Sustainable Agriculture: Nano-enabled strategies for food security in a changing climate

SUSTAINABILITY Masterclass

NOVEMBER
6 | 7 | 8 | 9
2023

Co-Organizers:

SUSTAINABILITY Masterclass

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6 | 7 | 8 | 9
2023

Co-Organizers:

Jason C. White, Ph.D.

Director, The Connecticut Agricultural Experiment Station, New Haven CT

Presented at the SUSTAINABILITY Masterclass, National and Kapodistrian University of Athens, Athens, Greece, November 6-9, 2023

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
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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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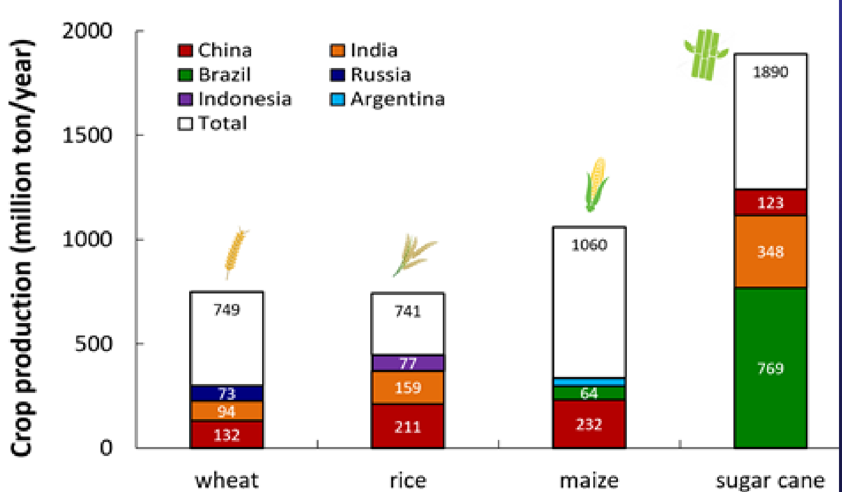
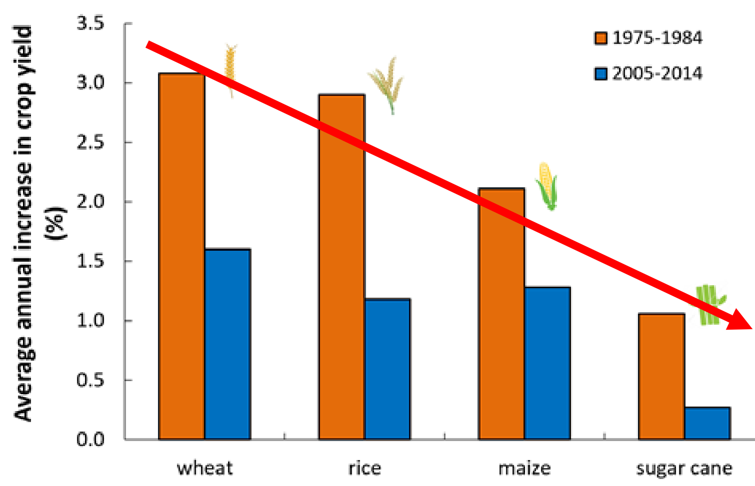




Why Nano-Agriculture?
Declining Global Food Security!!!


INSIGHTS

Science July 2020

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

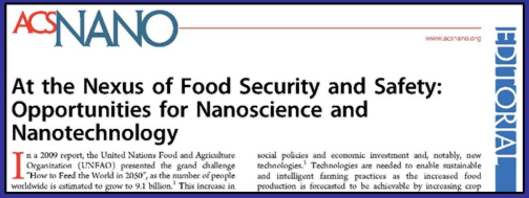
Helena Kahiluoto[a,1], Janne Kaseva[b], Jan Balek[c,d], Jørgen E. Olesen[e], Margarita Ruiz-Ramos[f], Anne Gobin[g], Kurt Christian Kersebaum[h], Jozef Takáč[i], Francoise Ruget[j], Roberto Ferrise[k], Pavol Bezak[l], Gemma Capellades[j], Camilla Dibari[k], Hanna Mäkinen[a], Claas Nendel[h], Domenico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

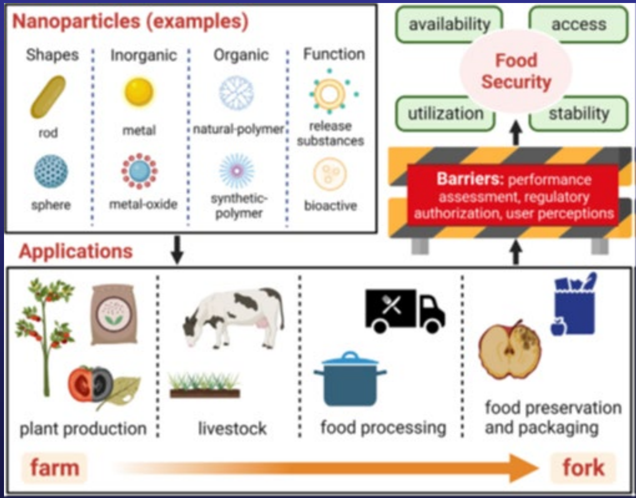
(and especially in combination) impede attempts to achieve progressive and effective policies

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-

- 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!!**



Kah et al. *One Earth* 6, 7:772-775.

“Nano” Research at the CAES

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

1. Applications: Nano-enabled agriculture

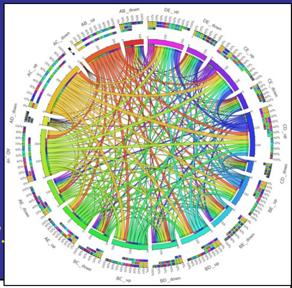
- Nano-enabled micro/macronutrient delivery platforms
- Nanoscale micronutrients to modulate crop nutrition for for disease suppression (ROS!)
- Nanoscale materials to enhance abiotic stress tolerance (ROS!), photosynthesis, induce RNA interference

www.ct.gov/caes

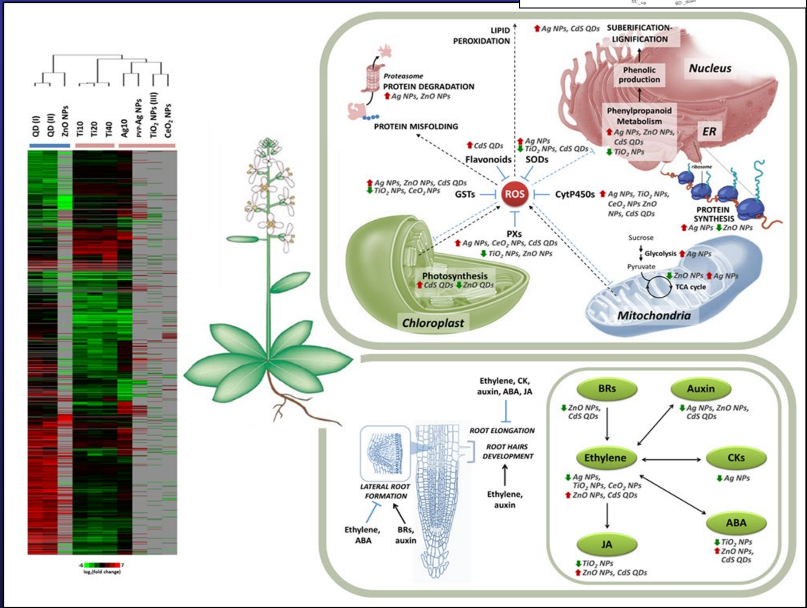
ROS ↕ ROS ↕ ROS ↕ ROS ↕ ROS ↕ ROS

2. Implications: Nanotoxicology

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

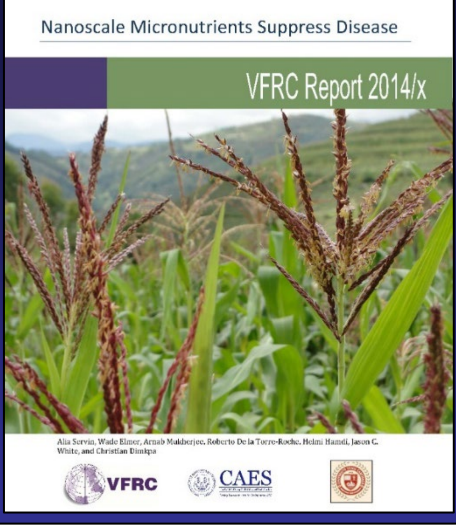


Ruotolo et al. 2018. *Environ. Sci. Technol.* 52:2451-2467.



Nanoscale Nutrients and Root Disease

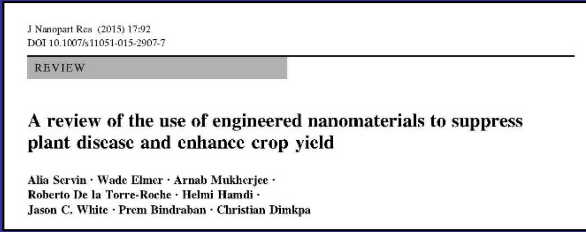
- ➢ In 2014, we began working on soil borne diseases; difficult to manage and reduce crop yields by 20%
- ➢ Fungal pathogens reduce US annual economic return by \$200 million; \$600 million on control
- ➢ Many micronutrients (Cu, Mn, Zn, Mg, B, Si…) stimulate or are part of plant defense systems
- ➢ 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**



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

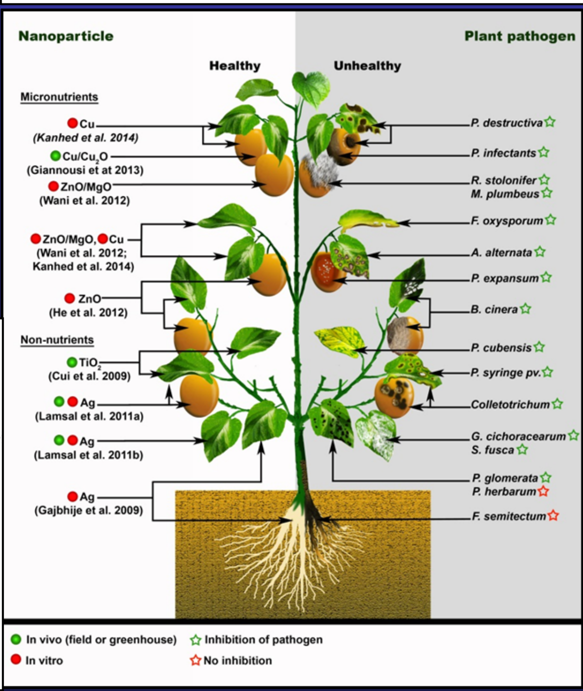


J Nanopart Res (2015) 17:92
DOI 10.1007/s11051-015-2907-7

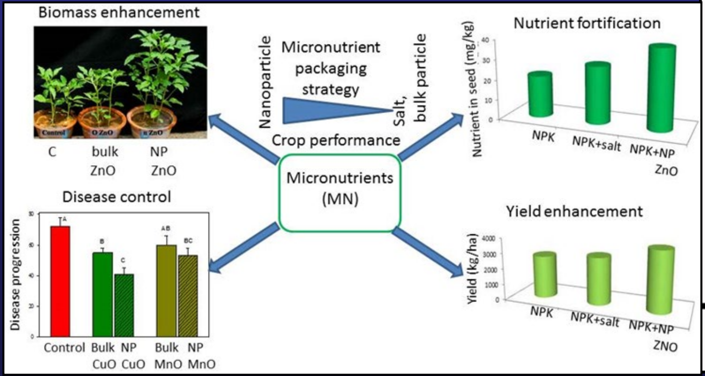
REVIEW

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

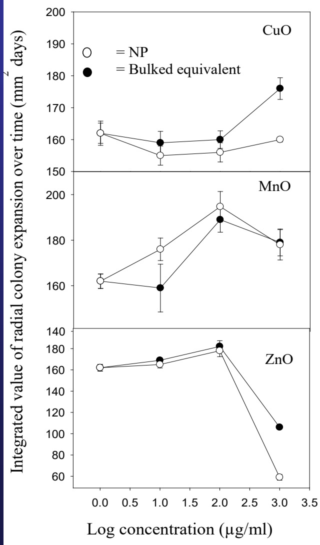


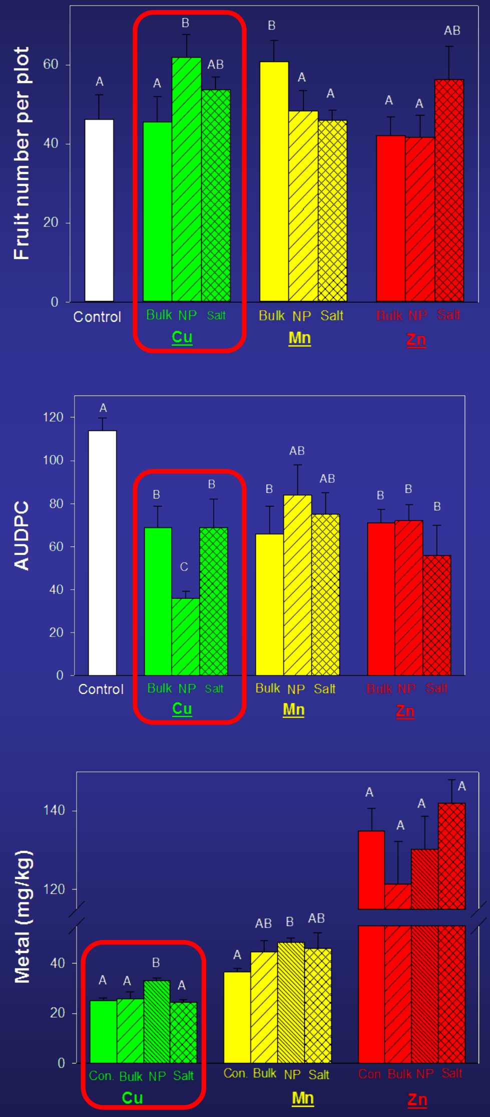
Servin et al. 2015. *J. Nano. Res.* 17:92.



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**

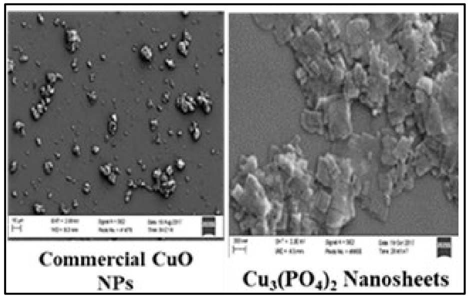




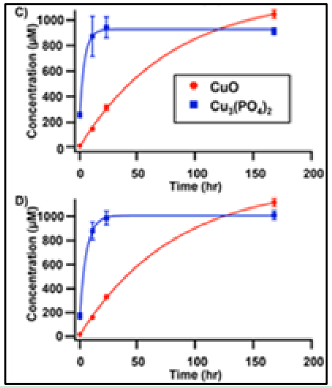
Elmer and White. 2016. *Environ. Sci.: Nano.* 3:1072-1079.

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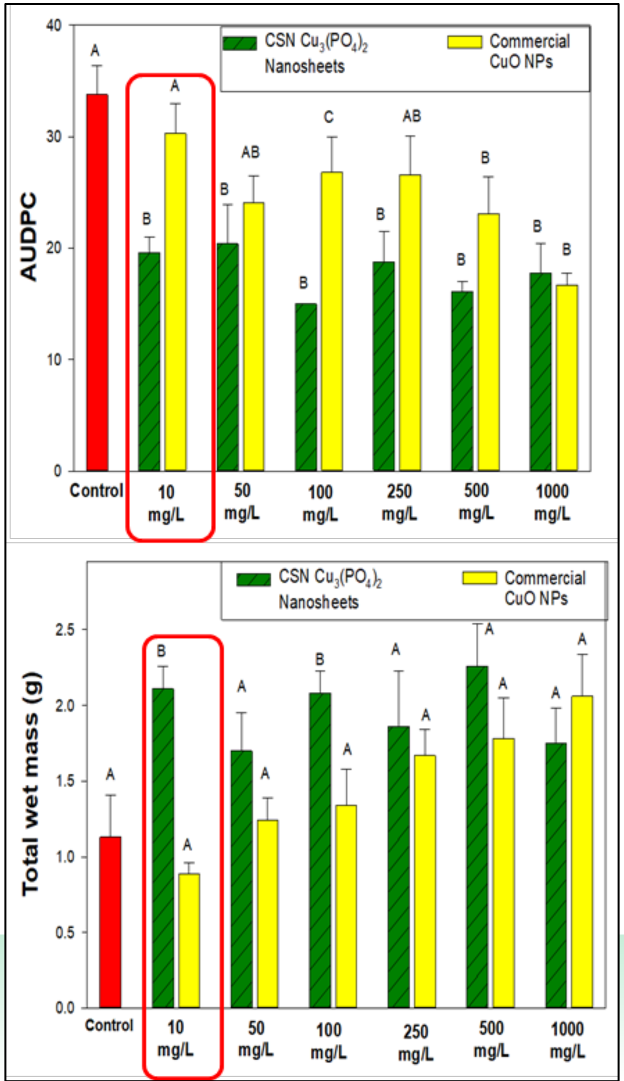
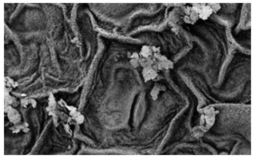
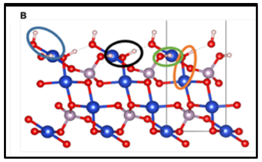
Borgatta et al. 2018. *ACS Sustain. Chem. Eng.* 6:14847-

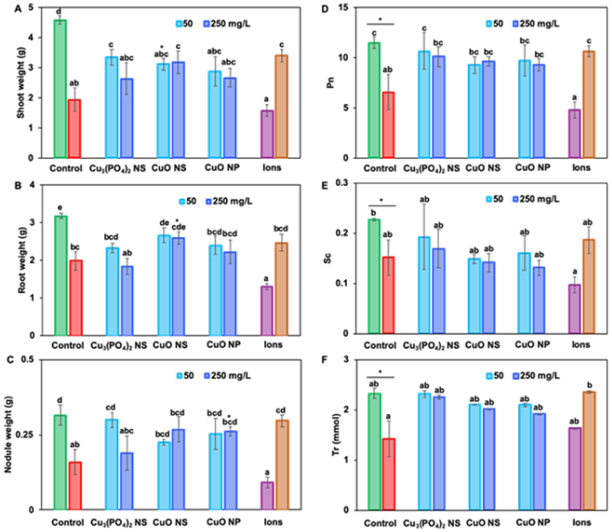


Tuning Particle Properties

- 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.








nature.com/nnano December 2020 Vol. 15 No. 12

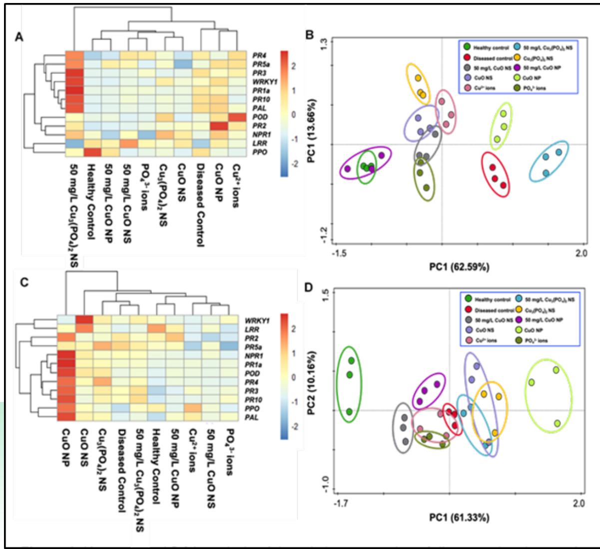
nature nanotechnology

2D PEROVSKITES
Back to fundamentals

RAMAN MICROSCOPY
Single-shot particle localization

QUANTUM COMPUTING
A two-qubit register from nuclear spins

Nanoscale copper for crop nutrition and protection



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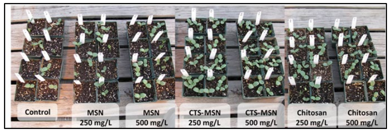
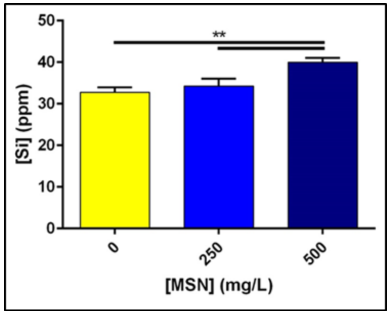
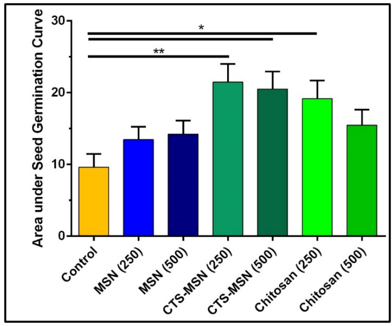
Ma et al. 2020. *Nature Nano* 15, 1033–1042

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







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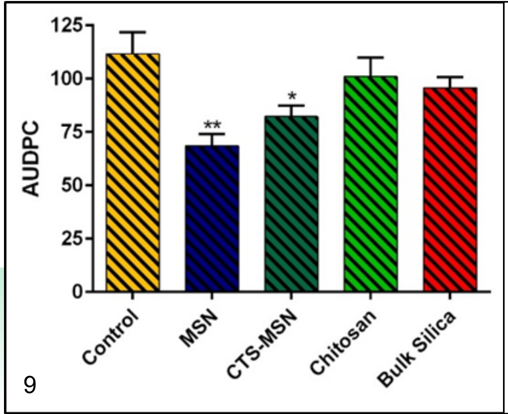
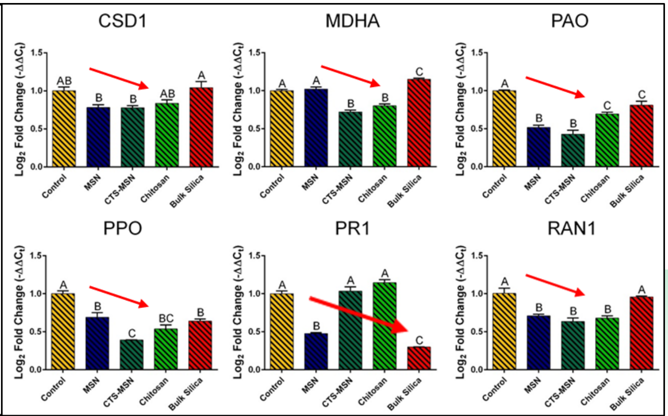
Buchman et al. 2019 *ACS Sus. Chem. Eng.* 7:19649-19659





The Center for Sustainable Nanotechnology

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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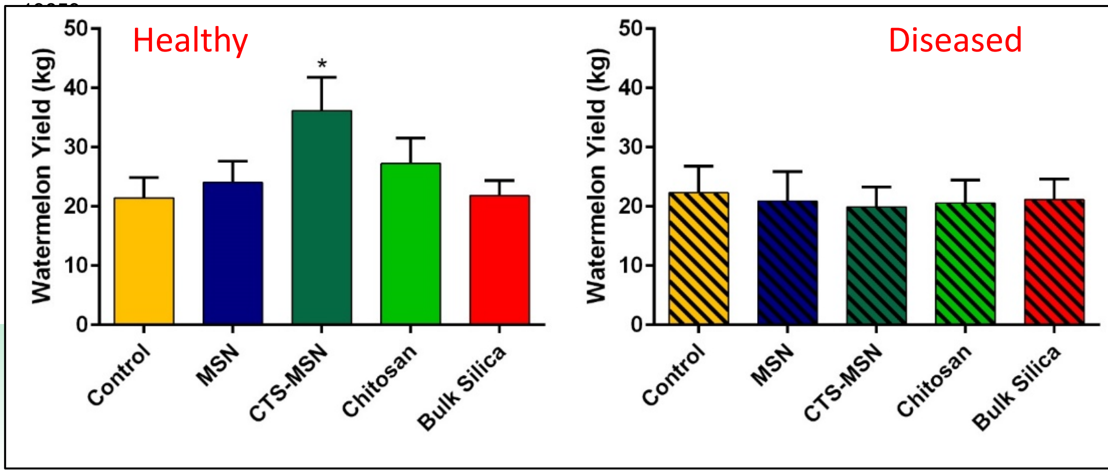

The Center for Sustainable Nanotechnology

Tuning Particle Properties

- In this study, silica nanoparticles (NPs) with tunable dissolution rates were synthesized and applied to watermelon (*Citrullus lanatus*) to enhance plant growth while mitigating development of the Fusarium wilt disease caused by *Fusarium oxysporum*.

- The hydrolysis rates of the silica particles were controlled by the degree of condensation of or the catalytic activity of aminosilane.

- In greenhouse and field studies, plants were foliar treated with 1.8 ml of a 1500 mg/L solution of the SiO_2 NPs, equating to about 2.7 mg of material

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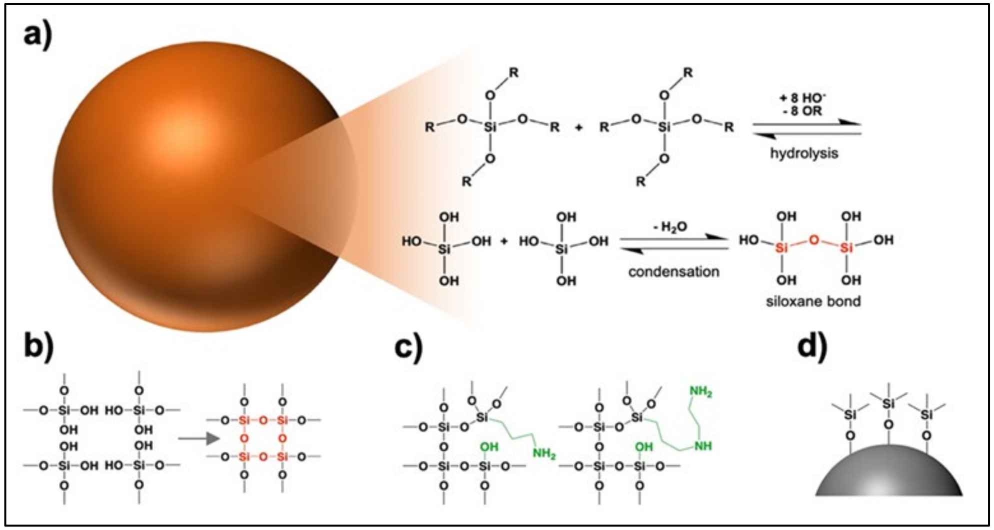
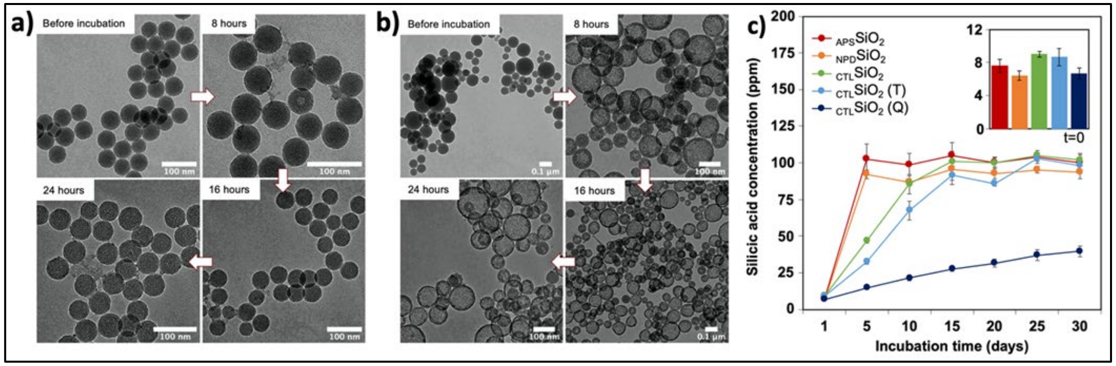
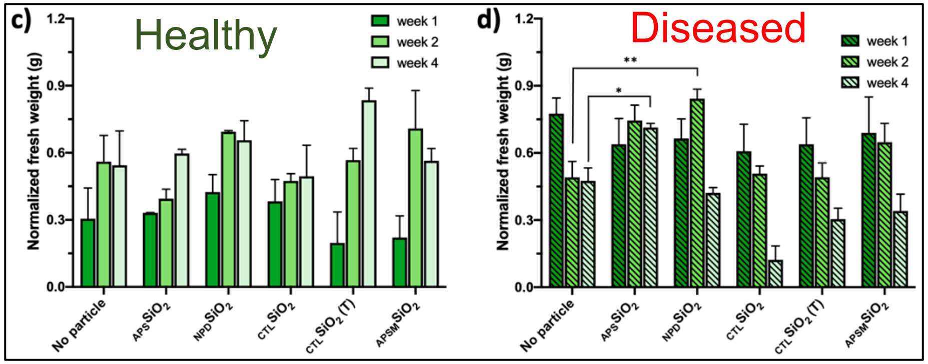


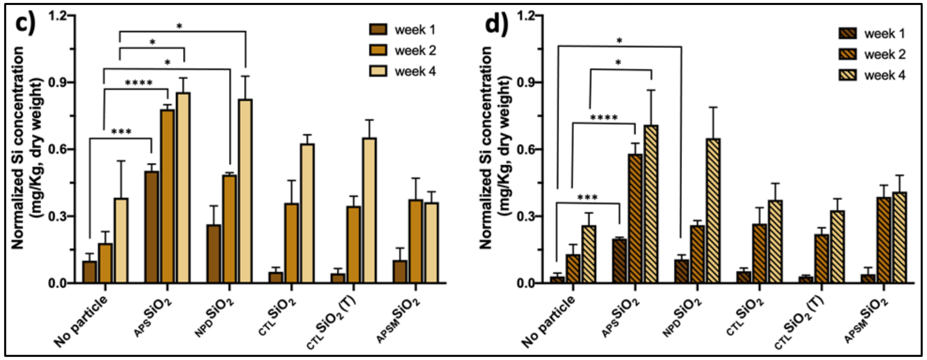


Kang et al 2021. *Environ. Sci. Technol.* 5, 20, 13513-13522

Tuning Particle Properties

- The results demonstrate that the plants treated with fast dissolving NPs maintained or increased biomass whereas the particle-free plants had a 34% decrease in biomass.
- Further, a higher silicon concentration was measured in root parts when the plants were treated with fast dissolving NPs, indicating effective silicic acid delivery.
- Interestingly, foliar application of silicic acid had no beneficial impact
- In a follow-up field study over 2.5 months, the fast-dissolving NP treatment enhanced fruit yield by 81.5% compared to untreated plants.
- These findings indicate that the colloidal behavior of designed nanoparticles can be critical to nanoparticle-plant interactions leading to disease suppression and plant health, as part of a novel strategy for nano-enabled agriculture





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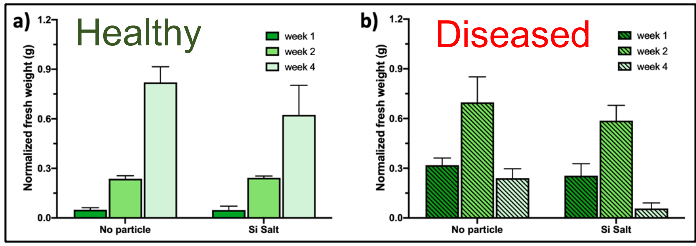

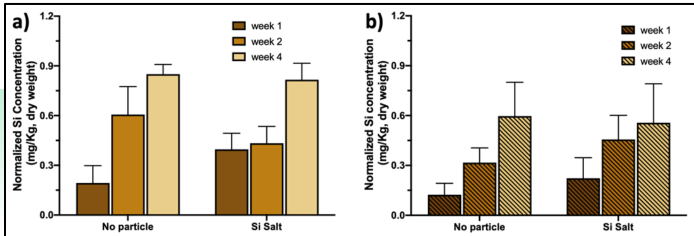

Kang et al 2021. *Environ. Sci. Technol.* 5, 20, 13513-13522

Nanoscale Seed Coatings

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

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

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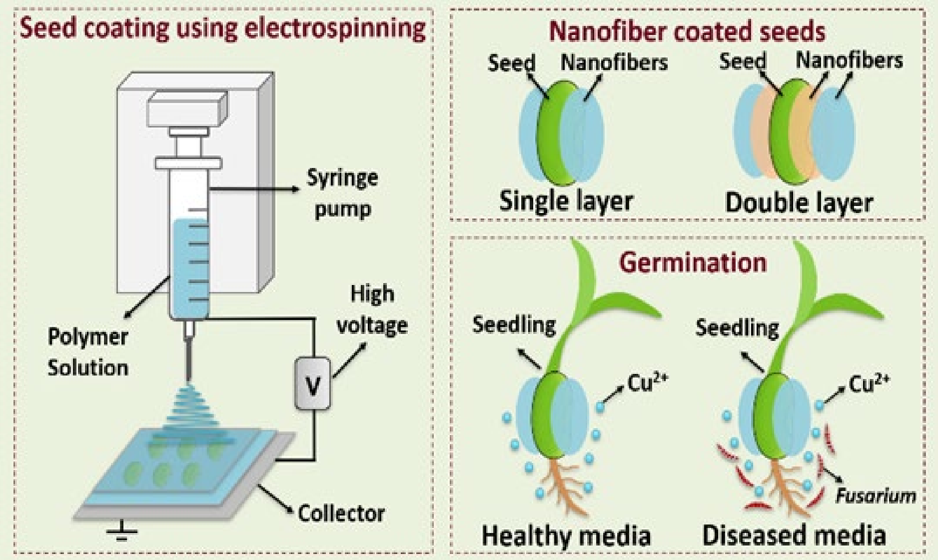
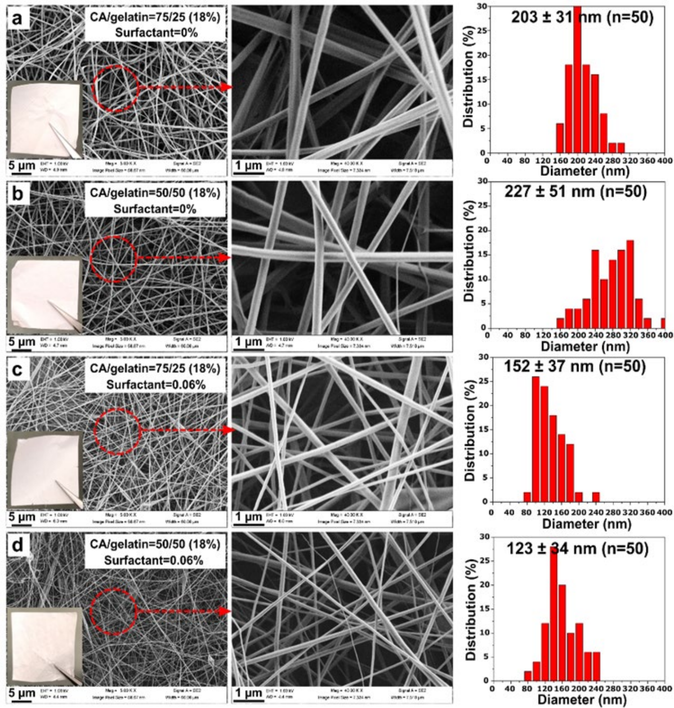
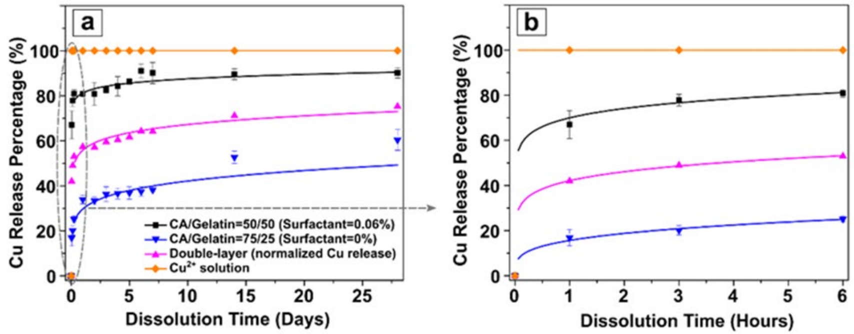


Xu et al. 2020 *ACS Sus. Chem. Eng.* 8, 25, 9537–9548

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





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!***

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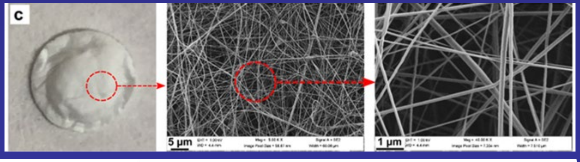
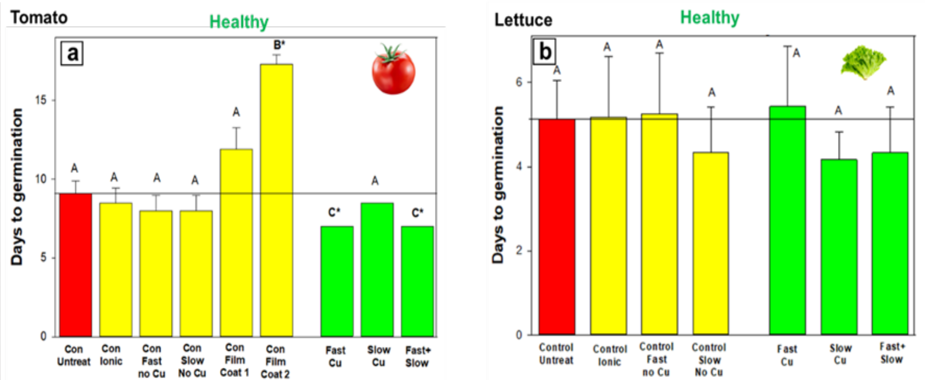
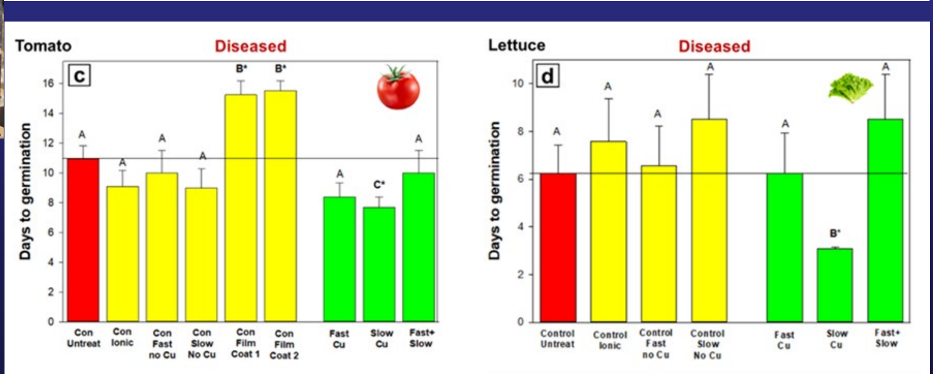


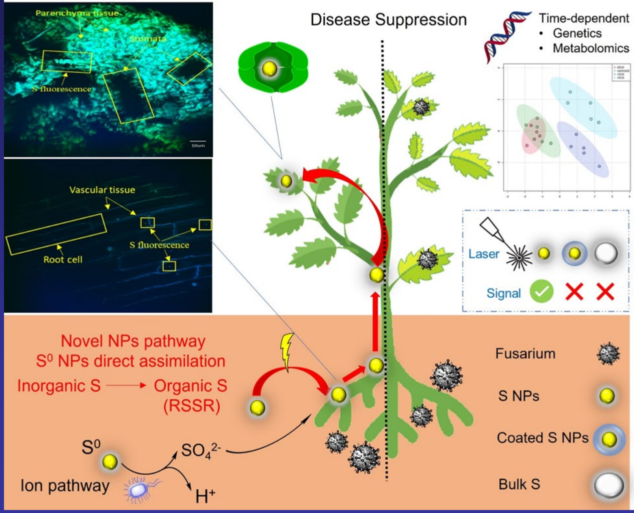


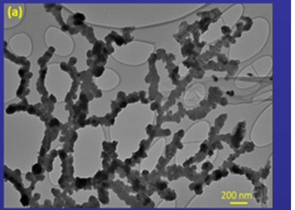


Xu et al. 2020 *ACS Sus. Chem. Eng.* 8, 25, 9537–9548

Nanoscale Sulfur and Disease

- Wang al 2022. Therapeutic delivery of nanoscale sulfur to suppress disease in tomato: In vitro imaging and orthogonal mechanistic investigation *ACS Nano* 16, 7, 11204–11217
- Pristine (nS) and stearic acid coated (cS) sulfur NPs added at 200 ppm to soil planted with tomato and infested with *Fusarium oxysporum*.
- Bulk sulfur (bS), ionic sulfate (iS), and healthy controls were included.
- Orthogonal endpoints measured included agronomic and photosynthetic parameters, disease severity/suppression, mechanistic biochemical and molecular endpoints including the time-dependent expression of 13 genes related to two S bioassimilation and pathogenesis-response, and metabolomic profiles by LC-MS





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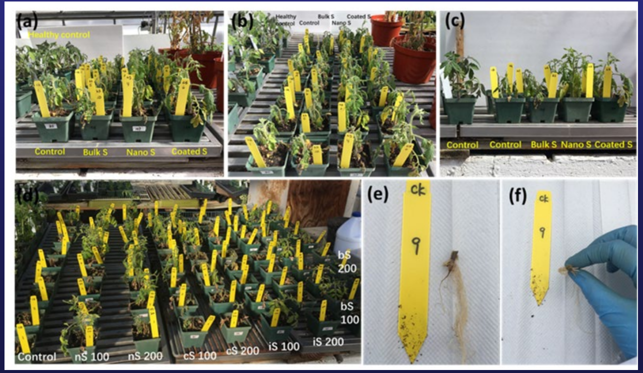
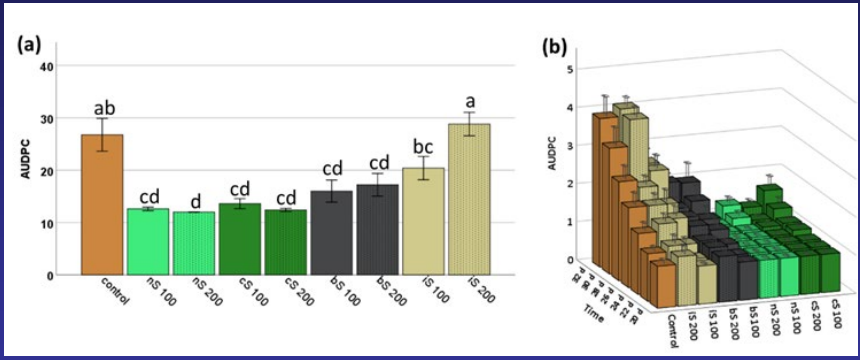
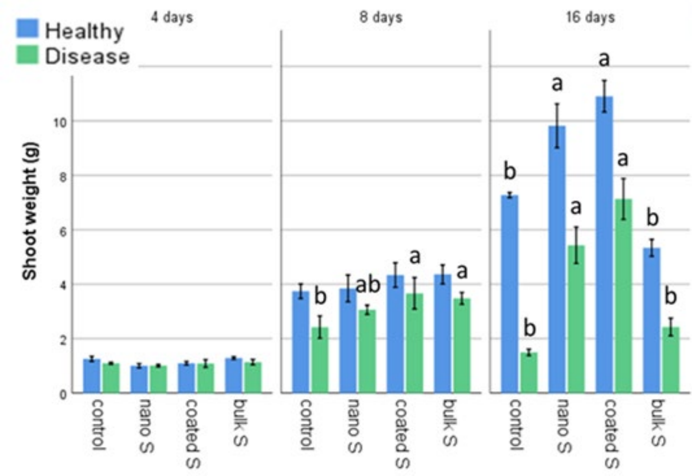


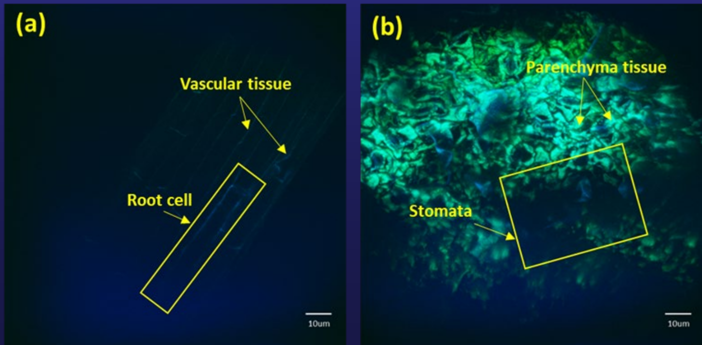
Wang et al 2022 *ACS Nano* 16, 7, 11204-11217

Nanoscale Sulfur and Disease

- Disease decreased plant biomass by up to 87%, but nS and cS amendment significantly reduced disease (AUDPC) by 54 and 56%, respectively.
- Increased in planta S accumulation was evident, with size-specific translocation ratios suggesting *different* uptake mechanisms.
- In vivo two-photon microscopy and time-dependent gene expression revealed a nanoscale-specific elemental S bioassimilation pathway within the plant that is separate from traditional sulfate accumulation.



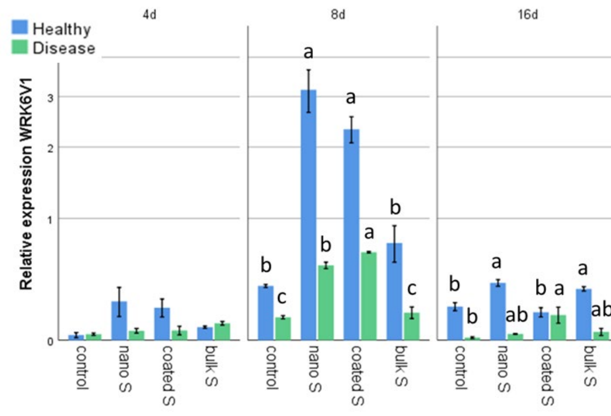


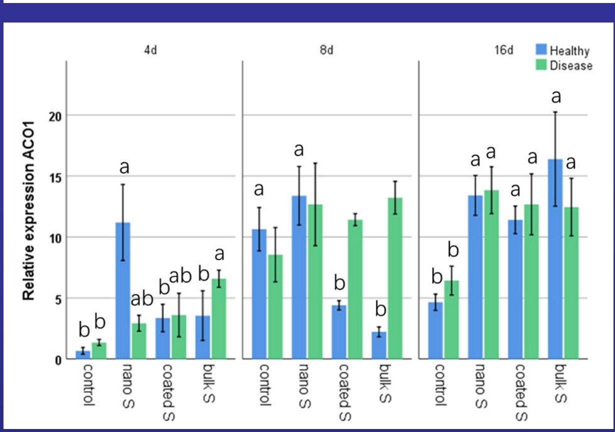


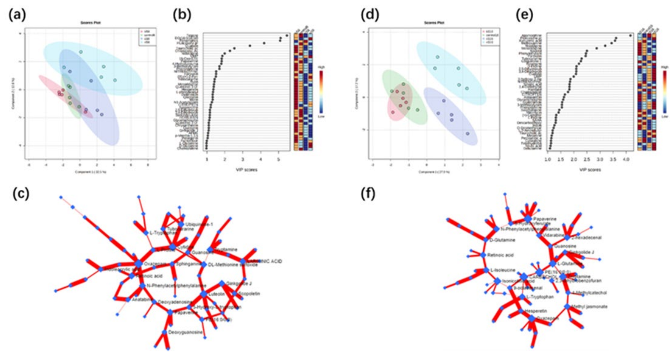
Wang et al 2022 *ACS Nano* 16, 7, 11204-11217

Nanoscale Sulfur and Disease

- ➢ These findings align with time-dependent metabolomics, which exhibited increased disease resistance and plant immunity related metabolites only with nanoscale treatment.
- ➢ For example, the expression of WRKY6v1 and ACO1 (both are defense-related genes) was upregulated in a time dependent fashion as a function of S size and coating
- ➢ The linked gene expression and metabolomics data demonstrate a time-sensitive physiological window where nanoscale stimulation of plant immunity will be effective.
- ➢ These findings provide mechanistic understanding of nanosulfur-mediated disease suppression and advance sustainable nano-enabled agricultural strategies to increase food production.



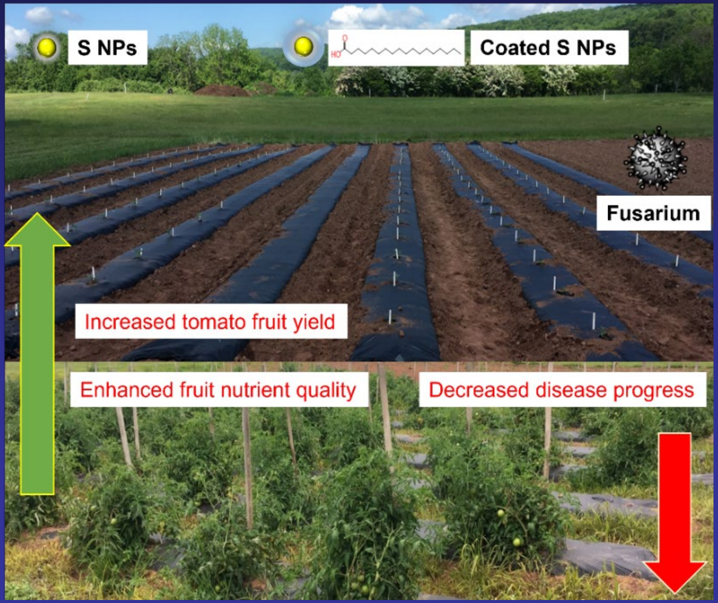




Wang et al 2022 *ACS Nano* 16, 7, 11204-11217

Nanoscale Sulfur and Disease

- Wang al. 2022. Surface coated sulfur nanoparticles suppress Fusarium disease in field grown tomato: Increased yield and nutrient biofortification *J. Agric. Food Chem.* 70, 45, 14377–14385
- In the infested treatments, cS significantly reduced disease severity compared to other treatments.
- Ca, Cu, Fe, and Mg content in the S-amended fruit were increased over diseased controls.
- On a per acre basis, a **$33** investment in nanoscale sulfur led to an increase in marketable yield from **4,920 kg per acre to 11,980 kg/acre** for healthy plants and from **1,135 kg/acre to 2,180 kg/acre** for Fusarium-infested plants
- These increases equate to an additional **$6,700-12,200** in economic return per acre.



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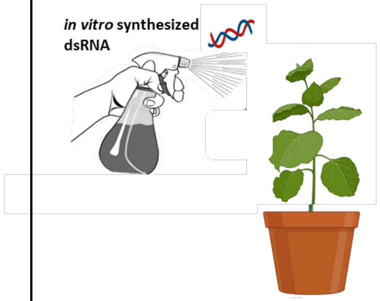
Wang et al 2022 *J. Agric. Food Chem.* 70, 45, 14377–14385

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

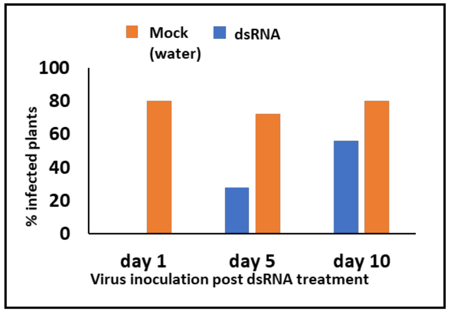


- ✓ non-GMO
- ✓ easy to generate in lab

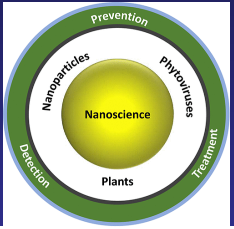
RNAi: RNA interference

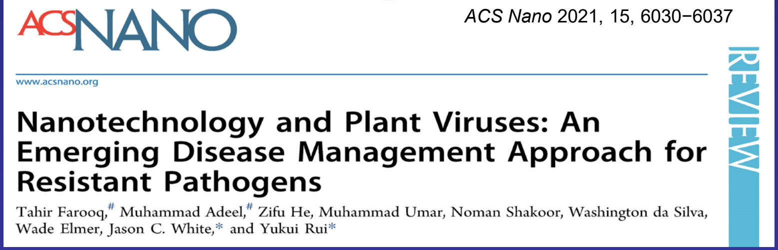
Concern: Longevity of protection window?

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

REVIEW

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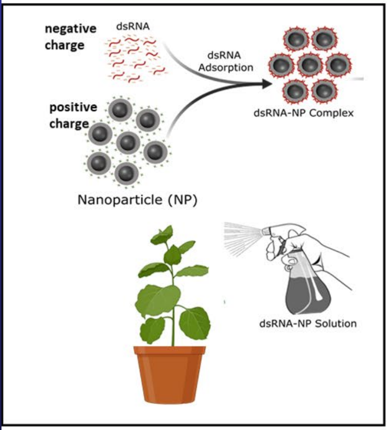
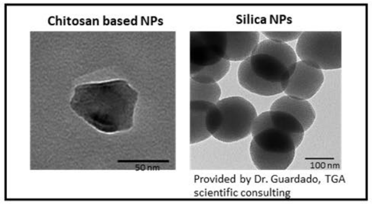
“Tunable release of dsRNA molecules into plants from sustainable nanocarriers: A novel management tool for viral Pathogens” Da Silva et al.

USDA
National Institute of Food and Agriculture

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

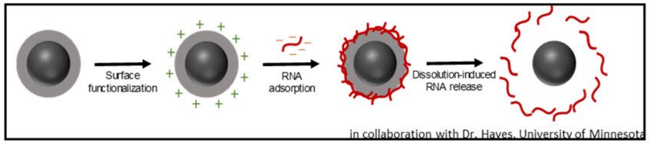


Nanoparticles being tested for dsRNA absorption and release



Provided by Dr. Guardado, TGA scientific consulting

Synthesize silica NPs for a more controlled dsRNA release

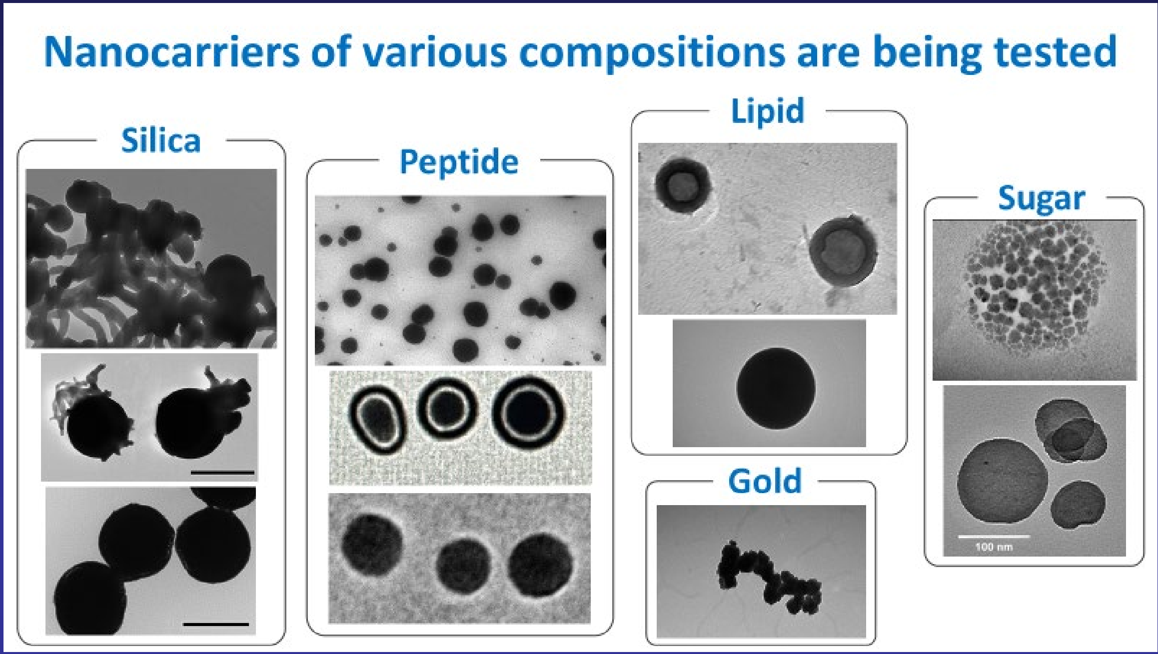


in collaboration with Dr. Hayes, University of Minnesota

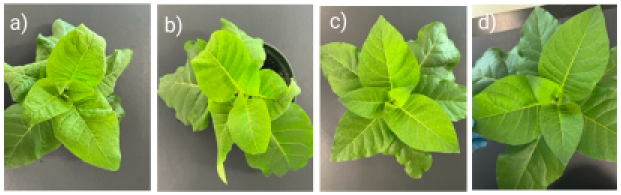
Identify most efficient dsRNA delivery system for virus control

RNA Interference and Viral Infection

- A wide range of materials are being investigated as potential carriers to deliver and provide controlled long-term release of various genetic cargo
- Current model system is potato and the PVY
- PVY is a single stranded RNA virus that infects mainly Solanaceous plants including, potato, tomato, pepper,…

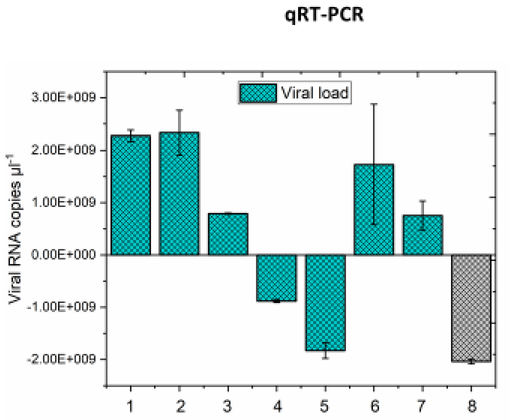

Nanocarriers of various compositions are being tested

Peptide-dsRNA nanocomplex treated with PVY infection?



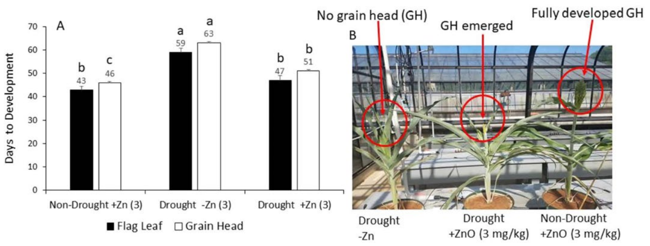
a) Positive control, b) dsRNA treated,
b) c) & d) Peptide-nano dsRNA treated

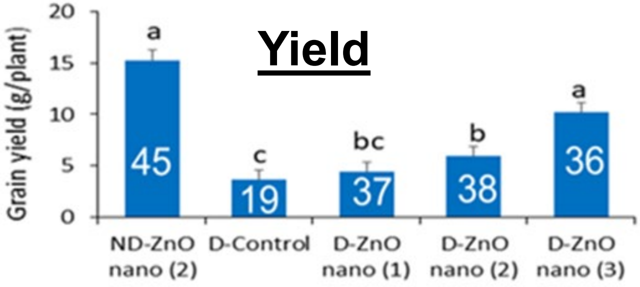
1. PVY-Positive control
2. PVY+peptide 1%
3. PVY+peptide nanoparticles
4. PVY+Peptide-dsRNA (100µg)
5. PVY+Peptide-dsRNA (200µg)
6. PVY+DsRNA (100µg)
7. PVY+DsRNA (200µg)
8. PVY-Negative control

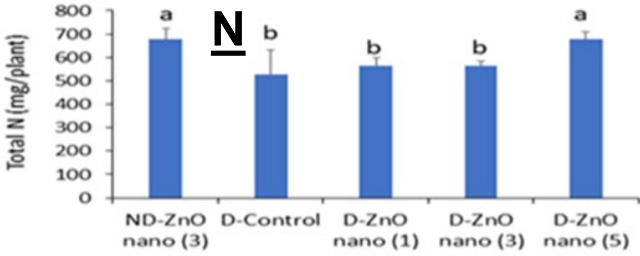


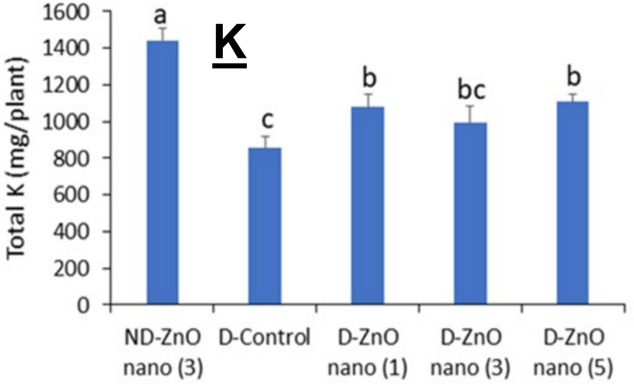
NP ZnO alleviates drought-induced damage

- 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%.





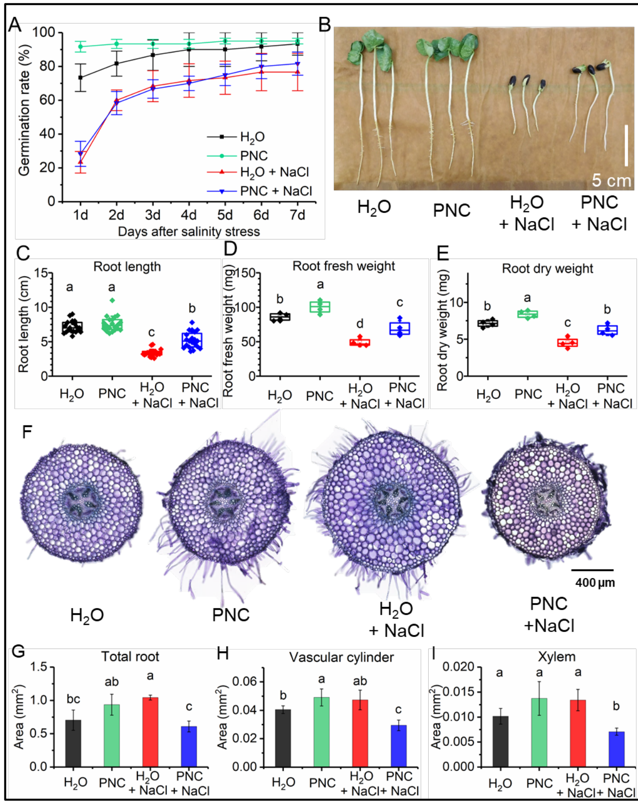


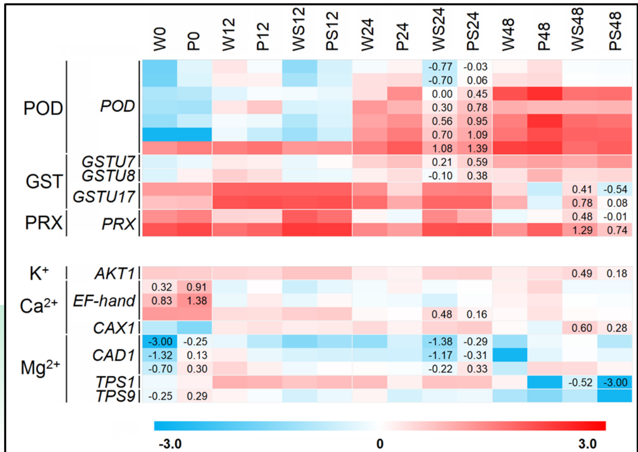


Dimkpa et al. 2019. *Sci. Total Environ.* 688:926-934.

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.





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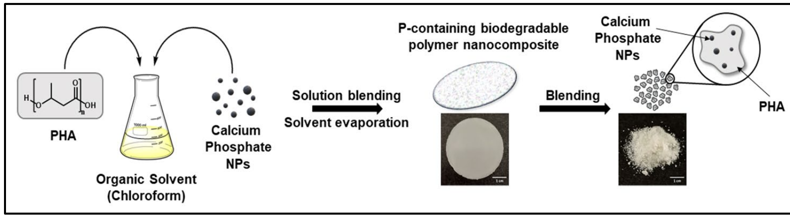
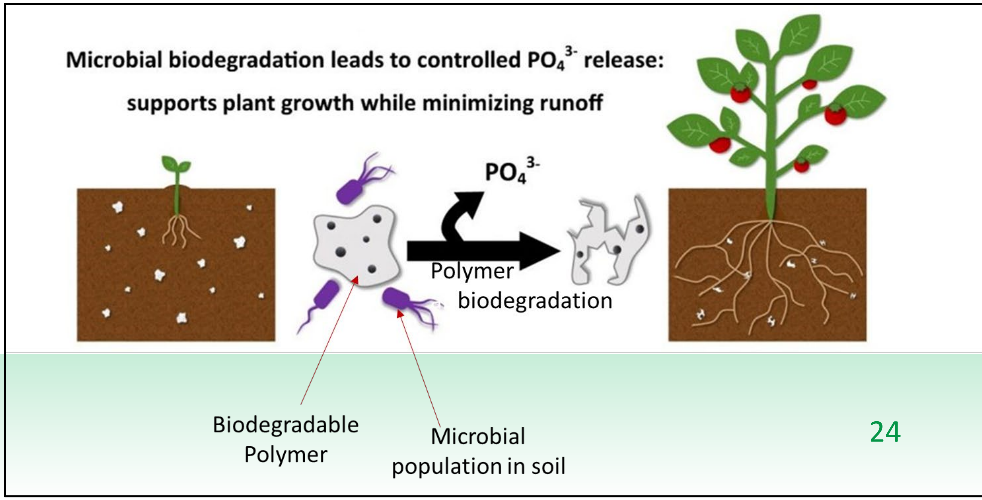
The Center for Sustainable Nanotechnology

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

Polymer Nanocomposites- P Delivery

- We propose to make a **tunable suite** 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).



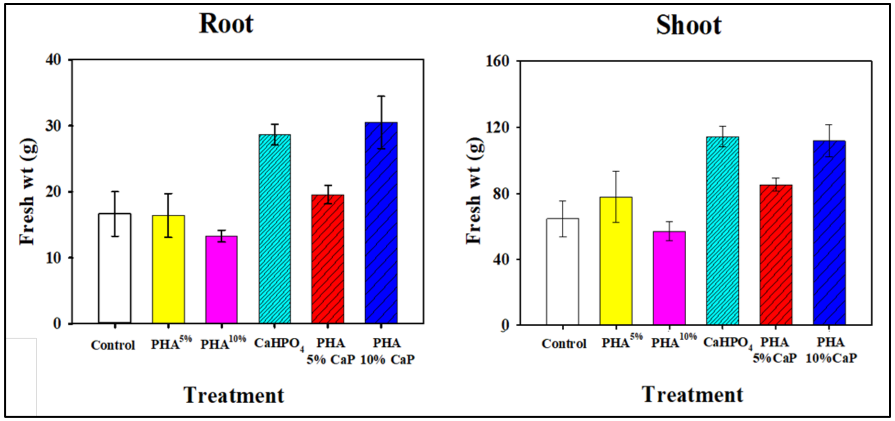


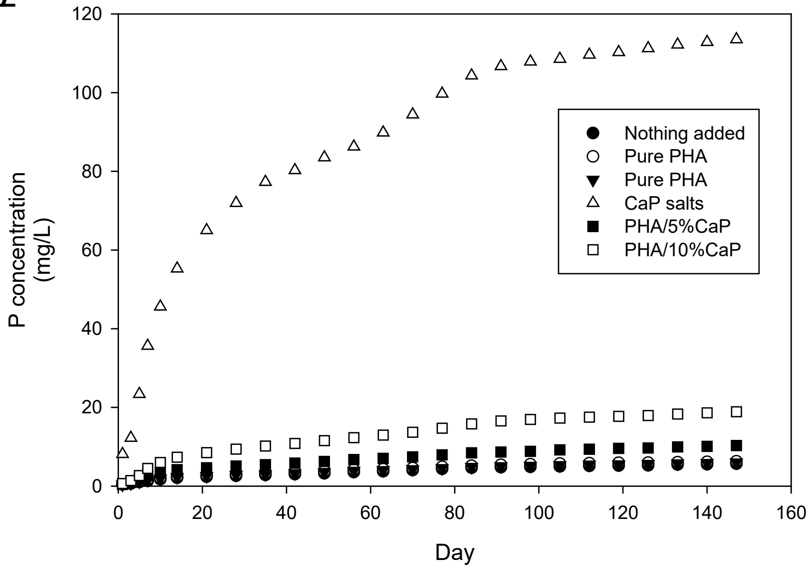
Sigmon et al. 2021 *ACS Agric. Sci. Technol.* 1, 5, 529–539

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.

www.ct.gov/caes





The Center for Sustainable Nanotechnology

USDA National Institute of Food and Agriculture

Sigmon et al. 2021 *ACS Agric. Sci. Technol*. 1, 5, 529–539

Polymer Nanocomposites- P Delivery

- **Sigmon et al. 2023** "Role of phosphorus and biodegradable polymer type on phosphorus fate and efficacy in a plant-soil system" *J. Agric. Food Chem.* https://doi.org/10.1021/acs.jafc.3c04735

- **Goal**- To understand how the properties of biodegradable polymer-nanoparticle composites vary with different P type fertilizer

Greenhouse experiment with Tomato (50 d, 40 mg P per replicate)

1) Control (Nothing added)
2) PHA Control
3) Calcium phosphate monobasic (Mono)
4) PHA-Mono
5) Calcium phosphate dibasic(Di)
6) PHA-Di
7) Hydroxyapatite nanoparticles(HAN)
8) PHA-HAN
9) Hydroxyapatite microparticles (HAM)
10) PHA-HAM
11) Calcium pyrophosphate nanoparticles (CAP)
12) PHA-CAP

- **Endpoints**- Amount of P released: leachate, soil column, and dissolution; Plant growth and health: biomass, tissue P concentration; Total and available P in soil after plant growth

USDA National Institute of Food and Agriculture

Sigmon et al. 2023 *J. Agric. Food Chem.*
https://doi.org/10.1021/acs.jafc.3c04735

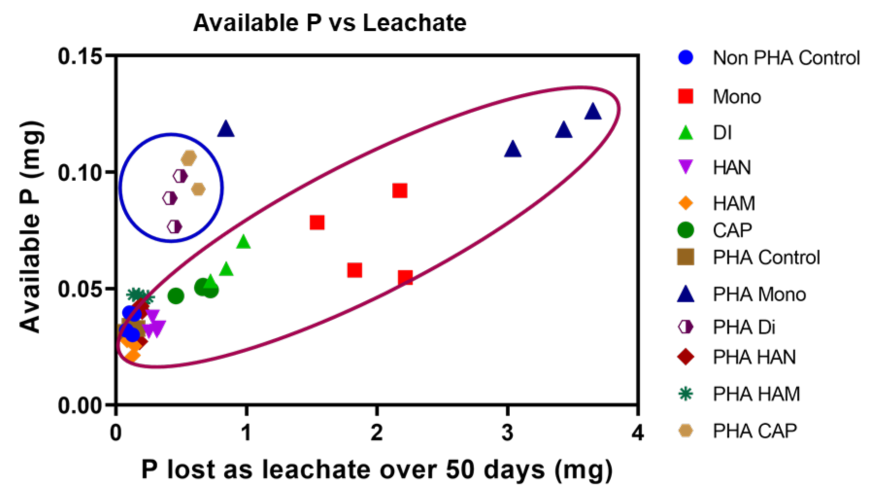
Polymer Nanocomposites- P Delivery

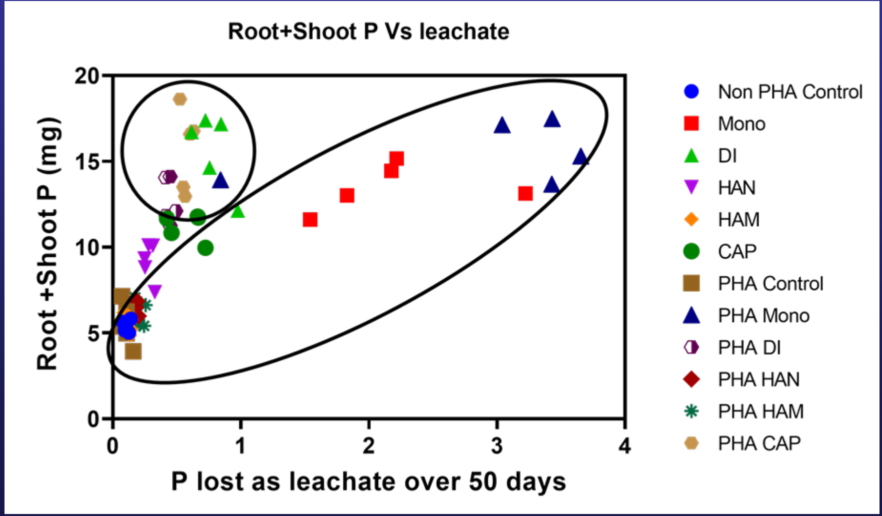
- Equivalent biomass across all P types, regardless of PHA presence

- Correlation analysis identified 3 performance classes :
  (i) HAM and HAN did not increase bioavailable P, plant P-uptake, or change P in runoff/leaching compared to controls;
  (ii) MCP, Di, CAP, and PHA-MCP increased P-uptake and/or bioavailable P but also increased P loss in runoff/leaching; and
  (iii) PHA-Di and PHA-CAP where increased bioavailable P and plant P-uptake were achieved with minimal P loss in runoff/leaching.

- Biopolymers can promote plant P-uptake and improve bioavailable soil P, mitigating the negative environmental impacts of P loss from agricultural systems

Sigmon et al. 2023 *J. Agric. Food Chem.* https://doi.org/10.1021/acs.jafc.3c04735

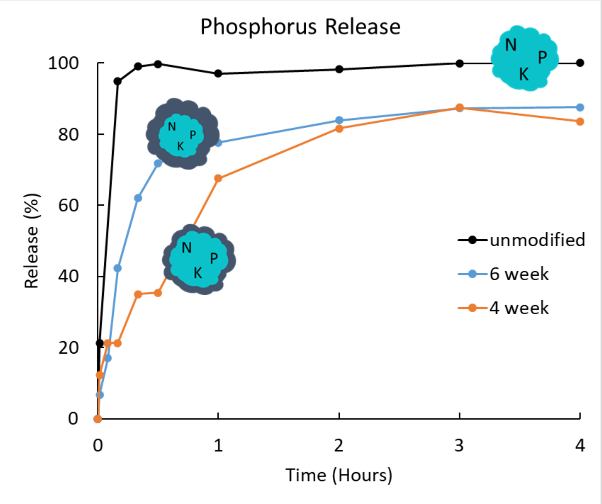


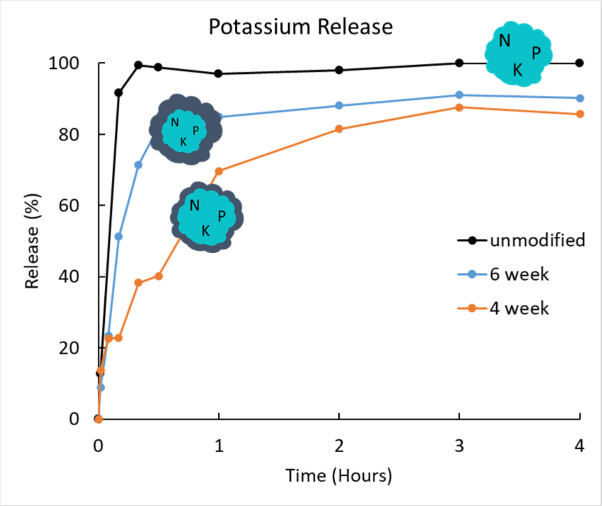


Controlled NPK Release- Nanocellulose

- **Gomez Maldonado et al. 2023** "Slowing soluble NPK release with hydrophobized nanocellulose-based hydrogels for enhanced efficiency fertilizers" *Environ. Sci.: Nano*. Submitted (Auburn, Hopkins, CAES)

- Cellulose nanofibrils-based hydrogels (CNFs) were regenerated from mixed softwood in acidic media and were loaded with NPK
- NPK-loaded CNFs were functionalized using the gas phase esterification; reaction time was varied to tune the hydrophobicity of NPK-CNF
- The more-esterified sample (6 weeks) released K and P more quickly than the 4-week despite a greater functionalization.
- This result counters the expectation that greater hydrophobicity should slow release; esterification beyond a critical point make break down the micro-nano structure, creating channels for rapid nutrient dissolution





Gomez-Maldonado et al. 2023 *Environ. Sci.: Nano*.
https://doi.org/10.1039/D3EN00306J

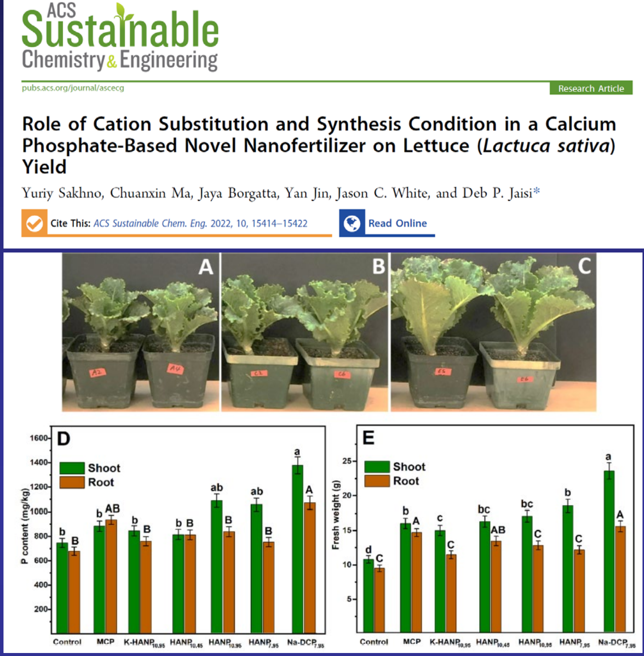
Phosphorus, UDel, and CAES

Sakhno et al. 2022

- HANPs and dicalcium phosphate anhydride (DCPA) under varying crystallization conditions (temperature, pH, and cation substitution) were tested on lettuce
- HANPs and DCPA stimulated lettuce growth, but the extent of enhancement was a function of synthesis condition

Sakhno et al. 2023

- Citrate-stabilized ACP nanoparticles (ACPcs) doped with micronutrients (B, Cu, Mg, and Zn)
- P resource use efficiency (RUE), accounting for crop yield and P lost in leachate, was higher in all ACPc than conventional MCP (monocalcium phosphate) and was about a log order higher in multi-micronutrient doped ACPcs

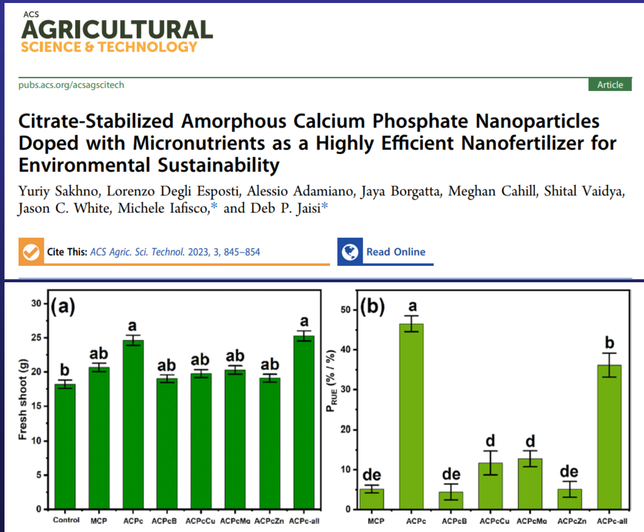


ACS Sustainable Chemistry & Engineering
pubs.acs.org/journal/ascecg
Research Article

Role of Cation Substitution and Synthesis Condition in a Calcium Phosphate-Based Novel Nanofertilizer on Lettuce (*Lactuca sativa*) Yield

Yuriy Sakhno, Chuanxin Ma, Jaya Borgatta, Yan Jin, Jason C. White, and Deb P. Jaisi*

Cite This: *ACS Sustainable Chem. Eng.* 2022, 10, 15414−15422 Read Online



ACS AGRICULTURAL SCIENCE & TECHNOLOGY
pubs.acs.org/acsagscitech
Article

Citrate-Stabilized Amorphous Calcium Phosphate Nanoparticles Doped with Micronutrients as a Highly Efficient Nanofertilizer for Environmental Sustainability

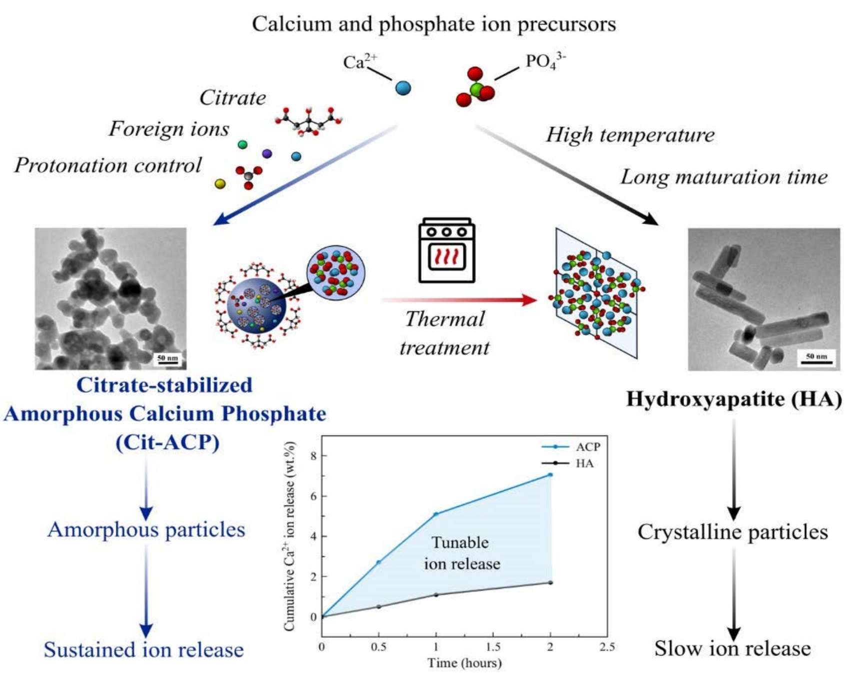
Yuriy Sakhno, Lorenzo Degli Esposti, Alessio Adamiano, Jaya Borgatta, Meghan Cahill, Shital Vaidya, Jason C. White, Michele Iafisco,* and Deb P. Jaisi*

Cite This: *ACS Agric. Sci. Technol.* 2023, 3, 845−854 Read Online

New USDA Project 2023-67021-39521

Calcium phosphate nanocomposites for improving nutrient use efficiency and crop yield and reducing loss: PD- Jaisi (UDel); CoPDs- White/Steven (CAES), Iafisco (NRC Italy)- 6/1/24-5/31-27

- Synthesize amorphous and crystalline calcium phosphate (ACC) nanocomposite as a micronutrient-doped novel nanofertilizer from waste recycled P.
- Develop a mechanistic, structure-function relationship of P release kinetics with structural and surface and interfacial characteristics of ACCPs and tune for optimal P release.
- Greenhouse experiments with plant species and apply the isotope tracking method to discriminate P uptake from ACCPs vs. other soil P pools and compare nutrient and resource use efficiencies (NUE and RUE) with conventional and slow-release fertilizers.
- Analyze microbiome and rhizosphere nutrient chemistry to quantify the positive and synergistic impacts of ACCPs against conventional and slow-release fertilizers.



Responsive Nanocapsules

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

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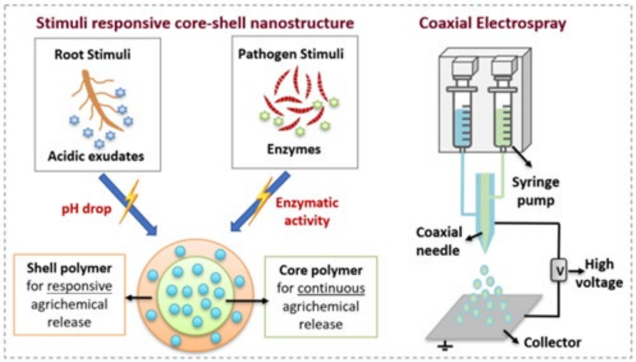
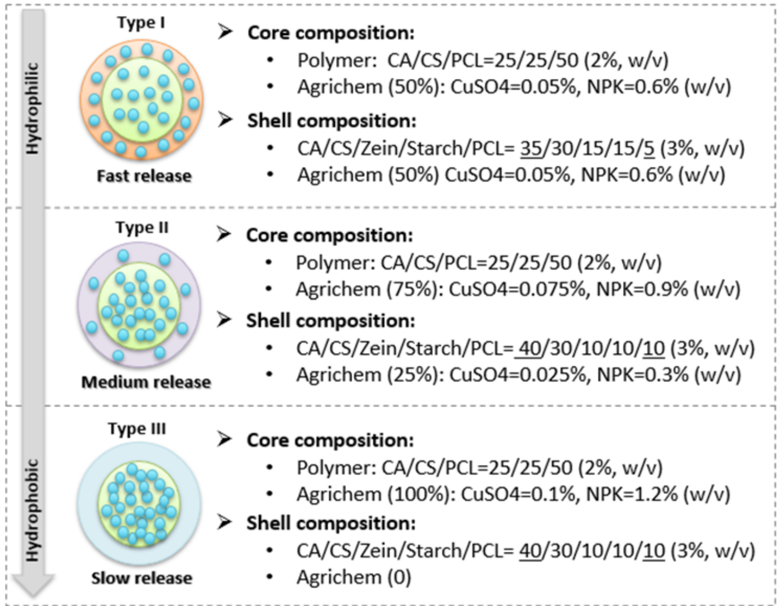
- Biopolymer-based multi stimuli responsive nanoplatform (i.e., core/shell nanostructure) was developed by a “green” electrospray approach for smart agrichemical delivery.
- The shell polymer was designed to be responsive to different triggers such as pH and microbial enzyme activity, and the core polymer was designed to continuously release the agrichemicals over the longer term.
- NPK and Cu were loaded at 100% and 25% label rates
- The pH and enzyme responsiveness was demonstrated by the analyte release kinetics as a function of chemical composition.
- Efficacy was evaluated in soil-based greenhouse studies using soybean and wheat.

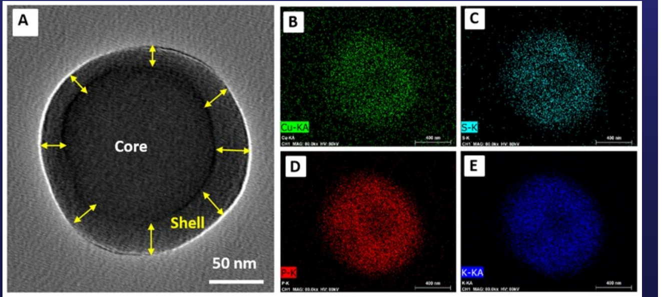




Type I
- **Core composition:**
  - Polymer: CA/CS/PCL=25/25/50 (2%, w/v)
  - Agrichem (50%): CuSO4=0.05%, NPK=0.6% (w/v)
- **Shell composition:**
  - CA/CS/Zein/Starch/PCL= <u>35</u>/30/15/15/<u>5</u> (3%, w/v)
  - Agrichem (50%) CuSO4=0.05%, NPK=0.6% (w/v)

Type II
- **Core composition:**
  - Polymer: CA/CS/PCL=25/25/50 (2%, w/v)
  - Agrichem (75%): CuSO4=0.075%, NPK=0.9% (w/v)
- **Shell composition:**
  - CA/CS/Zein/Starch/PCL= <u>40</u>/30/10/10/<u>10</u> (3%, w/v)
  - Agrichem (25%): CuSO4=0.025%, NPK=0.3% (w/v)

Type III
- **Core composition:**
  - Polymer: CA/CS/PCL=25/25/50 (2%, w/v)
  - Agrichem (100%): CuSO4=0.1%, NPK=1.2% (w/v)
- **Shell composition:**
  - CA/CS/Zein/Starch/PCL= <u>40</u>/30/10/10/<u>10</u> (3%, w/v)
  - Agrichem (0)



Xu et al. 2022 *ACS Nano*. 16, 4, 6034–6048

Responsive Nanocapsules

- Amendment of the responsive nanostructure at 25% NPK/Cu resulted in enhanced photosynthetic parameters in both soybean and wheat, as compared to conventional fertilizer controls at 100% the label rate.
- Moreover, the Zn and Na content in the leaves of 4-week old soybean seedlings were significantly increased with nanostructure amendment, indicating that NPK and Cu in this nanoscale form can potentially be used to modulate the accumulation of other important micronutrients as part of a potential biofortification strategy.

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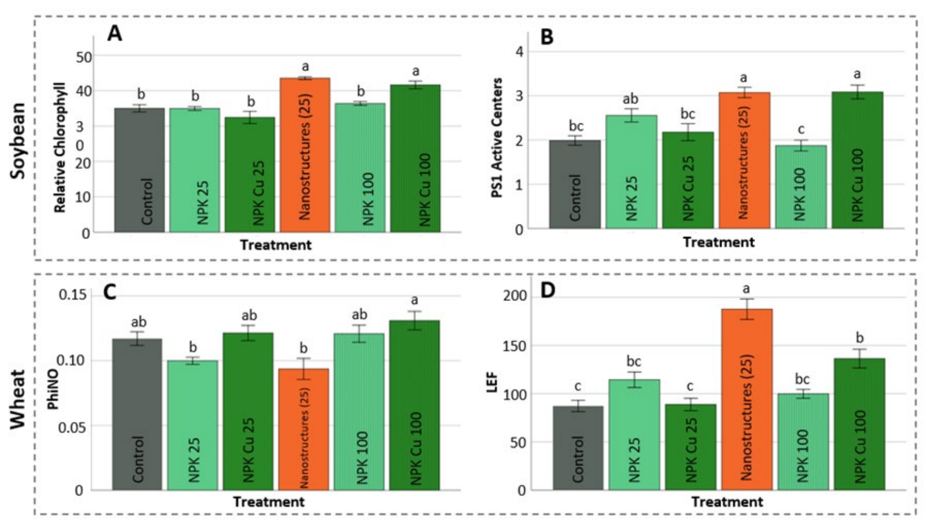
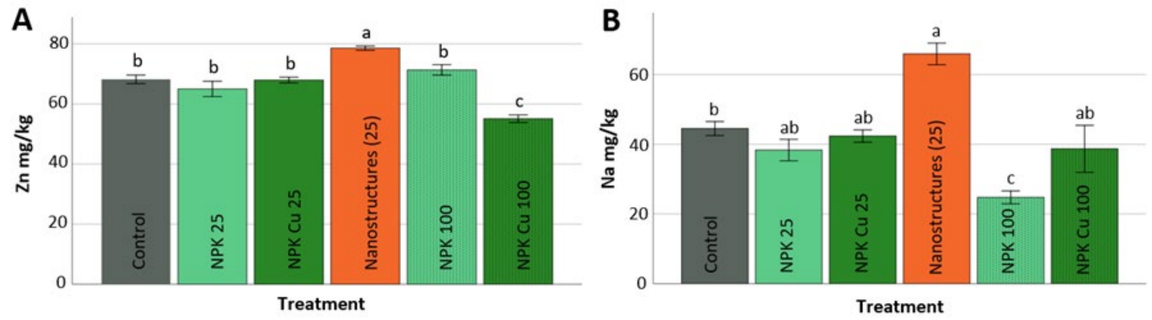


- This responsive core/shell nanostructure represents a novel and significant advance in the development of precision sustainable agriculture



Xu et al. 2022 *ACS Nano*.
16, 4, 6034–6048

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.

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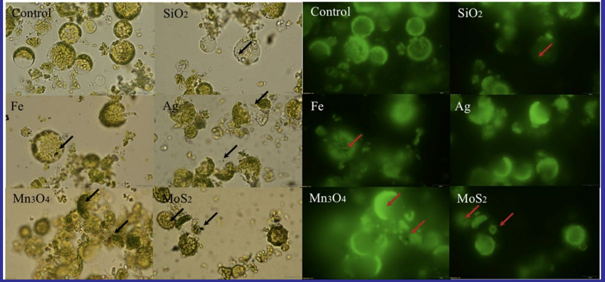
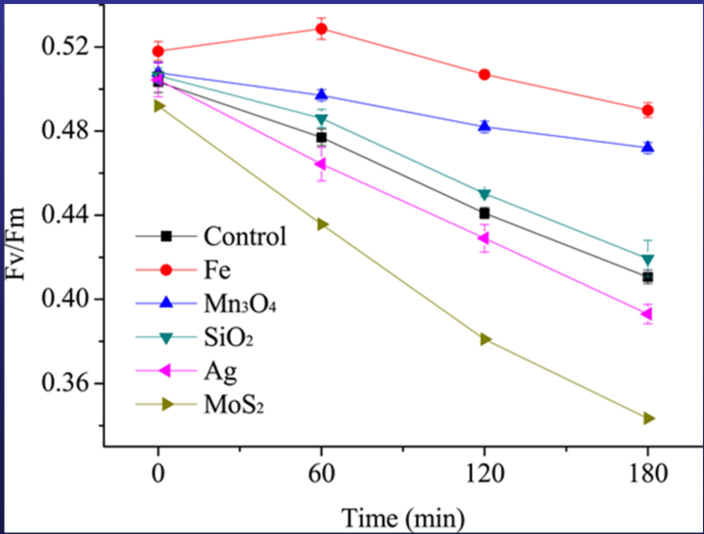
- Spinach leaf mesophyll protoplasts were cultivated with NPs (Fe, Mn_3O_4, SiO_2, Ag, and MoS_2) at 50 mg/L for 2 hours under illumination.
- Endpoints- maximum quantum yield, ATP production, photoelectrochemical measurements and GC-MS based metabolomics
- Whole plant exposure for comparison
- Photosynthetic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



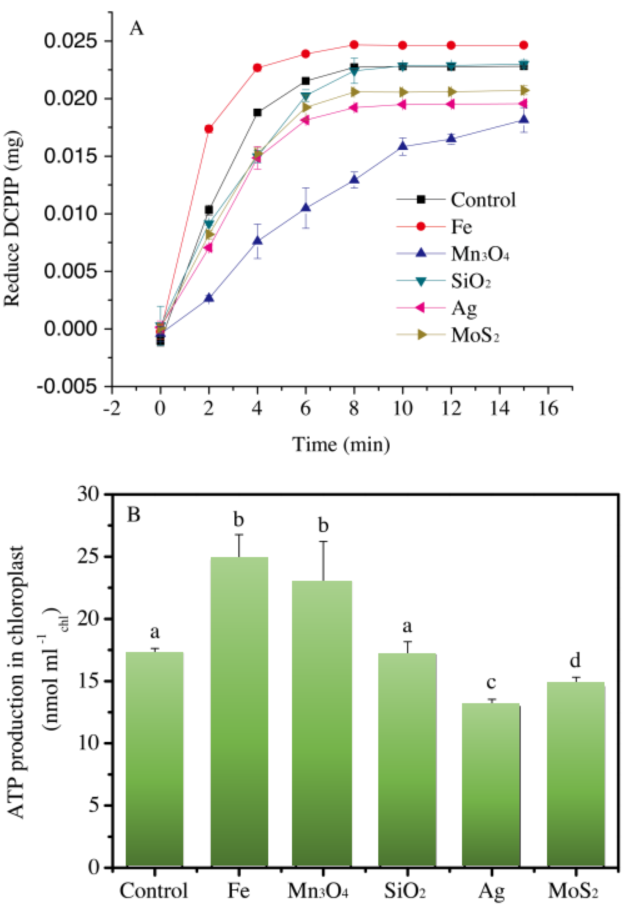


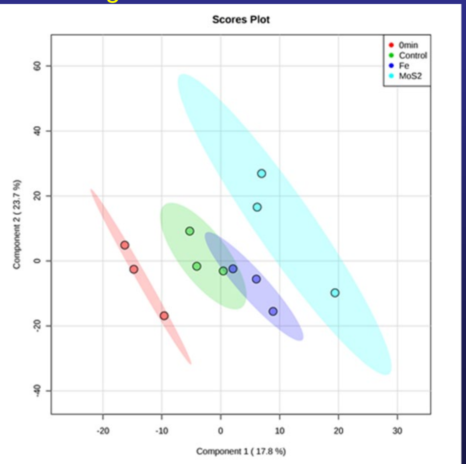
Wang et al. 2020 *J. Agric. Food Chem.* 68:3382-3389.

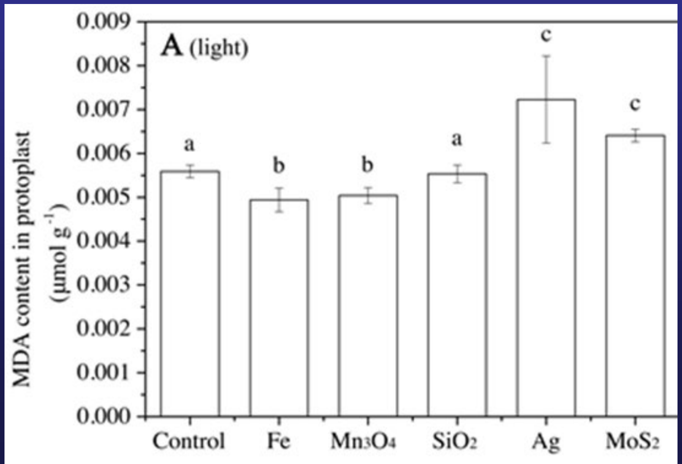
Mechanism of Enhanced Photosynthesis?

- 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.

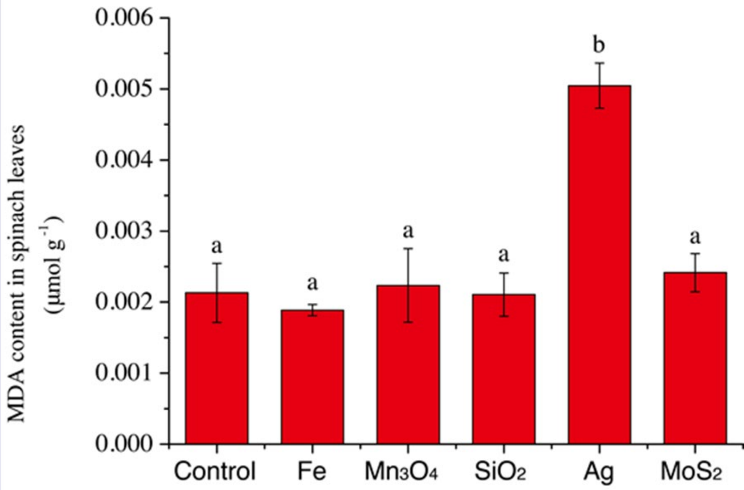


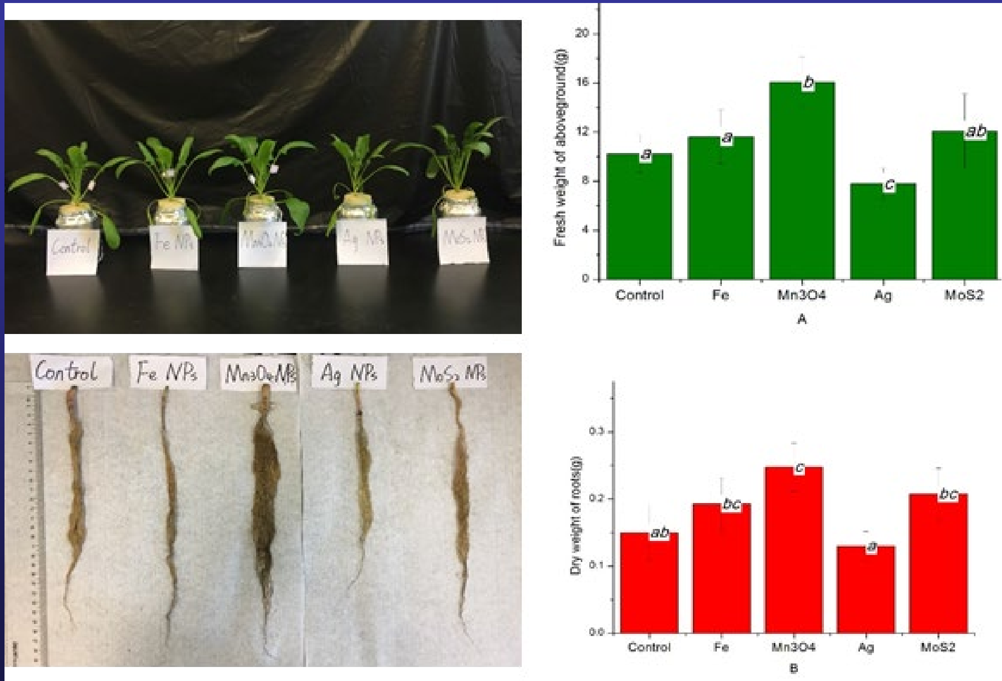




NPs Exposure to Whole Spinach

- MDA content was measured in leaves; Ag induced significant lipid peroxidation.
- Phenotypic images of spinach leaves and roots (**A** and **B**); fresh biomass of leaf and root (**C** and **D**).
- Mn_3O_4 significantly increased spinach leaf biomass by 57%.
- NP Ag significantly decreased plant shoot biomass by 24%
- The impact of different NPs on root biomass exhibited a similar pattern to the leaves. Mn_3O_4 NPs significantly increased root biomass by 65% and Ag decreased mass 13%.
- Mesophyll protoplasts are a good model

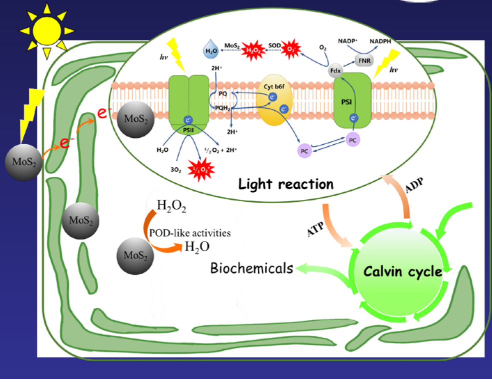


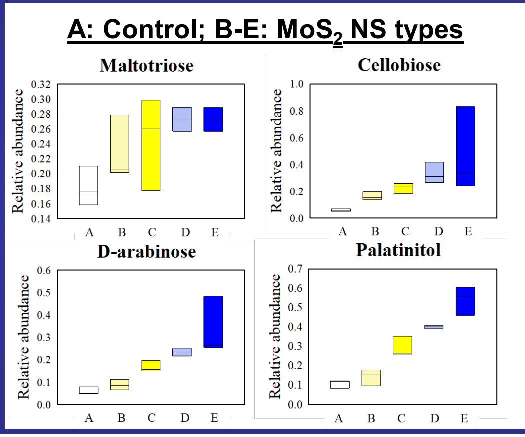


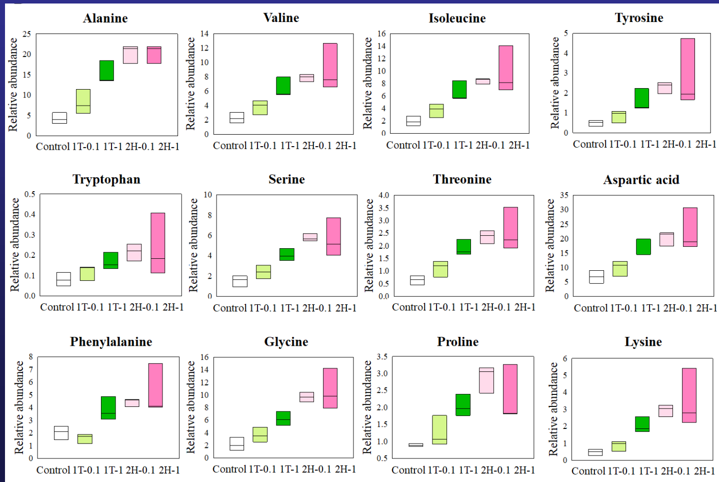
Wang et al. 2020 *J. Agric. Food Chem.* 68:3382-3389.

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.
- 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
- **New $750,000 USDA AFRI grant started May 1, 2023!**



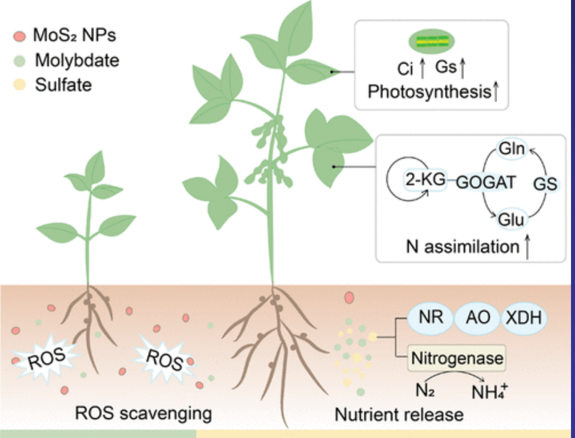


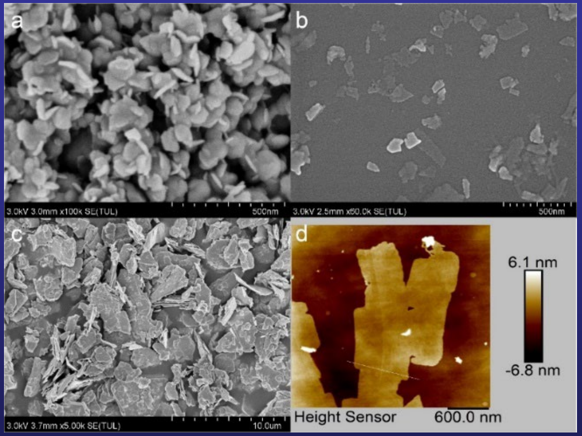


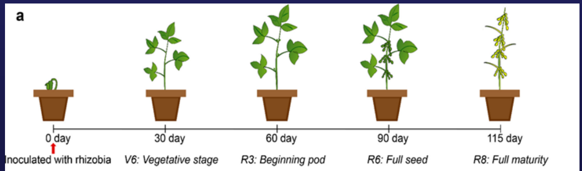
Chen et al. 2021 *ACS Nano* 15, 10, 16344–16356.

Nanoscale MoS_2 and Soybean

- **Li et al. 2023**. Molybdenum nanofertilizer boosts biological nitrogen fixation and yield of soybean through delaying nodule senescence and nutrition enhancement. *ACS Nano* 17, 15, 14761–14774.
- Soybean biological nitrogen fixation (BNF) is reduced by abiotic stresses.
- Enhancing BNF can alleviate global food insecurity and reduce the environmental impact of agriculture.
- This has proven challenging using current genetic modification or bacterial nodulation methods.
- Multifunctional MoS_2 NP and NS, MoS_2 Bulk, and Na_2MoO_4 were added to soil at 10, 100, 500 mg/kg; plants were harvested at 30, 60, 90 and 115 days
- Biomass, photosynthetic endpoints, tissue element content, nitrogen fixation enzymes, and expression of Mo-related genes were measured



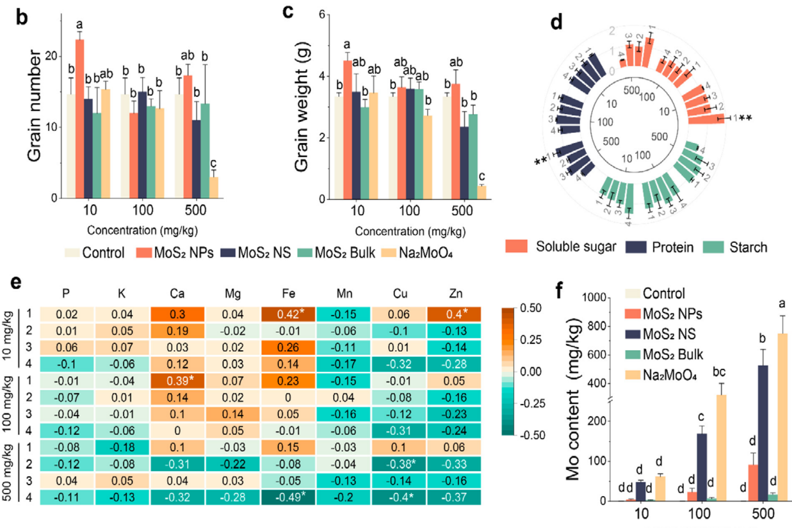




Li et al 2023 *ACS Nano* 17, 15, 14761-14774

Nanoscale MoS_2 and Soybean

- MoS_2 NPs (10 mg/kg) increased the grain number and weight by 46 and 30%; protein by 46% (500 mg/kg); soluble sugar by 91% (10 mg/kg).
- The remaining treatments had little effect
- N uptake/assimilation involves glutamine synthetase (GS), glutamate synthase (GOGAT), glutamate dehydrogenase (GDH).
- MoS_2 NPs (10 mg/kg) increased root GOGAT activity by 0.3 times; GDH by 0.45-fold (500 mg/kg).
- MoS_2 NPs (10 mg/kg) increased shoot GS and GOGAT activity by 2.2- and 1.5-fold; GOGAT activity by 2.08-fold (100 mg/kg),
- Enhanced GS-GOGAT cycle accelerated N assimilation and promoted photosynthesis through a cascade reaction, facilitating growth.



		P	K	Ca	Mg	Fe	Mn	Cu	Zn
10 mg/kg	1	0.02	0.04	0.3	0.04	0.42*	-0.15	0.06	0.4*
	2	0.01	0.05	0.19	-0.02	-0.01	-0.06	-0.1	-0.13
	3	0.06	0.07	0.03	0.02	0.26	-0.11	0.01	-0.14
	4	-0.1	-0.06	0.12	0.03	0.14	-0.17	-0.32	-0.28
100 mg/kg	1	-0.01	-0.04	0.39*	0.07	0.23	-0.15	-0.01	0.05
	2	-0.07	0.01	0.14	0.02	0	0.04	-0.08	-0.16
	3	-0.04	-0.01	0.1	0.14	0.05	-0.16	-0.12	-0.23
	4	-0.12	-0.06	0	0.05	-0.01	-0.06	-0.31	-0.24
500 mg/kg	1	-0.08	-0.18	0.1	-0.03	0.15	-0.03	0.1	0.06
	2	-0.12	-0.08	-0.31	-0.22	-0.08	-0.04	-0.38*	-0.33
	3	0.04	0.05	0.04	0.03	-0.05	-0.13	-0.14	-0.16
	4	-0.11	-0.13	-0.32	-0.28	-0.49*	-0.2	-0.4*	-0.37

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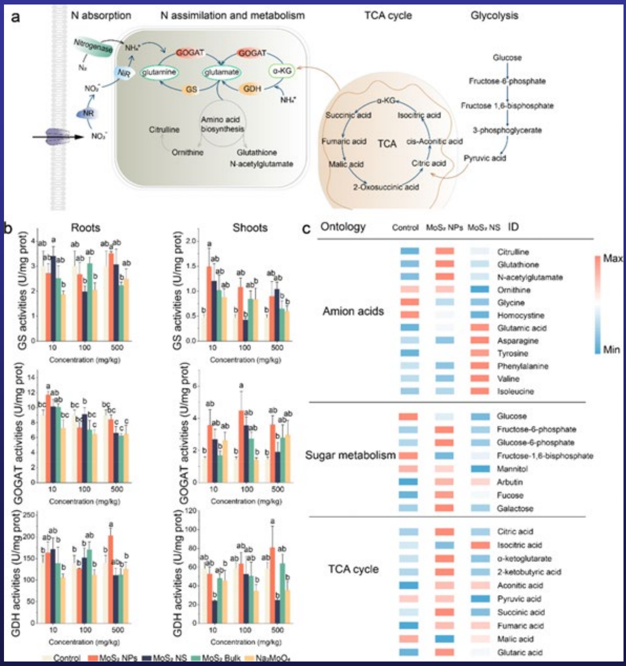
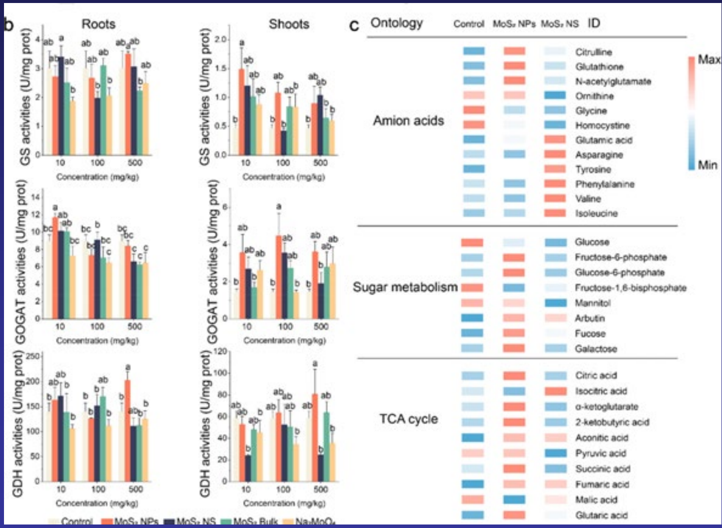
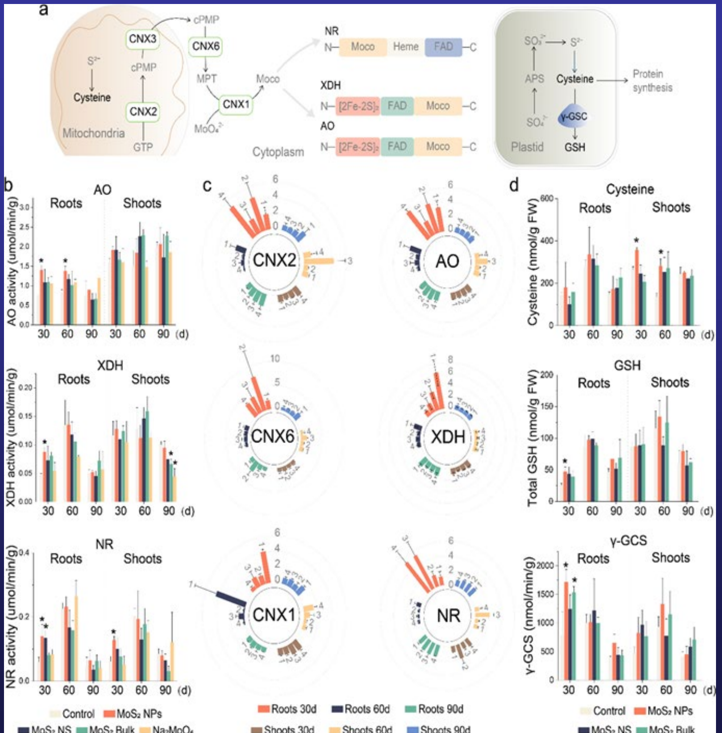


Li et al 2023 *ACS Nano* 17, 15, 14761-14774

Nanoscale MoS_2 and Soybean

- The leaf metabolome (500 mg/kg MoS_2 NPs/NS) was enriched in amino acid (N) and carbohydrate pathways (C)
- MoS_2 NPs increased sucrose synthesis and TCA metabolites
- MoS_2 NS enriched amino acids for stress response and increased sucrose breakdown
- Mo is the metal center for nitrogenase, nitrate reductase (NR), aldehyde oxidase (AO) and xanthine dehydrogenase (XDH); all are involved in N assimilation and other key pathways
- MoS_2 NPs increased tissue AO, XDH, NR by 64-138%; MoS_2 NS increased the NR 129%;
- MoS_2 bulk and Na_2MoO_4 had no effect
- MoS_2 NPs increased CNX1 expression (310%), which mediates insertion of Mo into several proteins to achieve biological activity

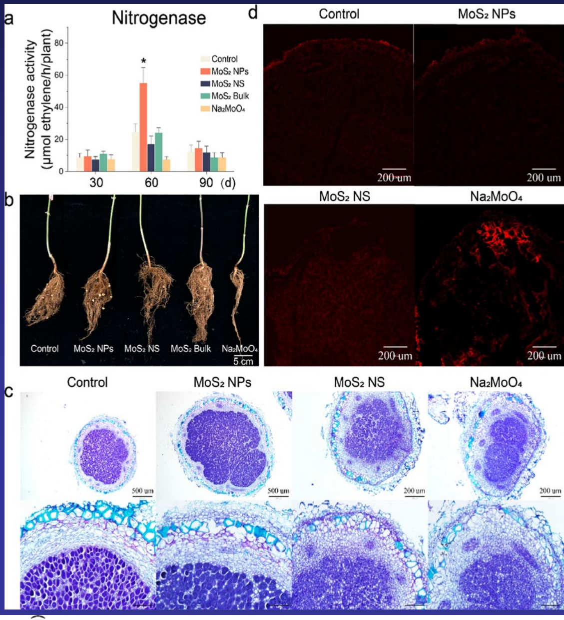


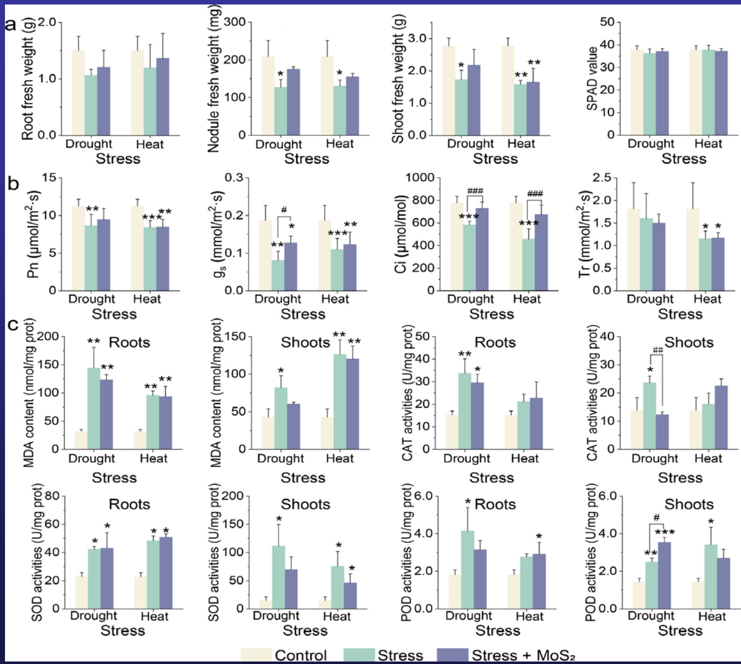


Li et al 2023 *ACS Nano* 17, 15, 14761-14774

Multifunctionality of MoS_2 NPs

- MoS_2 NPs enhanced nitrogenase activity by 122% at 60 days and increased nodule growth.
- At this stage, nodule senescence had started, and N_2 fixation was declining but nodules treated with MoS_2 NPs had higher symbiont density and reduced nodule ROS
- MoS_2 NPs demonstrated a clear potential to enhance soybean tolerance to abiotic stress (heat, drought) by capturing the ROS and providing essential Mo and S nutrients.
- The level of oxidative damage was also reduced, as demonstrated by the reduced MDA levels and antioxidative responses
- Soybean biomass, height, and photosynthetic output were significantly improved by MoS_2 NPs.

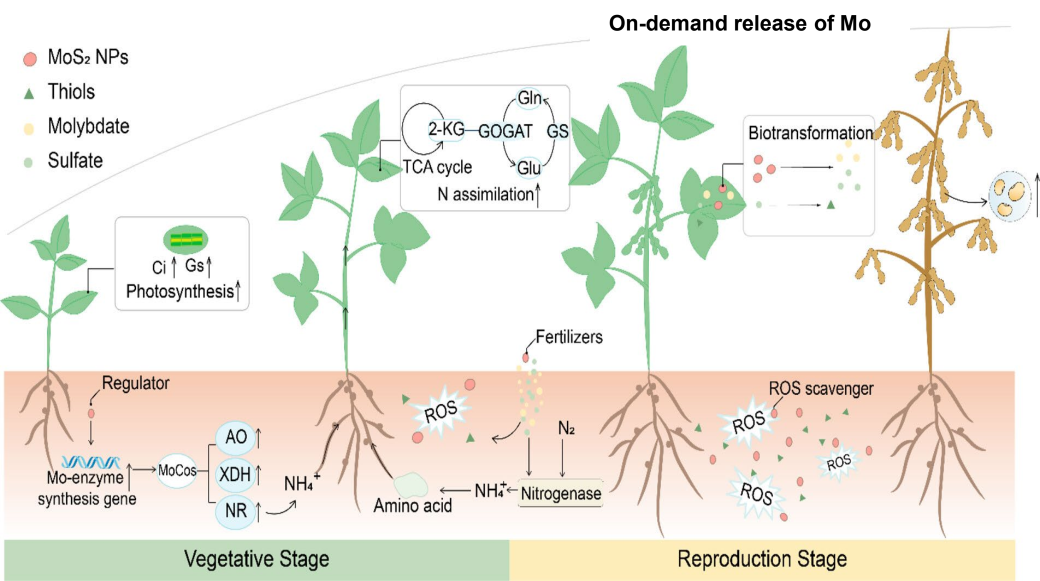




Li et al 2023 *ACS Nano* 17, 15, 14761-14774

Multifunctionality of MoS_2 NPs

- MoS_2 NPs release Mo in a responsive fashion to support BNF and capture ROS at different growth stages to promote soybean C and N assimilation.
- In the early stages (vegetative), seedlings are vulnerable to stress and MoS_2 NPs remain as intact particles to function as enzymes to capture the ROS while releasing a small portion of Mo to support nodule formation and N_2-fixation.
- At later stages (reproductive), soybean requires large amounts of nitrogen, and nodule function starts to decline due to senescence. However, MoS_2 NPs continuously dissolve and release more Mo to support N_2-fixation.
- The MoS_2 NPs act as nano-enzymes and maintain enzyme mimetic function, protecting the nodule cells and maintaining N_2-fixation ability by capturing ROS and delaying nodule senescence.



Li et al 2023 *ACS Nano* 17, 15, 14761-14774

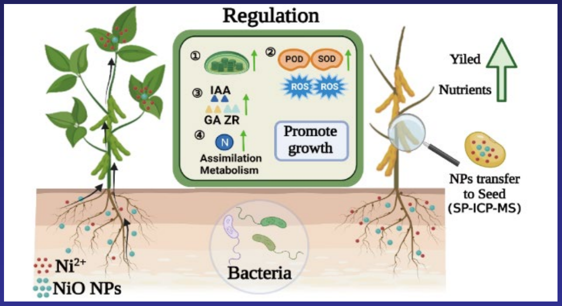
Other Recent Nutrition Work

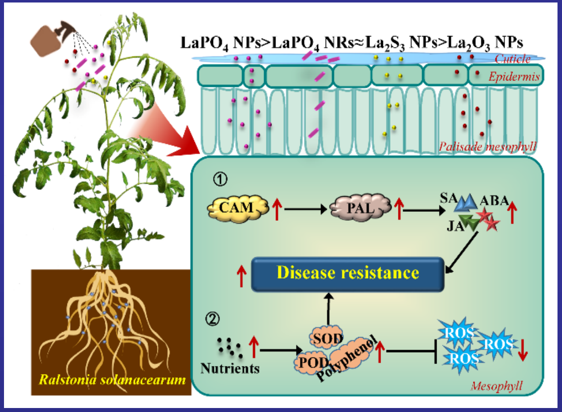
Other Nutrients

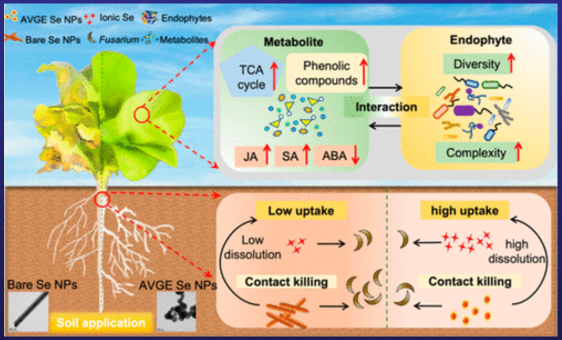
- Zhou et al. 2023. Nickel oxide nanoparticles improve soybean yield and enhance nitrogen assimilation. *Environ. Sci. Technol*. 57, 19, 7547–7558.
- Liao et al. 2023. Potential of novel magnesium nanomaterial to manage bacterial spot disease of tomato in the greenhouse and field conditions. *Plants* 12, 1832.
- Wang et al. 2023. Lanthanum-based nanomaterials suppress bacterial wilt in tomato: Importance of particle morphology and dissolution profile. *Environ. Sci.: Nano* 10, 747-760.

Green/Biosynthesis

- Shang et al. 2023. Aloe vera extract gel-derived selenium nanoparticles enhance disease resistance in lettuce by modulating the metabolite profile and bacterial endophytes composition *ACS Nano* 17, 14, 13672–1368472.
- Karmous et al. 2023. Biologically synthesized zinc and copper oxide nanoparticles using Cannabis sativa L. enhance soybean (Glycine max) defense against *Fusarium virguliforme*. *Pest. Biochem. Physiol*. 194, 105486
- Noman et al. 2022. Bio-functionalized manganese nanoparticles suppress *Fusarium wilt* in watermelon (*Citrullus lanatus* L.) by infection disruption, host defense response potentiation and soil microbial community modulation. Small 2205687.
- Prakash et al. 2022. Hybridization of chitosan and biosynthesized silver nanoparticles to enhance antimicrobial activity against phytopathogens in tomato (*Solanum lycopersicum*). *ACS Agric. Sci. Technol*. 2:719-733.
- Ahmed et al. 2022. Bioengineered chitosan-iron nanocomposite controls bacterial leaf blight disease by modulating plant defense response and nutritional status of rice (Oryza sativa L.). *Nano Today* 45, 101547



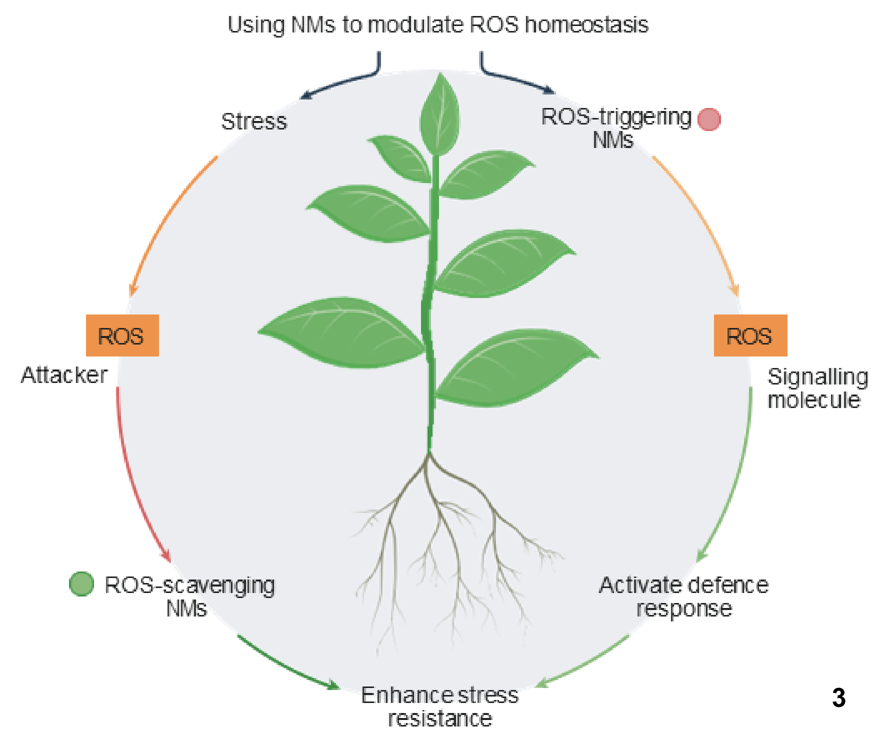




Nanomaterial Exposure and ROS

- Reactive oxygen species (ROS) are generated during basic cell metabolism but also as a function of xenobiotic exposure
- ROS can damage biomolecules (DNA, proteins) and organelles
- Although cells have systems to quench ROS, they are also important intracellular signaling molecules that can stimulate plant defense pathways

- Can we use ROS-scavenging and ROS-triggering nanomaterials to modulate ROS homeostasis for stress tolerance enhancement?
- The left pathway is “recovery or curative” **(lots of data here)**
- The right pathway is a “preventive” strategy **(?)**



Zhao et al 2022 *Nature Food* 3:829-836

ROS-Triggering/Stress Training?

- Chen et al. 2023. *ACS Nano* 17, 11, 10760–10773
- Three regimens of AgNPs-based “stress training”: seed priming (SP), leaf priming (LP), and combined seed- and leaf- priming (SLP) (40 mg/L)
- Trained rice seedlings were subsequently exposed to either rice blast fungus (*M. oryzae*.) or cold stress (10ºC).
- Metabolomic and transcriptomic profiling were used to understand the mechanisms and kinetics of plant response.

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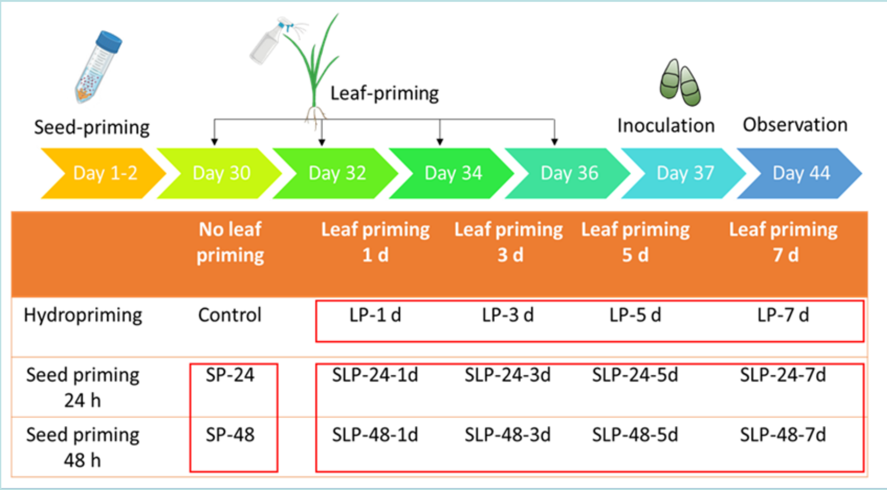
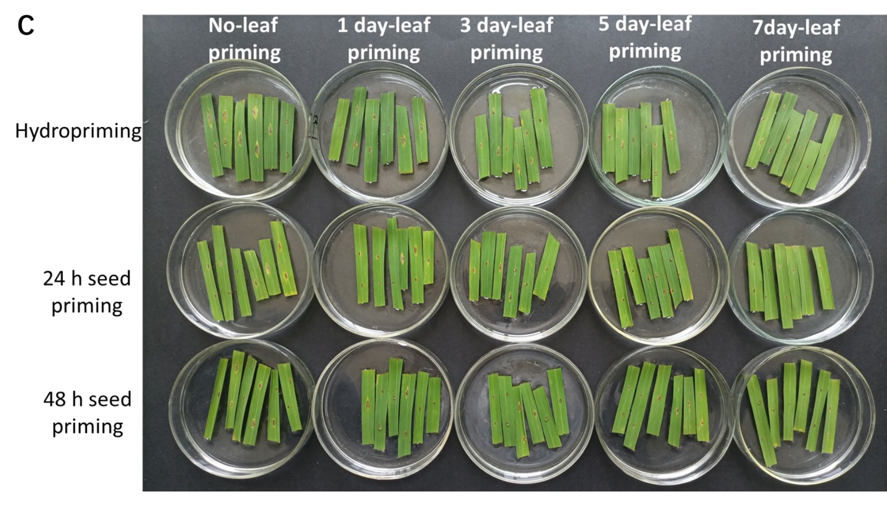
Engineering Climate-Resilient Rice Using a Nanobiostimulant-Based “Stress Training” Strategy

Si Chen, Zhengyan Pan, Weichen Zhao, Yanlian Zhou, Yukui Rui, Cong Jiang, Yi Wang, Jason C. White, and Lijuan Zhao*



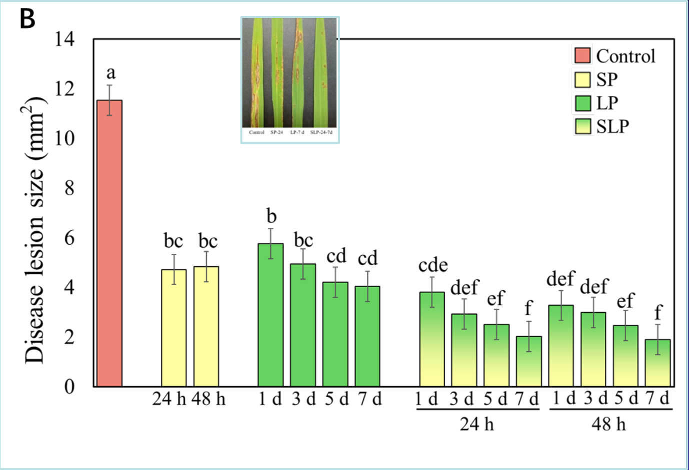
	No leaf priming	Leaf priming 1 d	Leaf priming 3 d	Leaf priming 5 d	Leaf priming 7 d
Hydropriming	Control	LP-1 d	LP-3 d	LP-5 d	LP-7 d
Seed priming 24 h	SP-24	SLP-24-1d	SLP-24-3d	SLP-24-5d	SLP-24-7d
Seed priming 48 h	SP-48	SLP-48-1d	SLP-48-3d	SLP-48-5d	SLP-48-7d

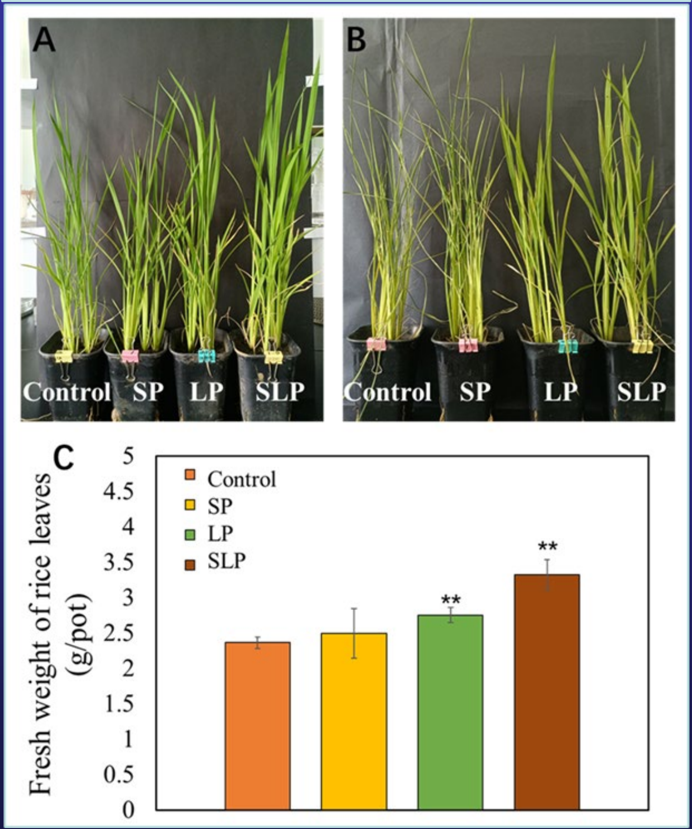


Chen et al 2023 *ACS Nano* 17, 11, 10760–10773

ROS-Triggering/Stress Training

- All “stress training” regimes, particularly SLP, significantly enhanced fungal pathogen resistance (lesion size reduced by 82% relative to un-trained control).
- Tolerance to cold stress was also significantly enhanced (leaf biomass increased by 35%).
- Metabolomic and transcriptomic profiling shows that “stress training” induced considerable metabolic and transcriptional reprogramming in rice leaves.





Chen et al 2023 *ACS Nano* 17, 11, 10760–10773

ROS-Triggering/Stress Training

- AgNPs-boosted ROS activated stress signaling pathways by oxidative post-translational modifications of stress related kinases, hormones, and transcriptional factors (TFs).
- These signaling pathways subsequently modulated defense gene expression, including specialized metabolites (SMs) biosynthesis, cell membrane lipid metabolism, and pathogen-plant interaction.
- AgNPs-triggered metabolic and transcriptional reprogramming enable a more rapid and intense response to future stresses.

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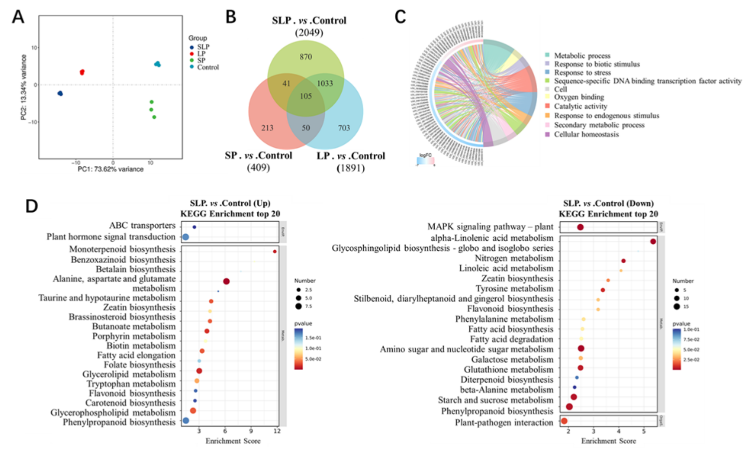
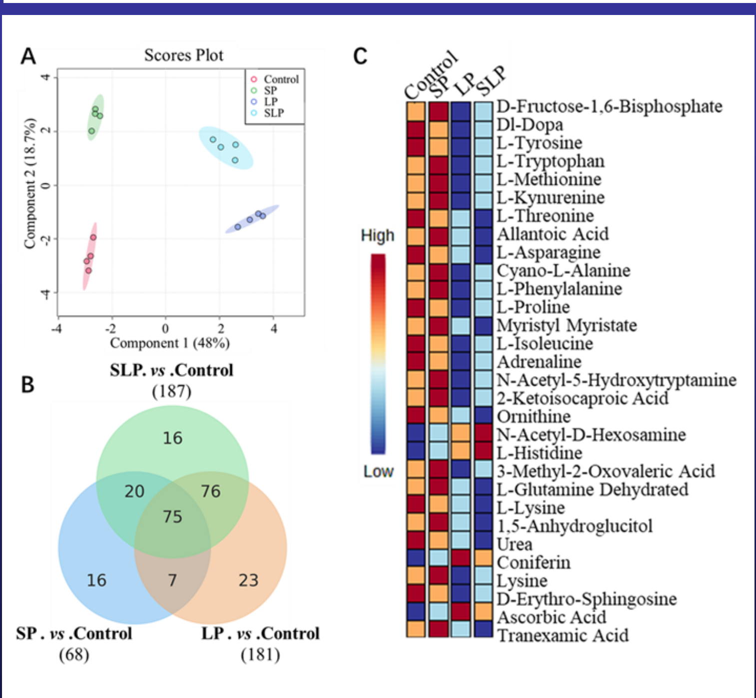
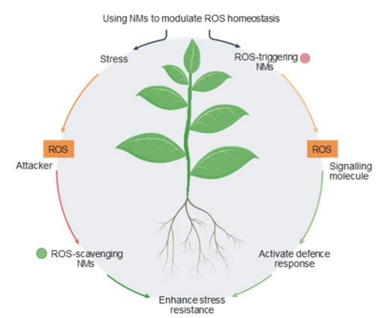


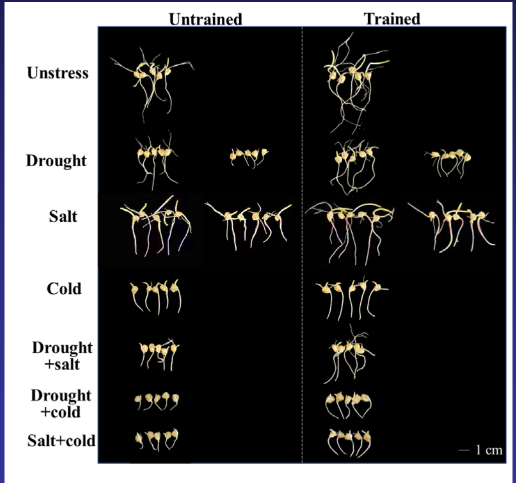


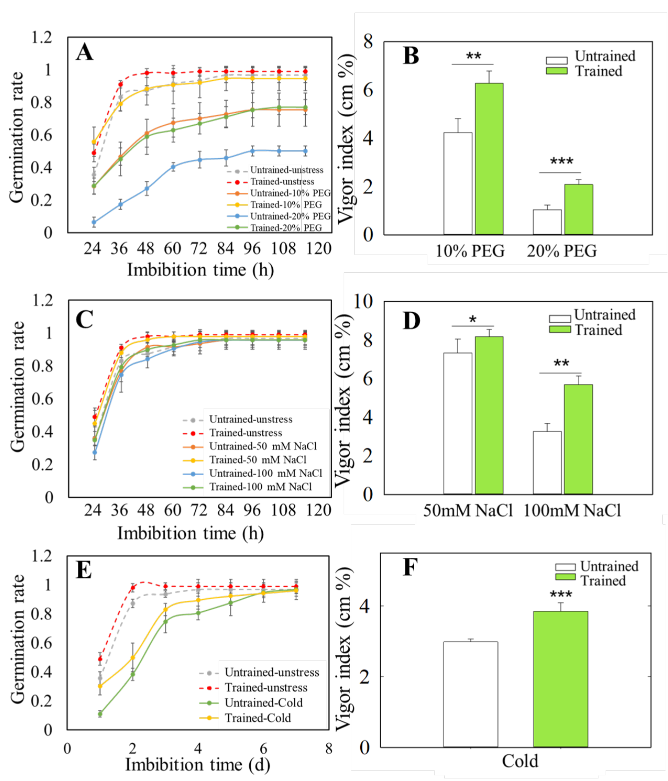


Chen et al 2023 *ACS Nano* 17, 11, 10760–10773

ROS-Triggering/Stress Training

- Chen et al. 2023. Seed-priming with ROS-generating nanoparticles enhanced maize tolerance to multiple abiotic stresses. *Environ. Sci. Technol*. In press
- Maize seeds treated or primed with 40 mg/L nanoscale Ag, Fe_2O_3 or Fe_3O_4 were subjected to single (drought, salinity, cold) or multiple (drought + cold, drought + salt, salt + cold) stresses.
- Seeds exhibited accelerated germination speed; increased germination rate, seedling vigor, and seedling growth under drought (10%-20% PEG), salinity (50-100 mM NaCl), and cold (15 ºC) stress
- Demonstrates enhanced resilience to diverse stress.

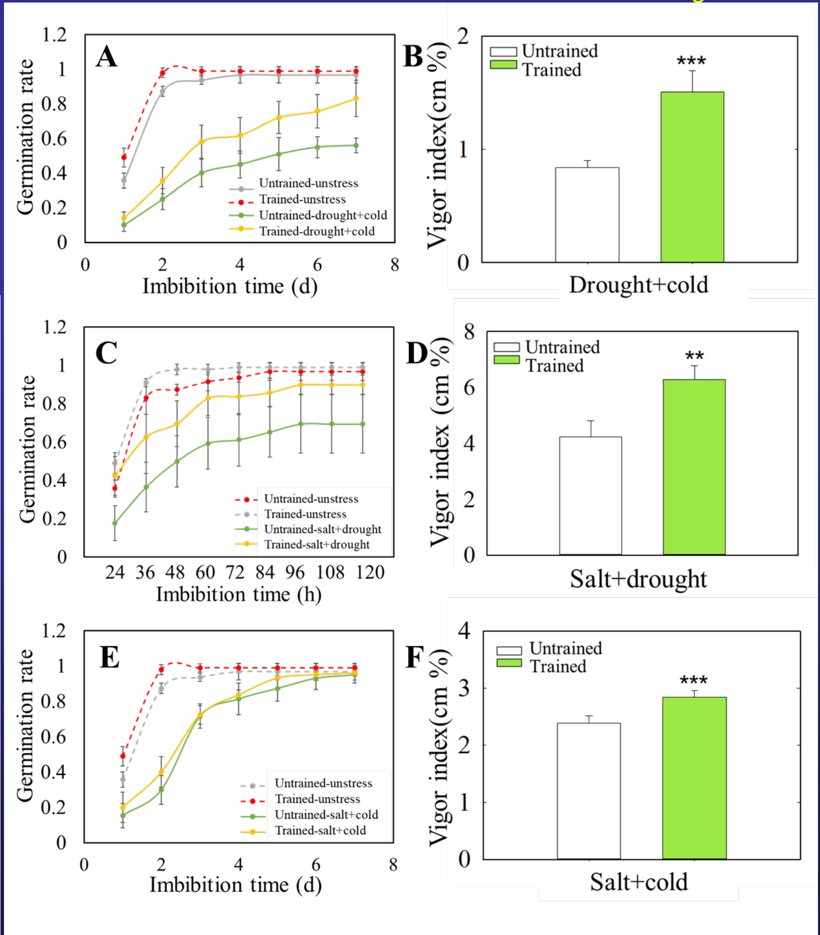


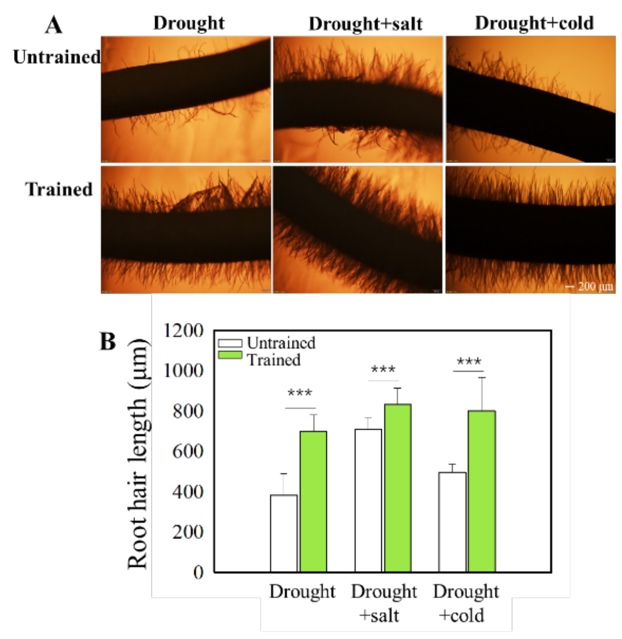


Chen et al 2023 *Environ. Sci. Technol.* In press

ROS-Triggering/Stress Training

- Importantly, maize resistance to simultaneous multiple stresses was significantly enhanced.
- Under drought conditions, seed training significantly boosted root hair density and length (%), which enabled greater tolerance to water deficiency in combination with salinity or cold stress.





Chen et al 2023 *Environ. Sci. Technol.* In press

ROS-Triggering/Stress Training

- ➢RNA-seq analysis reveals that Ag/Fe NPs seed training induced transcriptomic shift in maize seeds.
- ➢Plant hormone signal transduction and MAPK signaling pathways were activated and maintained through seedling growth.

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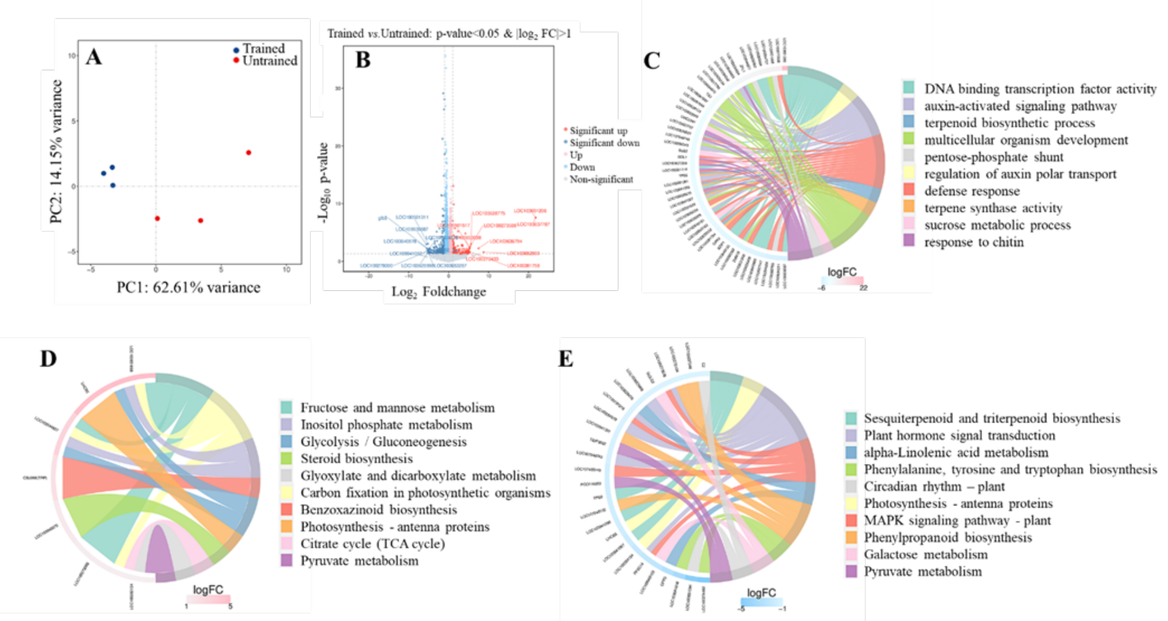
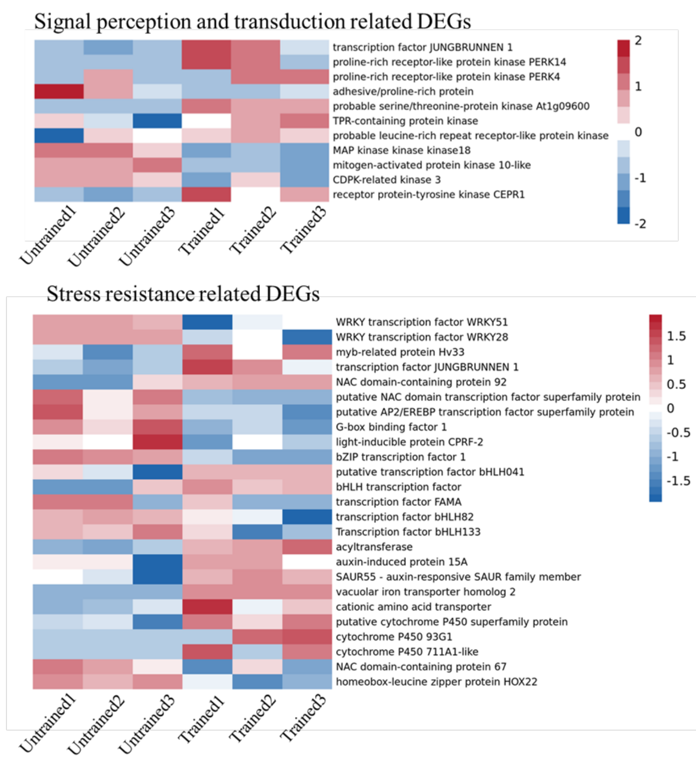




Nanopesticide Efficacy- US EPA 2022

- Nano-enabled responsive nanopesticides for sustainable agriculture and global food security
  Dengjun Wang, Navid B. Saleh, Andrew Byro, Richard Zepp, Endalkachew Sahle-Demessie, Todd P. Luxton, Kay T. Ho, Robert M. Burgess, Markus Flury, Jason C. White, and Chunming Su

nature nanotechnology ANALYSIS
https://doi.org/10.1038/s41565-022-01082-8
Check for updates

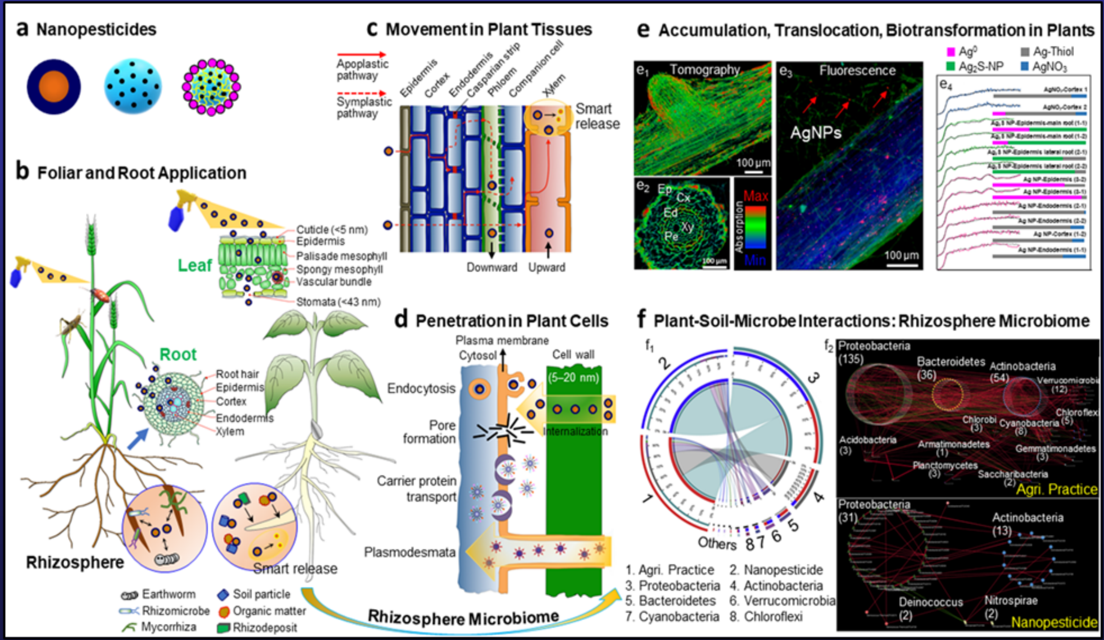
Nano-enabled pesticides for sustainable agriculture and global food security

Dengjun Wang[1,10], Navid B. Saleh[2], Andrew Byro[3], Richard Zepp[4], Endalkachew Sahle-Demessie[5], Todd P. Luxton[5], Kay T. Ho[6], Robert M. Burgess[6], Markus Flury[7], Jason C. White[8] and Chunming Su[9]

- 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).

Deng et al. 2022 *Nature Nano*. 17, 347–360

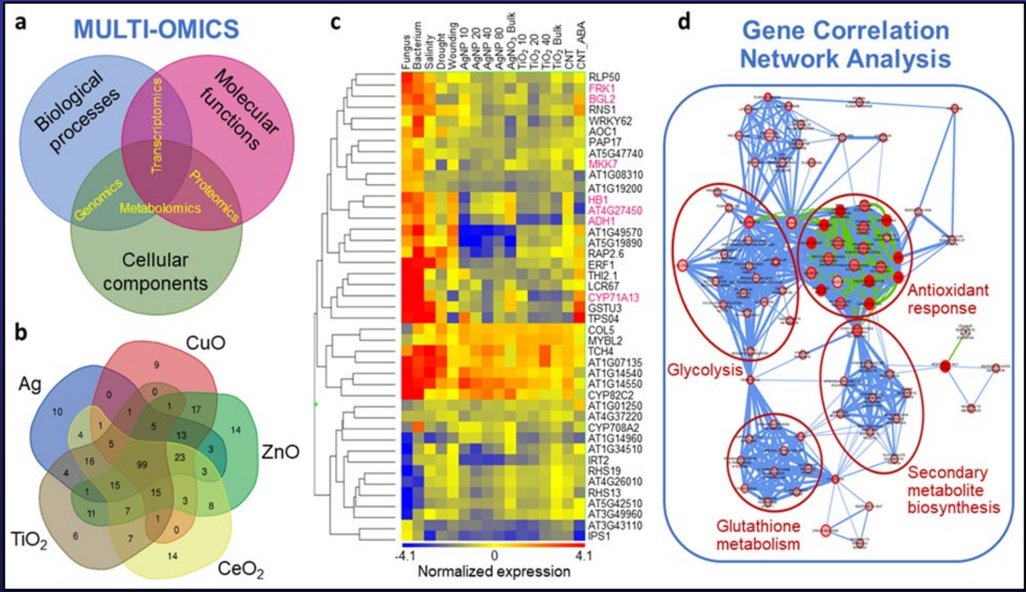
- The analysis shows that compared to conventional pesticides, their overall efficacy against target organisms is **31.5%** higher, including an 1**8.9%** increased efficacy in field trials.



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 impact

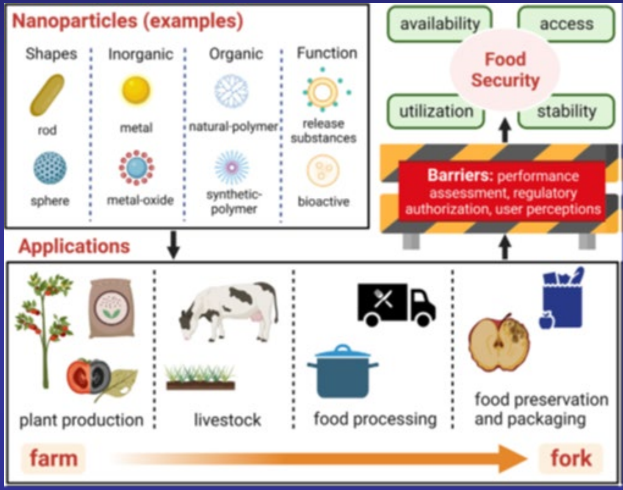
Deng et al. 2022 *Nature Nano*. 17, 347–360



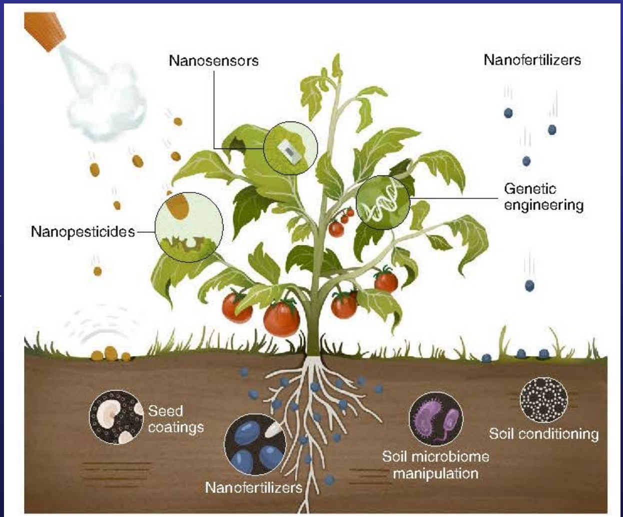
Conclusions

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

Kah et al. 2023 *One Earth* 6, 7:772-775.



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



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- **Marmiroli et al.**- Univ. of Parma, Italy; **Liu et al.**- CAS
- **Cao et al.**- CAAS; **Wang et al.**- Jiangnan Univ.
- **Paret et al.-** Univ. Fl.; **Lin et al.-** Zhejiang Univ.
- **Rui et al.**- China Agricultural Univ.; **Chen et al.-** RISF CAF
- **Tang et al.**- Guangxi Univ; **Wang et al.-** Huazhong Univ. of Sci. and Technol.;
- **At CAES**- Elmer, Dimkpa, Wang, Deng, Vaidya, De la Torre-Roche, Servin, Ma, Mukherjee, Zuverza-Mena, Shen, Tamez, Adisa, Borgatta, Majumdar, Wang, Pagano, Hawthorne, Musante, Thiel
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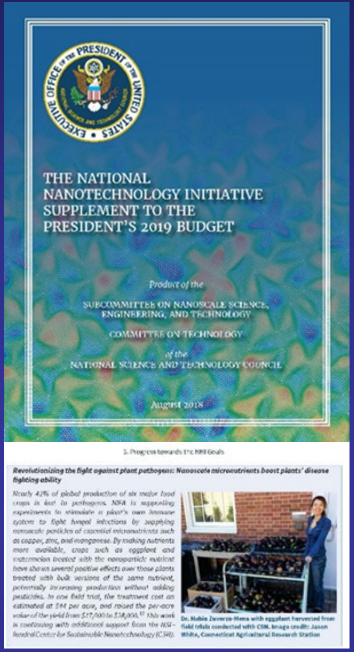

THE NATIONAL
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August 2018

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

www.ct.gov/caes