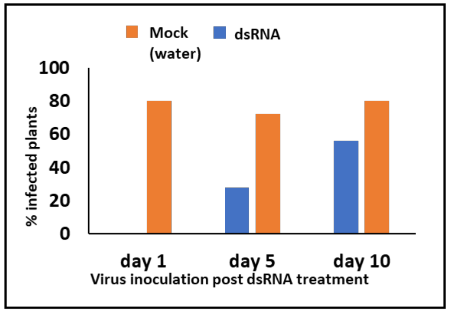


- ✓ non-GMO
- ✓ easy to generate in lab

RNAi: RNA interference

Concern: Longevity of protection window?

dsRNA application → **virus inoculation (1/5/10 days) post dsRNA application** → **symptom assessment**



dsRNA provides small protection window due to easy degradability of nucleic acid

ACS NANO

ACS Nano 2021, 15, 6030−6037

www.acsnano.org

Nanotechnology and Plant Viruses: An Emerging Disease Management Approach for Resistant Pathogens

Tahir Farooq,[#] Muhammad Adeel,[#] Zifu He, Muhammad Umar, Noman Shakoor, Washington da Silva, Wade Elmer, Jason C. White,* and Yukui Rui*

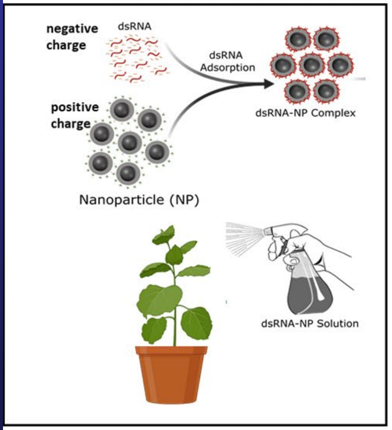
www.ct.gov/caes

"Tunable release of dsRNA molecules into plants from sustainable nanocarriers: A novel management tool for viral Pathogens" Da Silva et al.

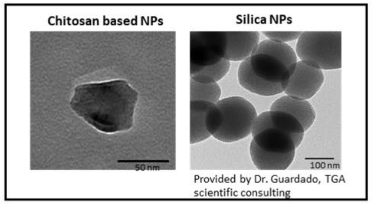
USDA National Institute of Food and Agriculture

Just funded!
1/1/2022 start

Nanoparticles as dsRNA carriers
- **Protection against nucleic acid degradation**
- **Sustained/controlled release of dsRNA**

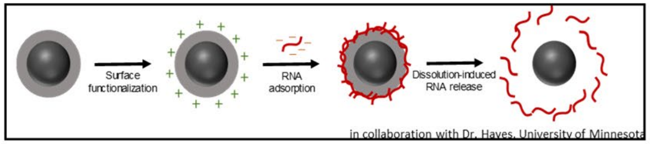


Nanoparticles being tested for dsRNA absorption and release



Provided by Dr. Guardado, TGA scientific consulting

Synthesize silica NPs for a more controlled dsRNA release

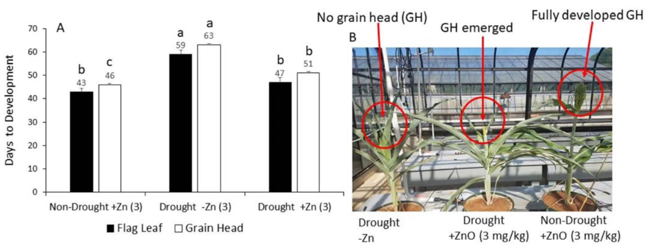


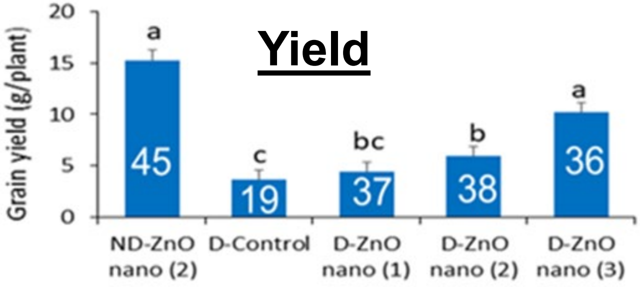
in collaboration with Dr. Hayes, University of Minnesota

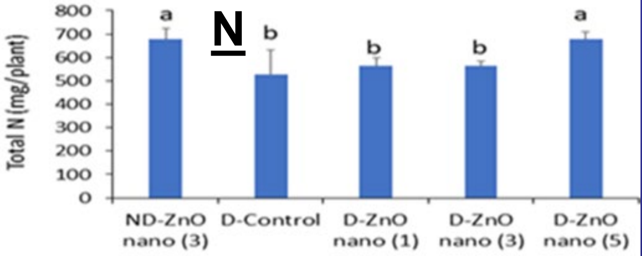
Identify most efficient dsRNA delivery system for virus control

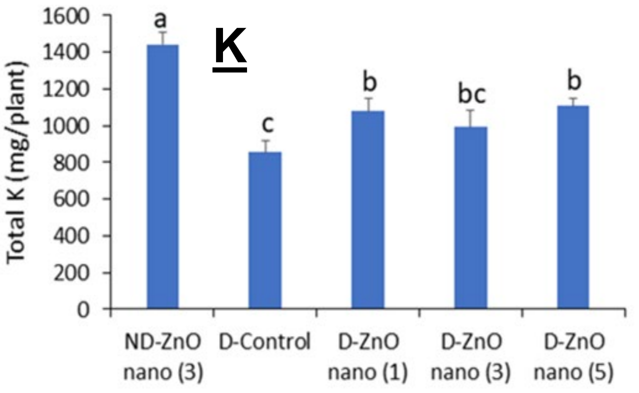
NP ZnO alleviates drought-induced damage

- Soil amended with ZnO-NPs at 1, 3, and 5 mg Zn/kg; drought imposed 4 weeks after sorghum seed germination (40% field moisture capacity).
- Leaf and grain head emergence delayed 6-17 d by drought; delays were reduced to 4-5 days by ZnO-NPs
- Drought reduced grain yield (76%); ZnO-NPs improved grain yield under drought by 22-183%.
- Drought lowered grain Zn content by 32%; ZnO-NPs improved (89-100%) grain Zn under drought.
- Drought inhibited total N acquisition by 22%; ZnO-NPs (5 mg/kg) restored total N levels.
- K by 41%; ZnO-NPs improved total K acquisition by 16-30%.





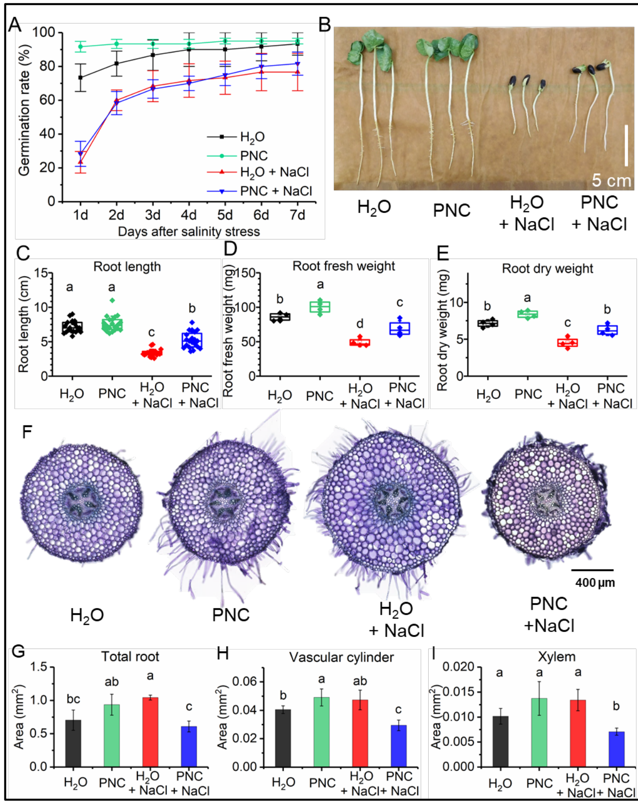


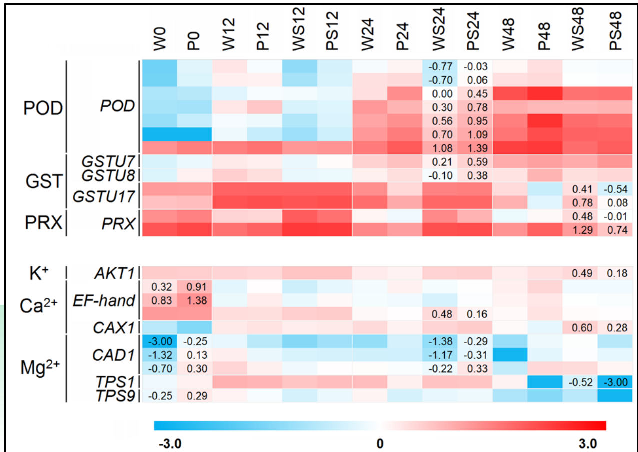


Dimkpa et al. 2019. *Sci. Total Environ.* 688:926-934.

Nanoscle CeO_2 and Salinity

- Cotton seeds were primed with 500 mg/L PNC poly(acrylic acid)-coated cerium oxide nanoparticles (PNC) (24 h in water) and germinated under salinity stress (200 mM NaCl)
- PNC were in the seed coat, cotyledon, and root apical meristem.
- Priming increased root length (56%), mass (39%), modified root structure, and increased root vigor (114%) under salt stress.
- Priming decreased root ROS accumulation (46%) and alleviated root morphological/physiological changes induced by salinity stress.
- Roots from exposed seeds had similar Na, decreased K (6%), greater Ca (22%) and Mg content (60%) compared to controls.
- 4779 root transcripts were differentially expressed by priming relative to controls; DEGs were associated with ROS pathways (13) and ion homeostasis (10)
- Seed priming with NMs provides a sustainable and scalable tool to improve plant stress tolerance.





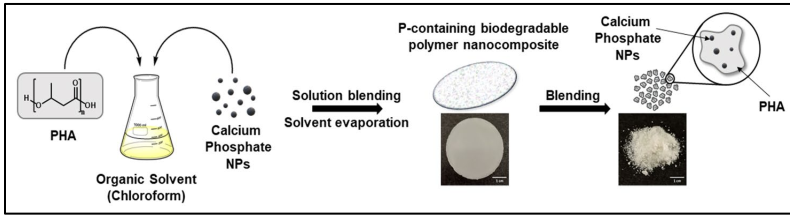
The Center for Sustainable Nanotechnology

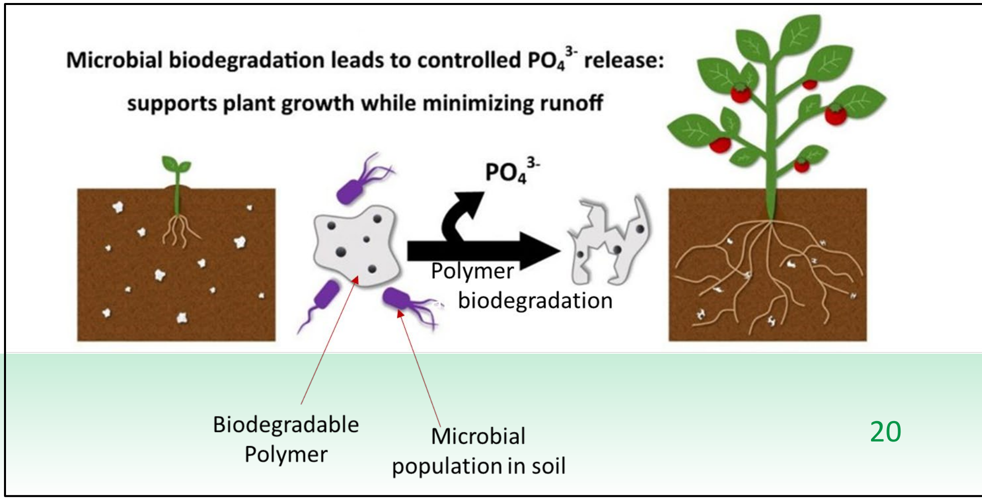
www.ct.gov/caes

An et al. 2021 *Environ. Sci.: Nano* 7:2214

Polymer Nanocomposites- P Delivery

- We propose to make a **<u>tunable suite</u>** of biodegradable polymer nanocomposite fertilizers that will release P to plants as desired rates.
- Polyhydroxyalkanoate (PHA) is a highly biodegradable polymer made by bacteria.
- We used solution blending to make composites of PHA and calcium phosphate (CaP) nanoparticles (NPs); then we mix that composite into soil with plants.
- As native bacteria in soil biodegrade the PHA, CaP is released from the polymer matrix and becomes available to plants.
- There is little or no P run-off because CaP is retained in the PHA until it is biodegraded and released.
- This responsive platform is tunable (changing polymers or co-polymer ratios).





Sigmon et al. 2021 *ACS Agric. Sci. Technol.* DOI: 10.1021/acsagscitech.1c00149

Polymer Nanocomposites- P Delivery

- ➢ Polymer nanocomposites added to soil with tomato plants; compared to CaP salts that mimic traditional fertilizers for 150 days (full life cycle).
- ➢ Leachate (i.e., runoff) was collected periodically and P in runoff was measured with ICP-OES
- ➢ The nanoscale polymers reduced P "run-off" by **10-fold!**
- ➢ Plant biomass, chlorophyll, fruit yield, nutritional content, total protein, and lycopene content were all statistically equivalent between conventional P and the nanocomposite P materials.

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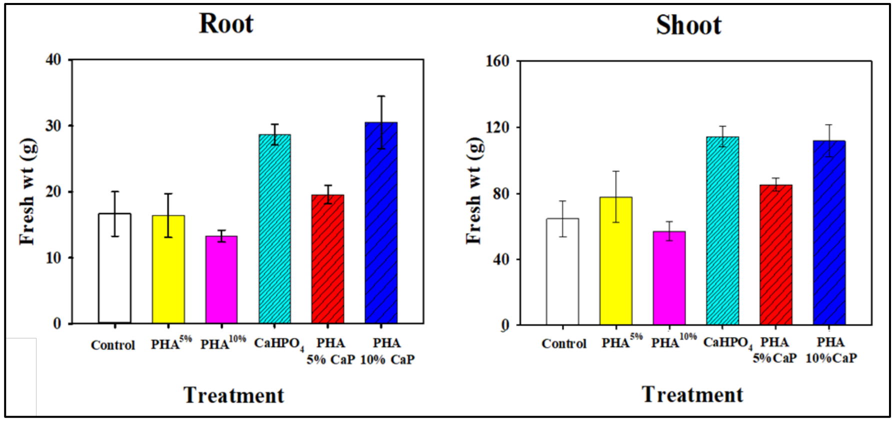
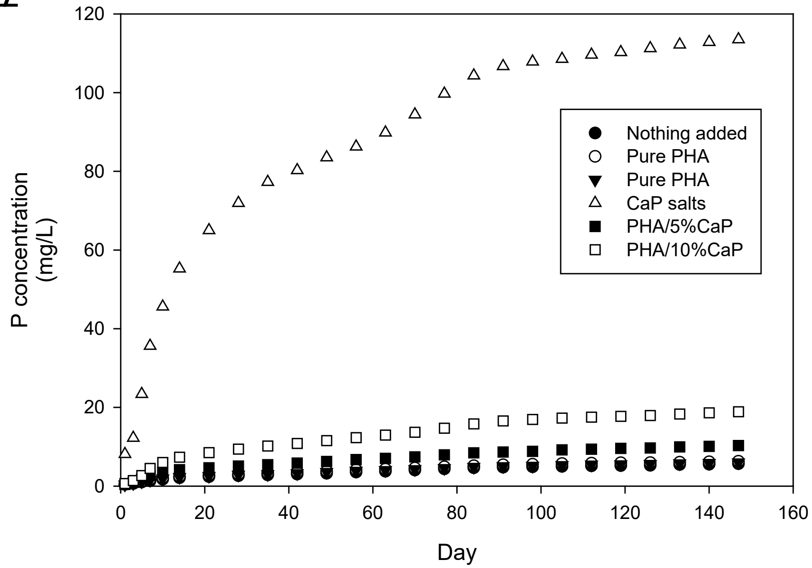




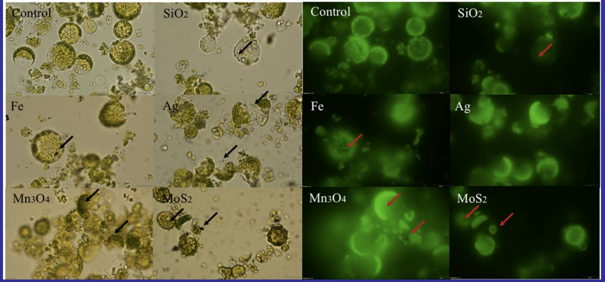
Sigmon et al. 2021 *ACS Agric. Sci. Technol*. DOI: 10.1021/acsagscitech.1c00149

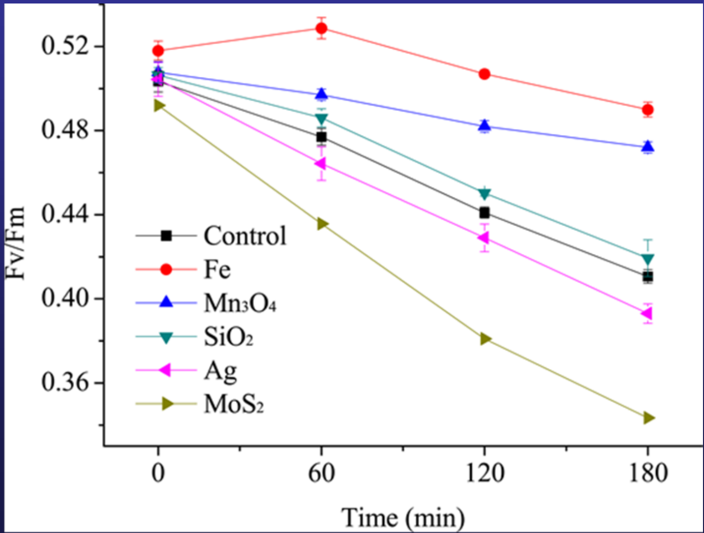
Enhancing Photosynthesis

- Conducted in collaboration with Nanjing Univ., Nanjing Technical Univ., and the Univ. of Texas El Paso
- Some NPs have exhibited potential for promoting photosynthesis and this could potentially enhance crop productivity.
- Understanding the fundamental interactions between NPs and plants is crucial for the sustainable development of nano-enabled agriculture.

www.ct.gov/caes

- Spinach leaf mesophyll protoplasts were cultivated with NPs (Fe, Mn_3O_4, SiO_2, Ag, and MoS_2) at 50 mg/L for 2 hours under illumination.
- Endpoints- maximum quantum yield, ATP production, photoelectrochemical measurements and GC-MS based metabolomics
- Whole plant exposure for comparison
- Photosynthetic efficiency (maximum quantum yield) was significantly increased by Mn_3O_4 and Fe NPs and decreased by NP Ag and MoS_2



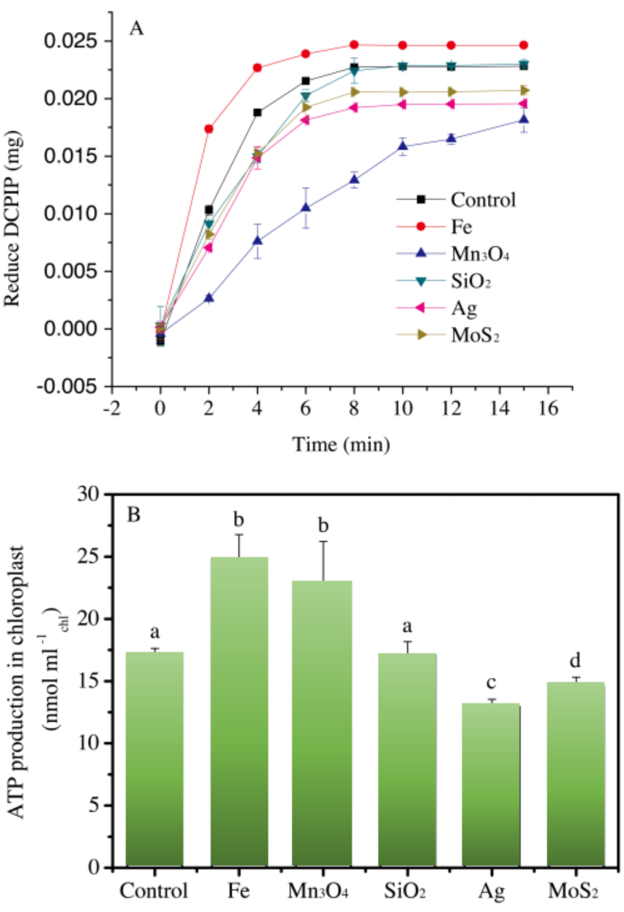


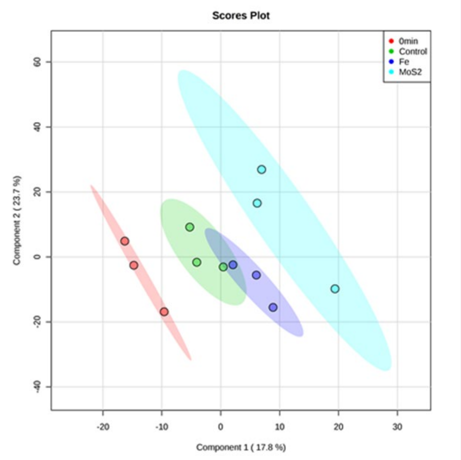
Wang et al. 2020 *J. Agric. Food Chem.* 68:3382-3389.

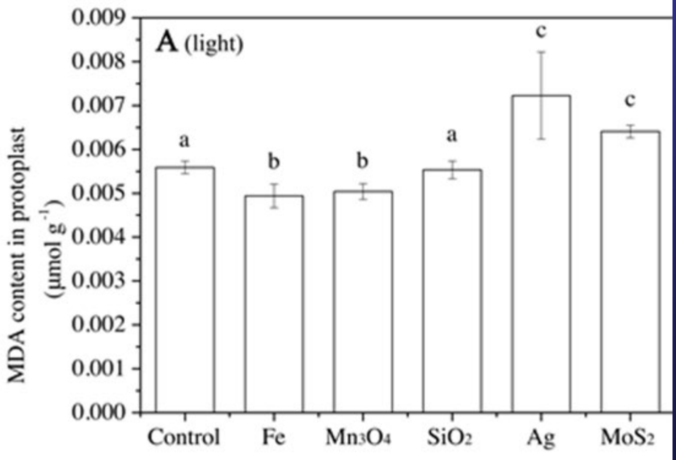
Mechanism of Enhanced Photosynthesis?

- The Hill reaction was performed; the dye DCPIP intercept electrons in the thylakoid membrane and is an indicator of photosynthesis.
- NP Fe increased DCPIP reduction; NP Fe and Mn_3O_4 increased ATP production
- NP Ag and MoS_2 decreased ATP production
- NP Fe and Mn_3O_4 decreased lipid peroxidation; NP Ag and MoS_2 increased lipid peroxidation
- Clear separation of metabolite profiles with NPs

Wang et al. 2020 *J. Agric. Food Chem.* 68:3382-3389.

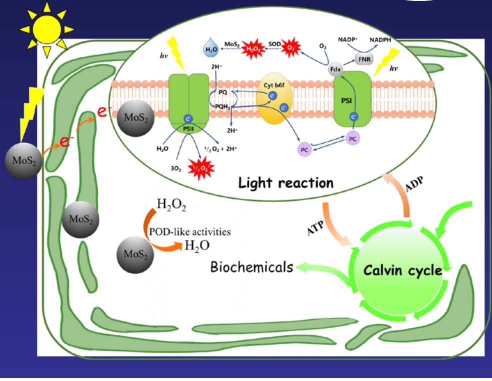




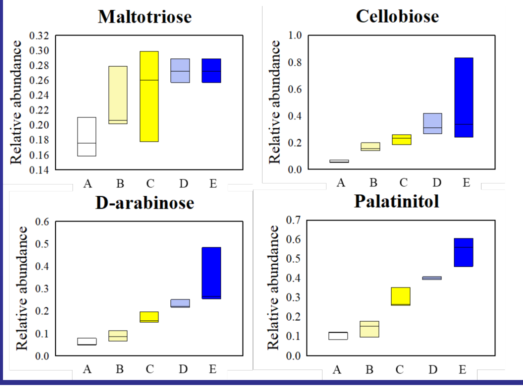


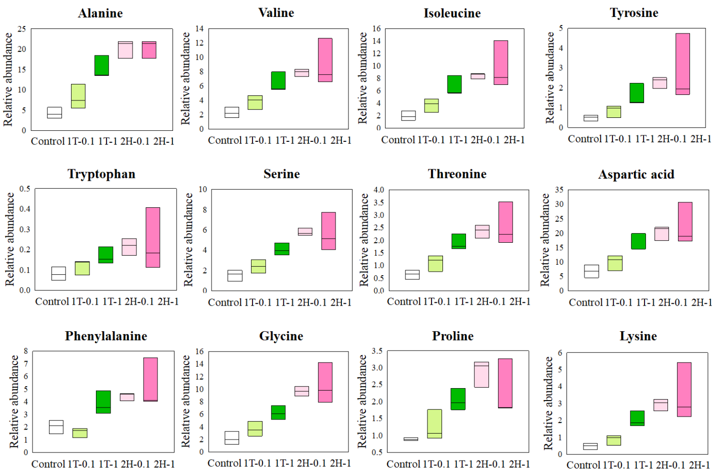
MoS_2 Nanosheets and Metabolism

- The effects of molybdenum disulfide (MoS_2) nanosheets (NS) on a N_2-fixation cyanobacteria by monitoring growth and metabolome changes.
- MoS_2 NS did not exert overt toxicity at 0.1 and 1 mg/L.
- Intracellular semiconducting MoS_2 nanosheets absorb light and generate photo-excited electrons that are transferred to the chloroplast electron transport chain and supply reducing power
- These semiconducting properties and the enzyme-like activities of MoS_2 NS promoted *Nostoc* metabolism, including enhancing carbon fixation via accelerating the Calvin Cycle.
- MoS_2 NS also boosted the production of sugars, fatty acids, amino acids.
- The altered C metabolism subsequently drove proportional changes in N metabolism.
- These intracellular metabolic changes in C and N cycling could be highly useful in agriculture



A: Control; B-E: MoS_2 NS types

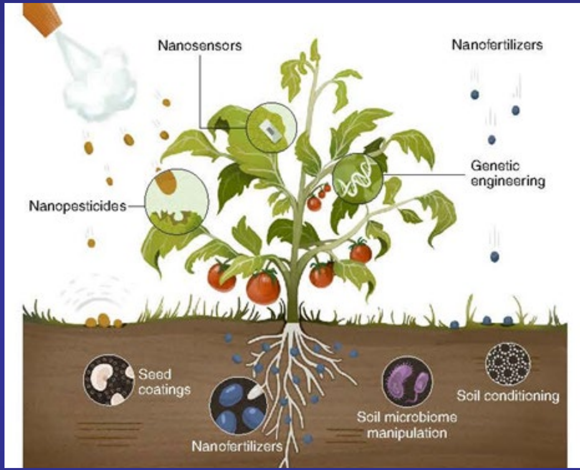


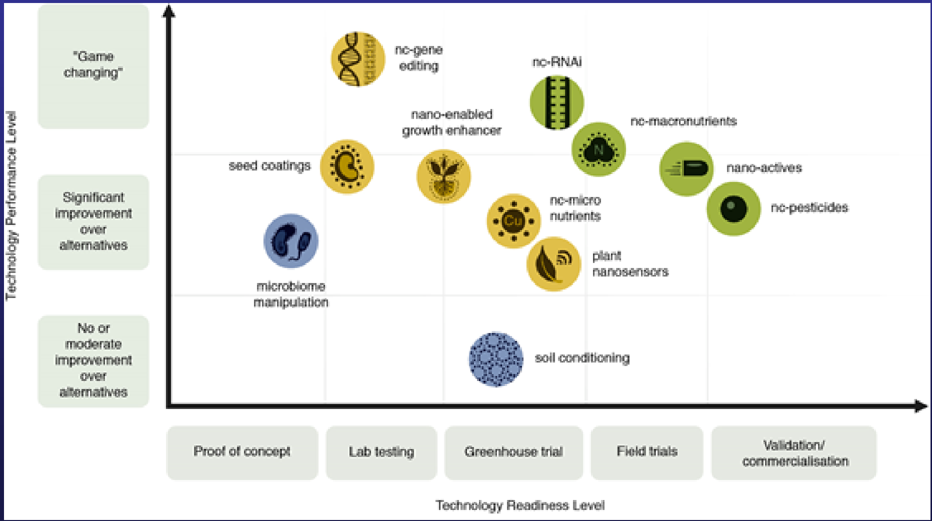


Chen et al. 2021 *ACS Nano* 15, 10, 16344–16356.

Technology Readiness?!?

- July 2019 workshop at McGill University entitled “Technology readiness and overcoming barriers to sustainably implement nanotechnology-enabled plant agriculture”
- “Nanotechnology offers potential solutions to the most vexing problems preventing more sustainable agriculture, including increasing nutrient utilization efficiency, improving the efficacy of pest management, combating climate change impacts, and reducing adverse environmental impacts.”
- Many promising nanotechnologies have been proposed and evaluated at different scales, but barriers to implementation that must be addressed to promote technology adoption including:
  - Efficient delivery at field scale
  - Regulatory and safety concerns, and
  - Consumer acceptance
- We ranked the technology readiness and potential impacts for a wide range of agricultural applications of nanotechnology, and **propose a path forward** to overcome these barriers and develop effective, safe, and acceptable nanotechnologies for agriculture



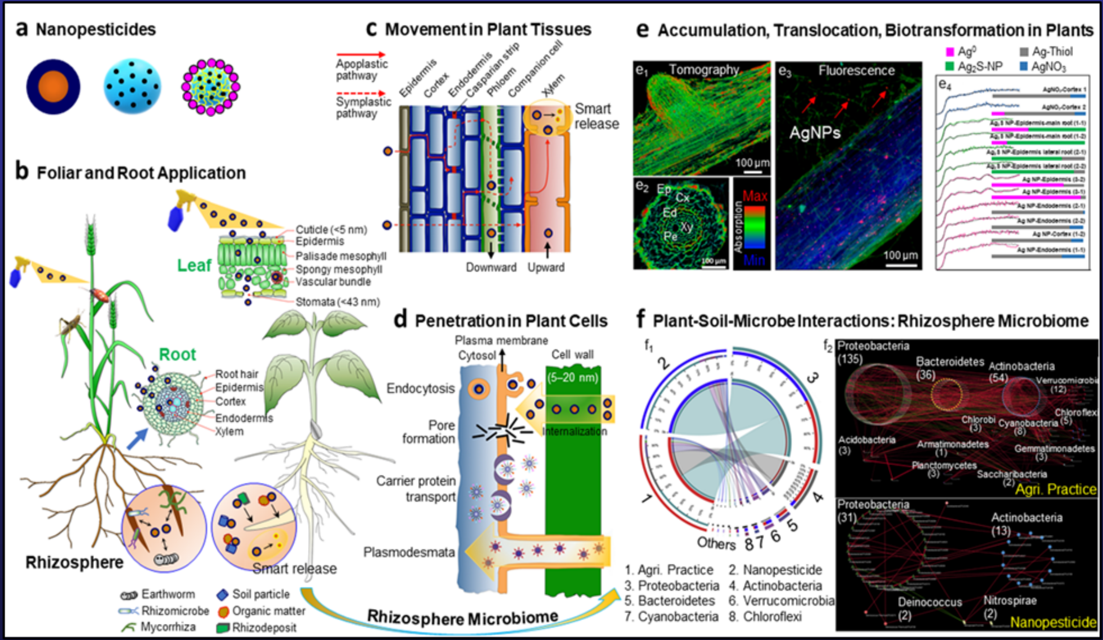


Hoffman et al. 2020 *Nature Food* 1:416-425

Nanopesticide Efficacy- US EPA 2022

- Nano-enabled responsive nanopesticides: A path toward sustainable agriculture and global food security
  Dengjun Wang, Navid B. Saleh, Andrew Byro, Richard Zepp, Endalkachew Sahle-Demessis, Todd P. Luxton, Kay T. Ho, Robert M. Burgess, Markus Flury, Jason C. White, and Chunming Su
- A meta-analysis on the key properties of nanopesticides in controlling agricultural pests compared to their conventional analogs (36,658 Google Patents; 500 peer-reviewed papers between 2015 and 2021).
- The analysis shows that when compared to conventional pesticides, their overall efficacy against target organisms is **31.5%** higher, including an 1**8.9%** increased efficacy in field trials.

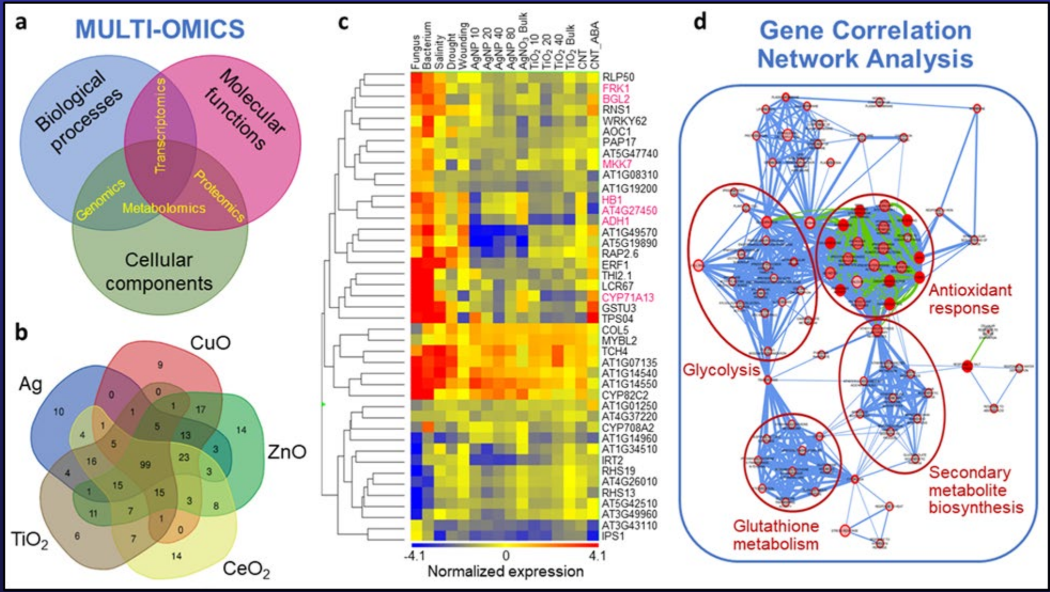
Deng et al. 2022 *Nature Nano*. In press



Nanopesticide Efficacy- US EPA 2022

- Nanopesticides toxicity toward nontarget organisms is **43.1%** lower
- The premature loss of AIs prior to reaching target biota is reduced by **41.1%**, paired with a lower leaching potential of AIs by **22.1%** in soils.
- Other benefits include enhanced foliar adhesion, improved crop yield and nutrition, and intelligent/responsive nanoscale delivery platforms of AIs to mitigate biotic and abiotic stresses (e.g., heat and drought).
- Uncertainties associated with the adverse effects of some nano-pesticides are not well-understood and require further investigation.
- Overall, nanopesticides are potentially more efficient, sustainable, and resilient with less environmental impacts

Deng et al. 2022 *Nature Nano*. In press



NSF Science and Technology Center (STC) for Food Innovation (C-FOOD)

- Preliminary proposal submitted on February 1; invited full proposals due August 29.
- These are 5-year, $30 million dollar Centers, with potential authorization for a second 5 years ($60 million total)
- A team from **Rutgers University (RU)**, Harvard University (HU), the Massachusetts Institute of Technology (MIT), Louisiana State University (LSU), the University of Puerto Rico (UPR), and the **Connecticut Agricultural Experiment Station (CAES)** proposes to create a Science and Technology Research Center for Food Innovation (C-FOOD) with the vision to lead the great food transformation for the 21st century using an exceptionally innovative, convergent transdisciplinary systems approach.

Science and Technology Centers: Integrative Partnerships (STC)
Discovery and Innovation to Address Vexing Scientific and Societal Challenges

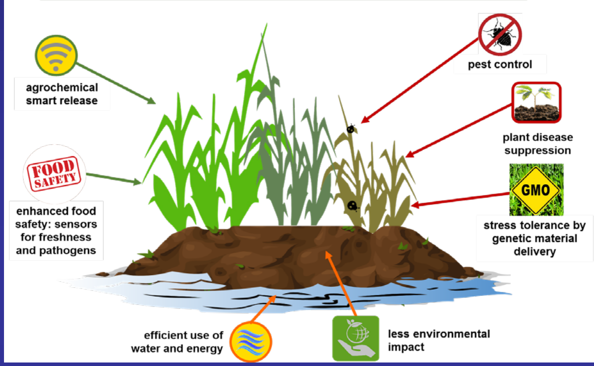
PROGRAM SOLICITATION
NSF 22-521

Contact me if you are interested in Details of the STC C-FOOD

Conclusions

- Nanotechnology has the potential to dramatically improve agriculture; to literally help feed the world

White and Gardea-Torresdey, 2018 *Nature Nanotech.* 13:627-629.



- Nanoscale materials can be used to promote plant health to deter/suppress disease, to more precisely and efficiently deliver nutrients, promote photosynthesis, and increase abiotic stress tolerance
- Because of this and because of widespread use of nanomaterials in other sectors, exposure in the food supply could be significant and applications must be safe and sustainable!

Hoffman et al. 2020 *Nature Food* 1:416-425

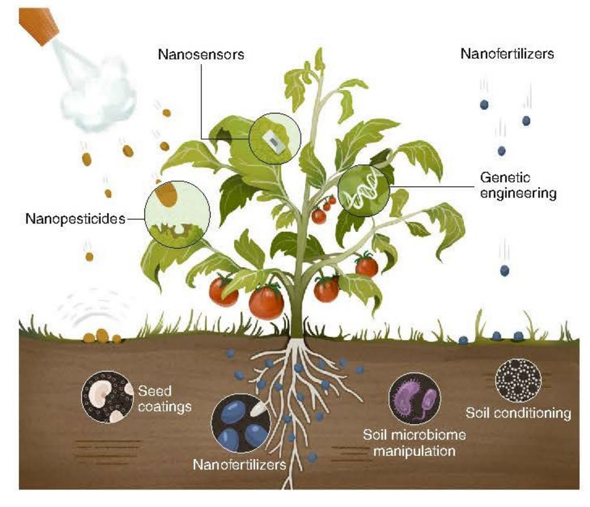
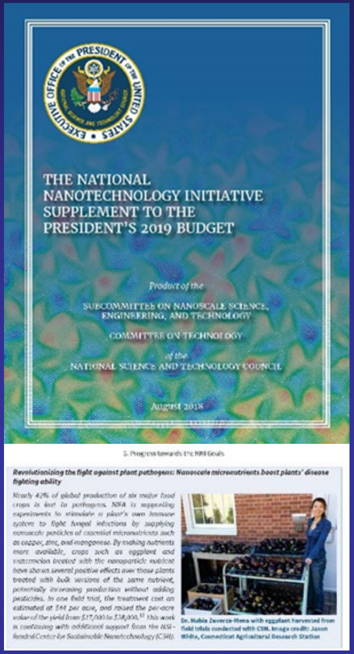


Fig. 2 | Potential application of nanotechnology in plant agriculture.

- An understanding of **mechanisms of action/ interaction** is needed to enable accurate risk assessment
- This includes an understanding of potential secondary yet significant effects, such as those in the microbiome

Acknowledgements

- **Hamers et al.**- Center for Sustainable Nanotechnology (NSF CCI)
- **Demokritou et al-** Rutgers/Harvard Univ. TH Chan School of Public Health
- **Xing, Parkash**- UMass; **Paret et al.**- Univ. of Florida
- **Marmiroli et al.**- Univ. of Parma, Italy
- **Gardea-Torresdey et al.**- UTEP; **Cao et al.**- CAAS
- **Ri and Zhao et al.-** Nanjing Univ.; **Liu et al.**- CAS
- **Keller et al.**- UCSB; **Lin et al.-** Zhejiang Univ.
- **Rui et al.**- China Agricultural Univ.; **Chen et al.-** RISF CAF
- **Wang et al.**- Jiangnan Univ.; **Tang et al.**- Guangxi Univ; **Wang et al.-** Huazhong Univ. of Sci. and Technol.
- **At CAES**- Da Silva, Vaidya, Elmer, Dimkpa, De la Torre-Roche, Servin, Ma, Mukherjee, Zuverza-Mena, Shen, Tamez, Adisa, Borgatta, Majumdar, Wang, Hawthorne, Musante, Thiel
- **Funding**- USDA NIFA AFRI, USDA Hatch, FDA FERN, CSN/NSF



THE NATIONAL NANOTECHNOLOGY INITIATIVE SUPPLEMENT TO THE PRESIDENT'S 2019 BUDGET

Product of the

SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

COMMITTEE ON TECHNOLOGY

of the

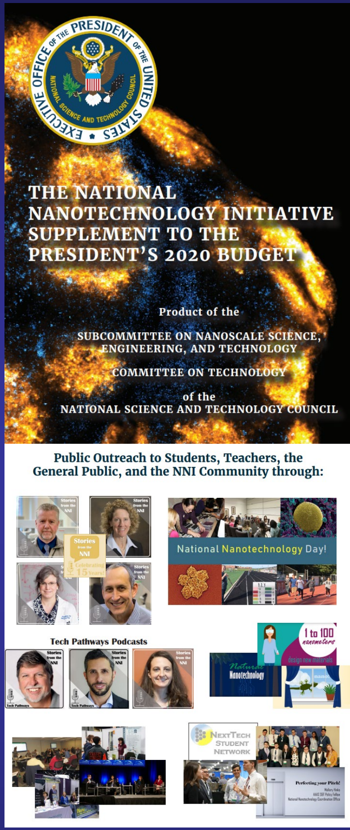
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

August 2018

3. Progress towards the NNI Goals

Revolutionizing the fight against plant pathogens: Nanoscale micronutrients boost plants' disease fighting ability

Dr. Nubia Zuverza-Mena with eggplant harvested from field trials conducted with CSN. Image credit: Jason White, Connecticut Agricultural Research Station



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COMMITTEE ON TECHNOLOGY

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

Public Outreach to Students, Teachers, the General Public, and the NNI Community through:

www.ct.gov/caes