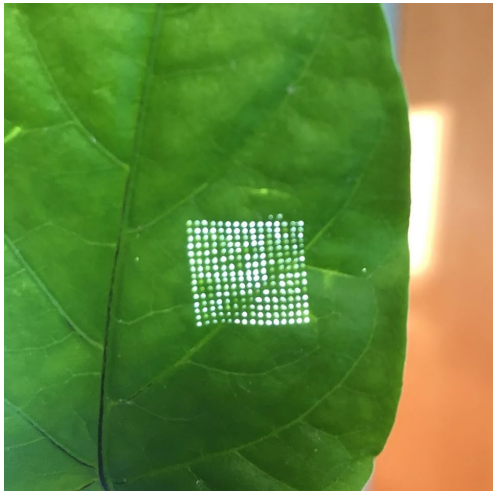
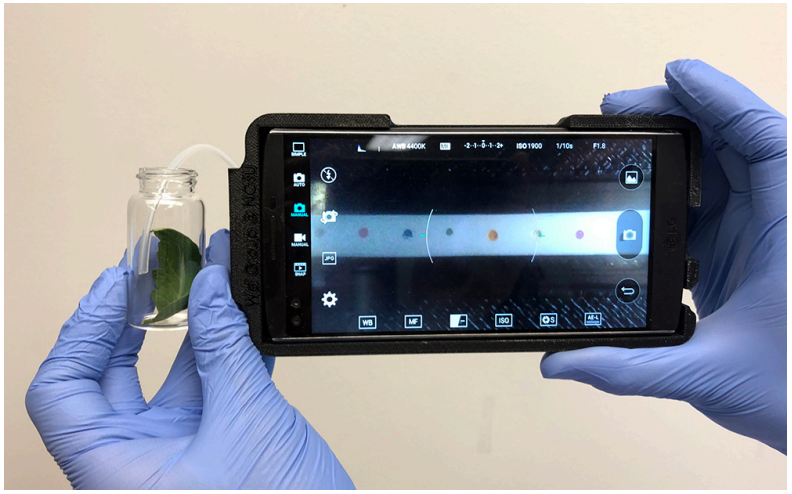
AgBio Sensors: Opportunities and Progress





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Collaborators: Jean Ristaino and the Cluster, Zhen Gu (UCLA)

Importance of Plant Disease Surveillance

POLICY FORUM | FOOD SECURITY

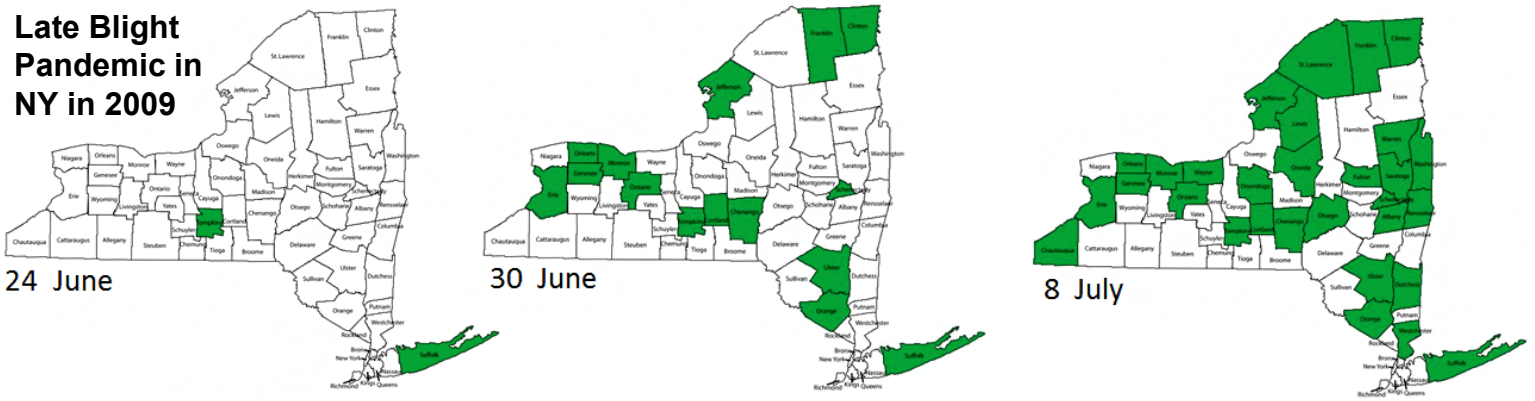
A global surveillance system for crop diseases

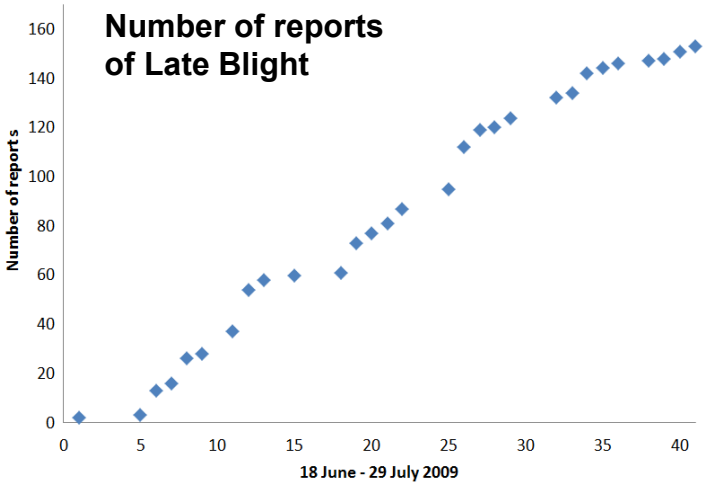
M. Carvajal-Yepes[1], K. Cardwell[2], A. Nelson[3], K. A. Garrett[4], B. Giovani[5], D. G. O. Saunders[6], S. Kamoun[7], J. P. L...
+ See all authors and affiliations

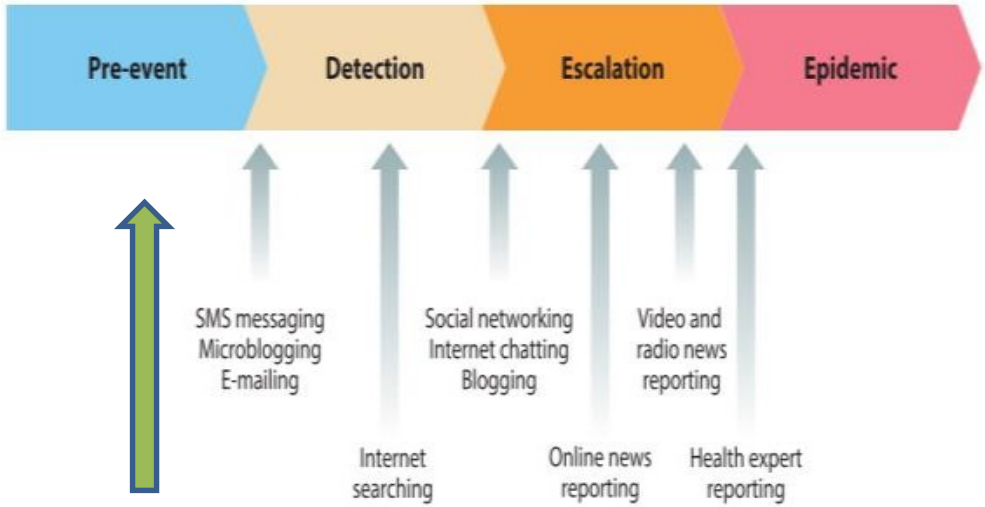
Science 28 Jun 2019:
Vol. 364, Issue 6447, pp. 1237-1239
DOI: 10.1126/science.aaw1572

- "To satisfy a growing demand for food, global agricultural production must increase by 70% by 2050. However, pests and crop diseases put global food supplies at risk."
- "The benefits of faster, more accurate detection and diagnostic technologies have not been evenly applied to LICs (low-income countries), where emerging diseases can be particularly devastating."
- The United Nations General Assembly has declared 2020 as the International Year of Plant Health (IYPH)

The Need for In-Field Sensor Technology







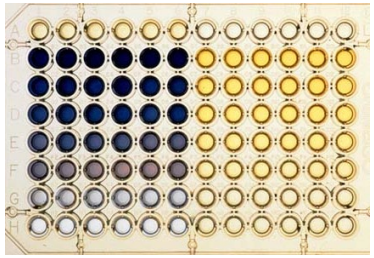
Introduce sensors here

APS Features 2012 doi:10.1094/APSFeature-2012-08
Plant Disease 2013, 97, 296-306

The Existing Toolbox

Laboratory Methods

- Nucleic acid amplification (NAA)
- Enzyme-linked immunosorbent assay (ELISA)



Field Methods

ImmunoStrip, Agdia

RIDA®SMART APP Mycotoxin

Chlorophyll meter

Spectroscopic imaging

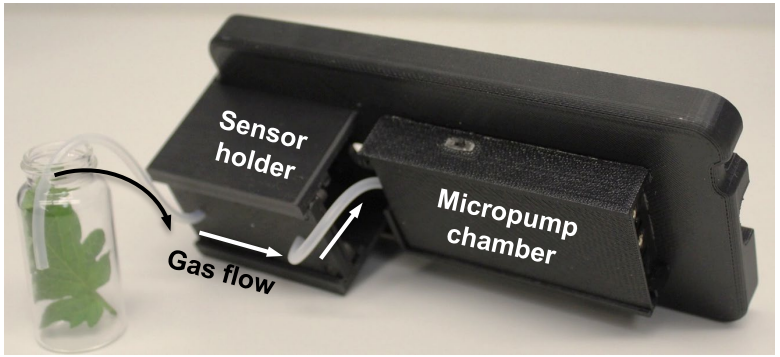
Electronic nose (e-nose)

New Sensors for AgBio and Plants

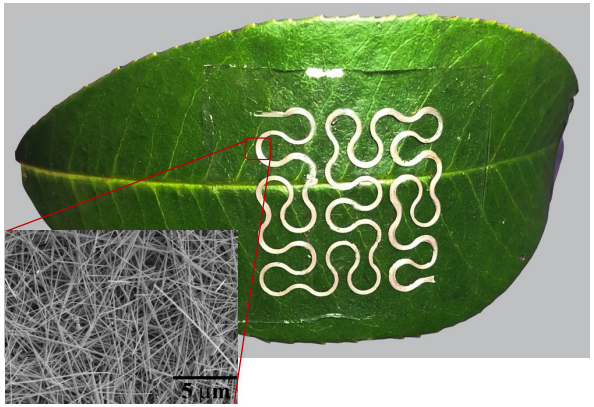
Microneedle-based plant DNA extraction

Collaborators: Zhen Gu (BE, UCLA), Jean Ristaino (EPP, NCSU)

Plant VOC sensor



Plant wearables

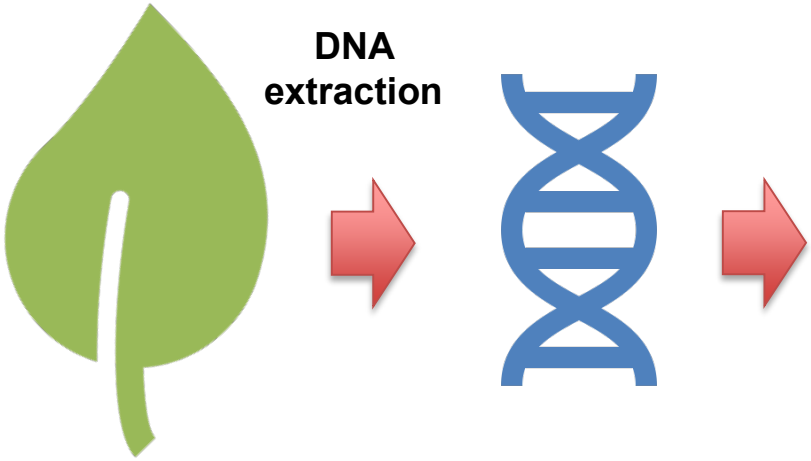


Collaborator: Yong Zhu (MAE, NCSU)

Handheld Molecular Diagnostic System

An integrated diagnostic system for:

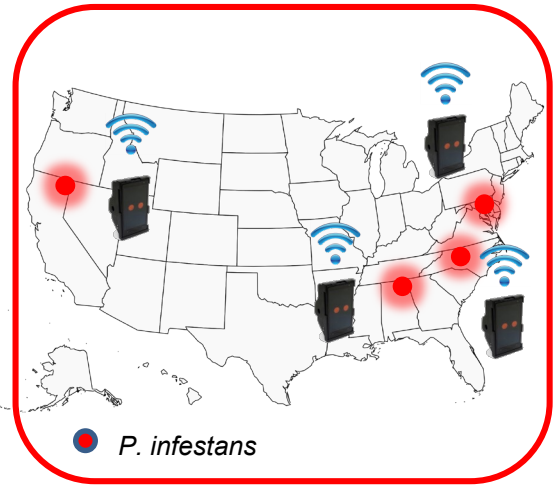
- Sample preparation
- Amplification
- Quantification
- Geospatial monitoring



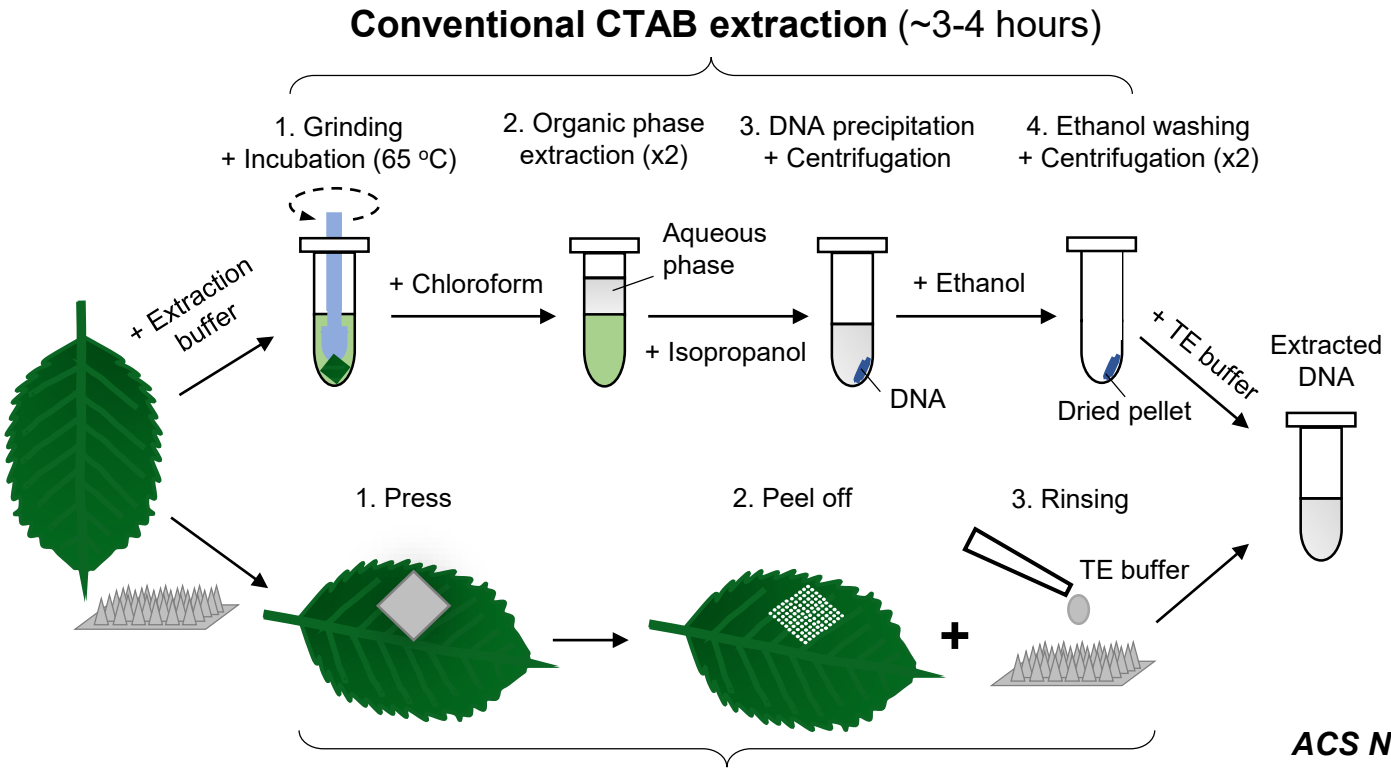
Amplification cassette

Smartphone readout

Geospatial Mapping



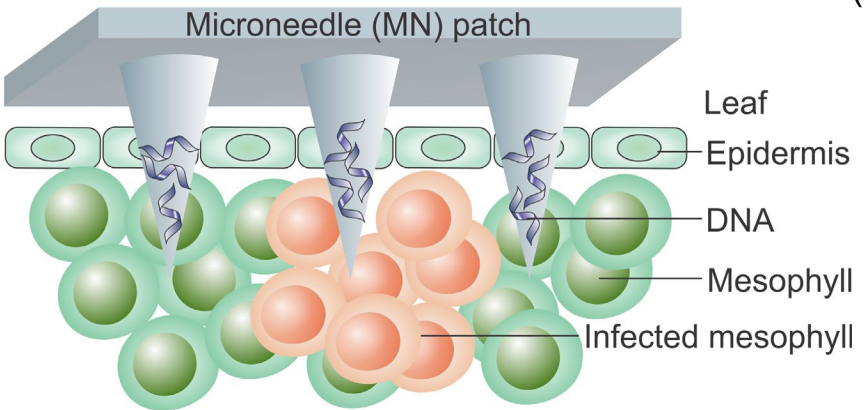
Microneedle Patch for Rapid DNA Extraction

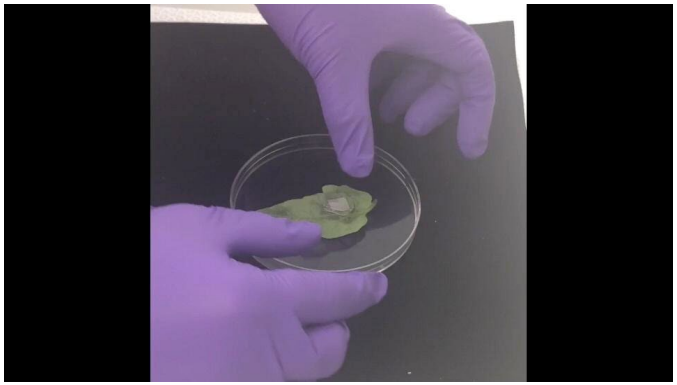


Rajesh

Collaborators:
Jean Ristaino (EPP)
Zhen Gu (BE, UCLA)

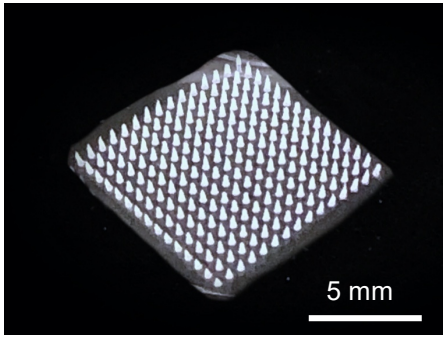
ACS Nano, 2019, 13, 6540-6549

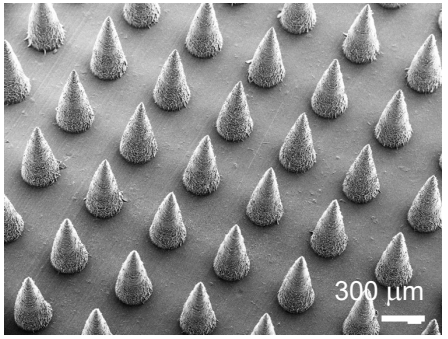




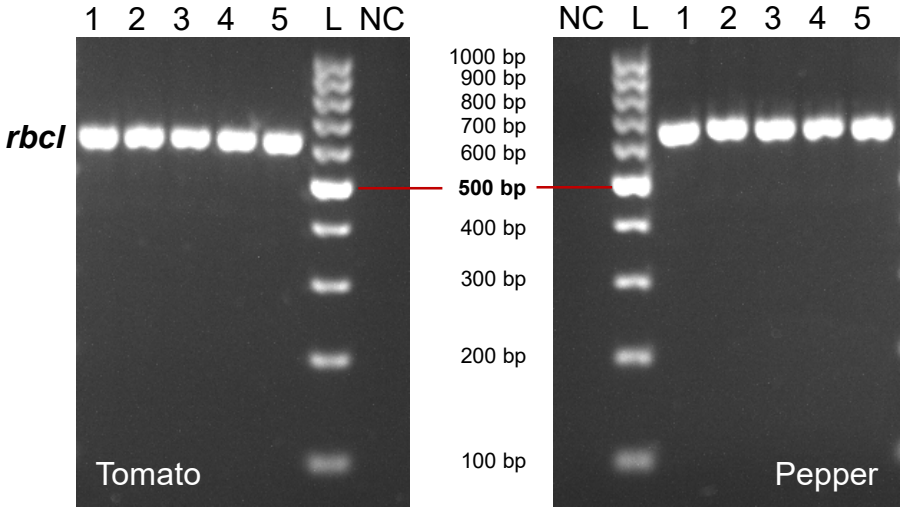
Extraction of Assay-Ready DNA without Purification

- Polyvinyl alcohol (PVA) microneedle patch

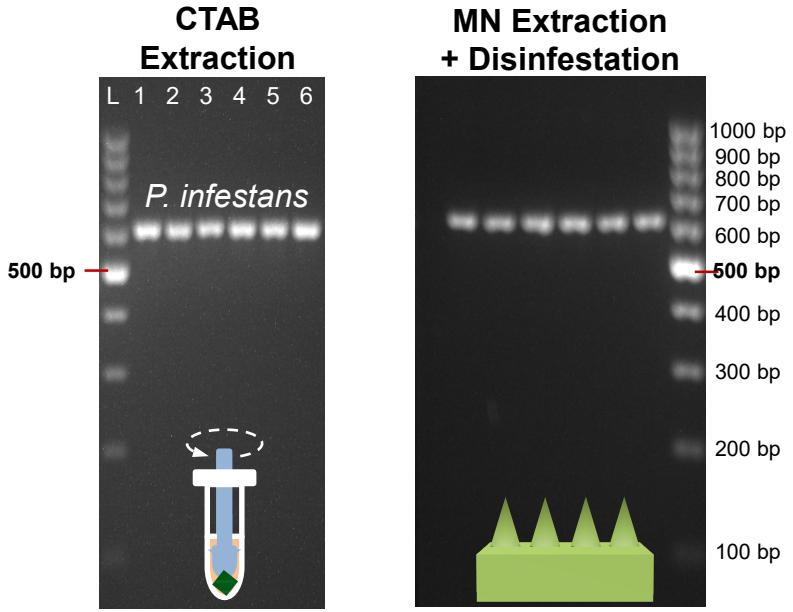




- Amplification of rbcL gene

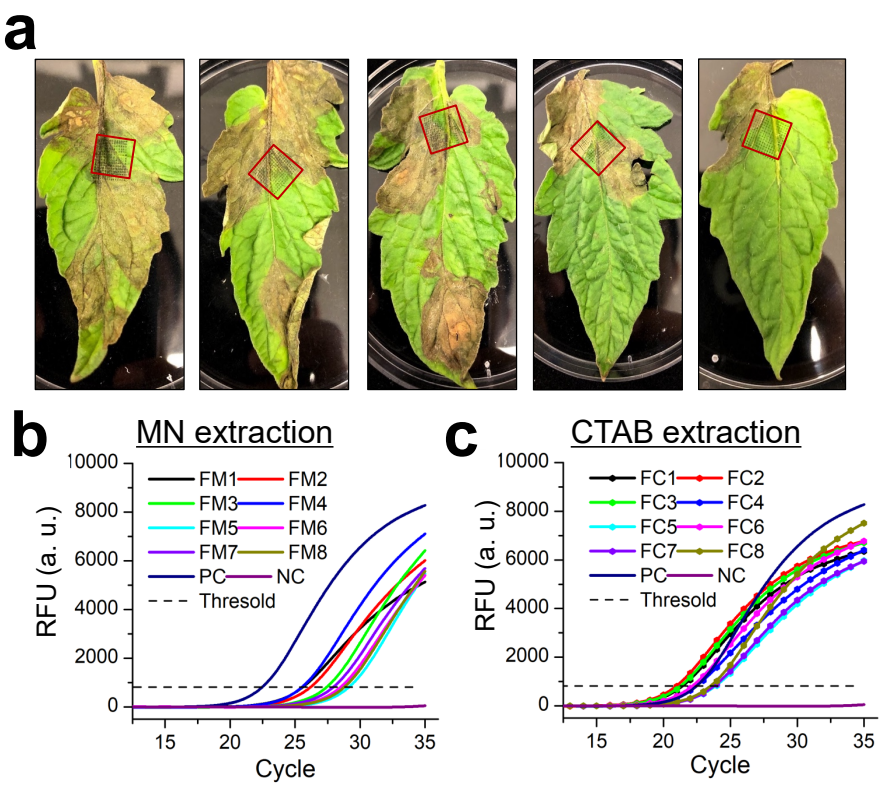


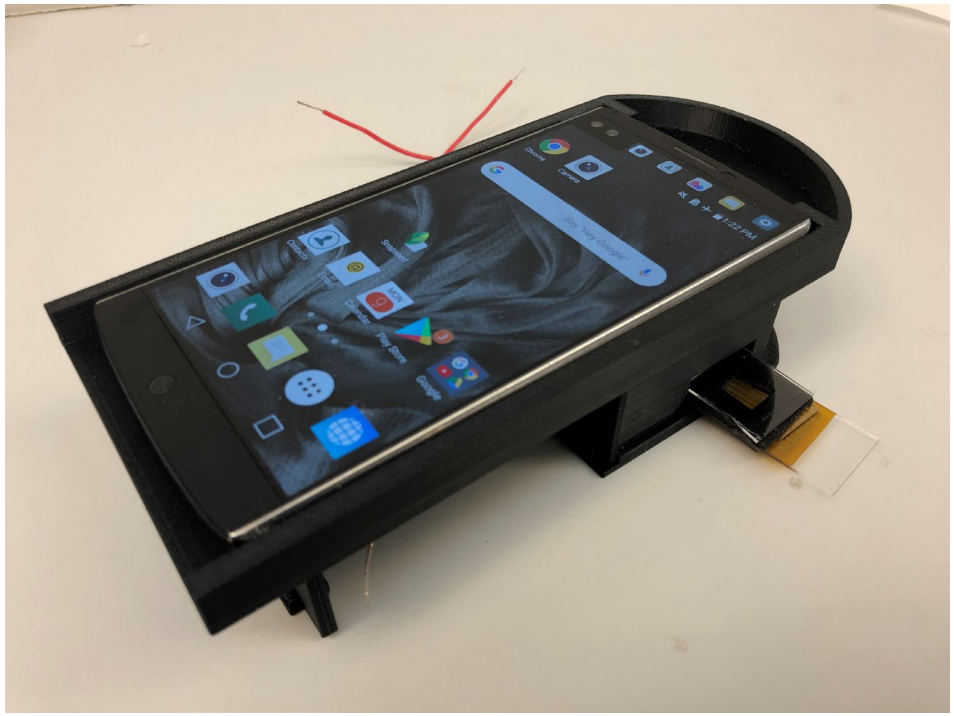
- Amplification of *P. infestans* gene



ACS Nano, 2019, 13, 6540-6549

Extraction of Pathogen DNA for Rapid Diagnosis

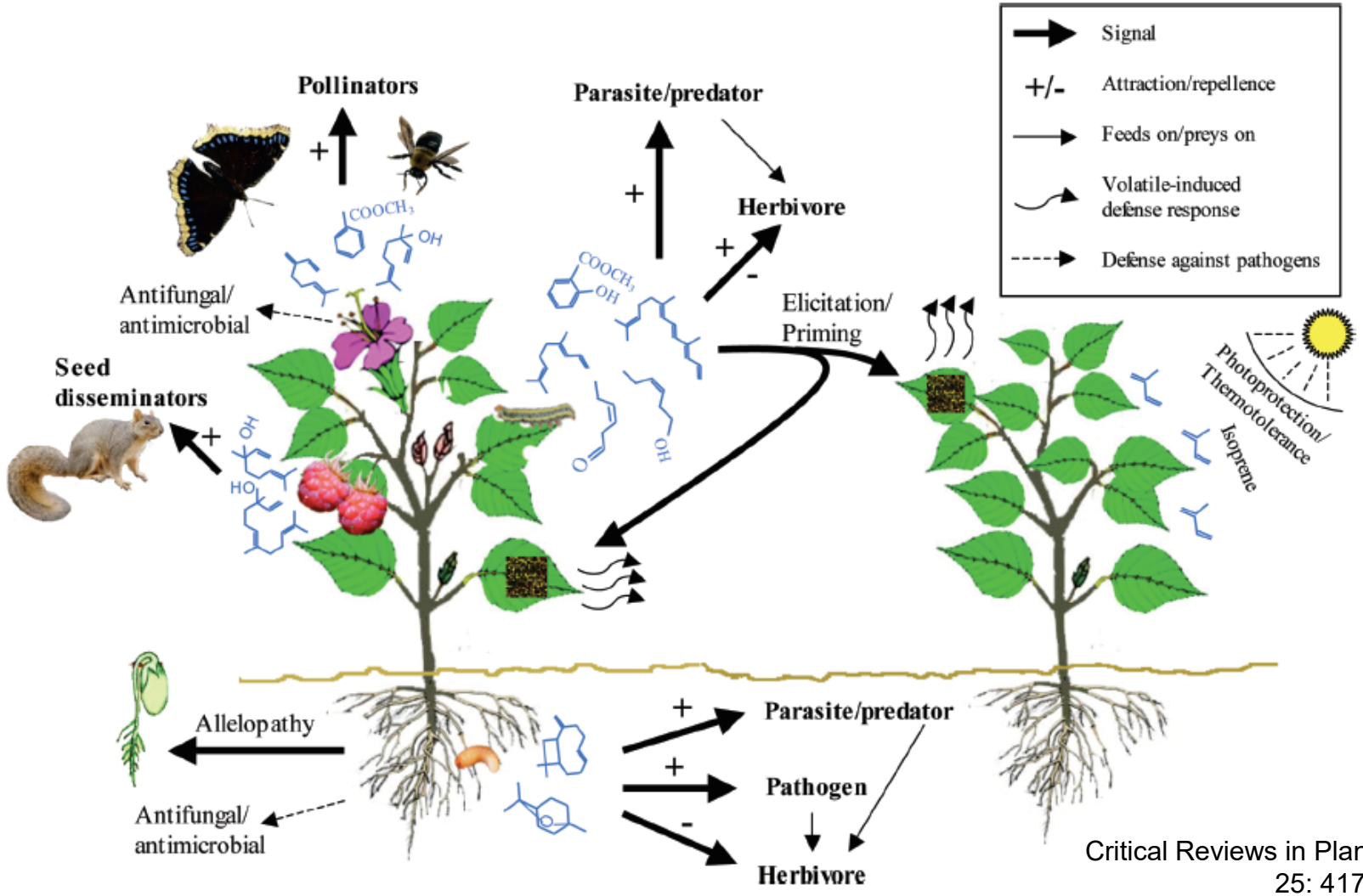




- Prototype of smartphone-based amplification and readout system

ACS Nano, 2019, 13, 6540-6549

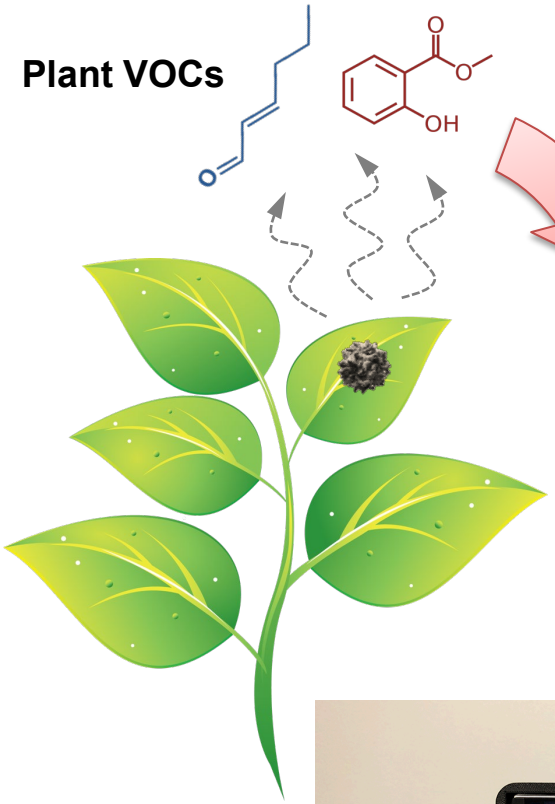
Noninvasive Diagnosis of Plant Diseases by Volatile Organic Compound (VOC) Analysis



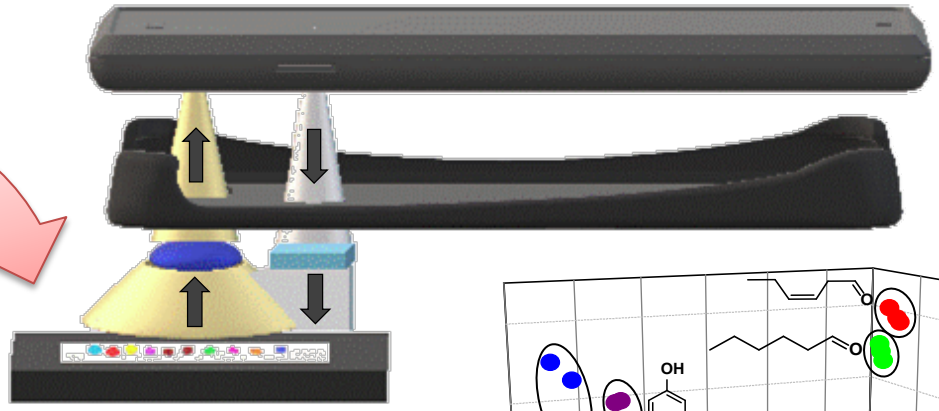
Critical Reviews in Plant Sciences, 25: 417–440, 2006

Smartphone-Based Plant VOC Sensor

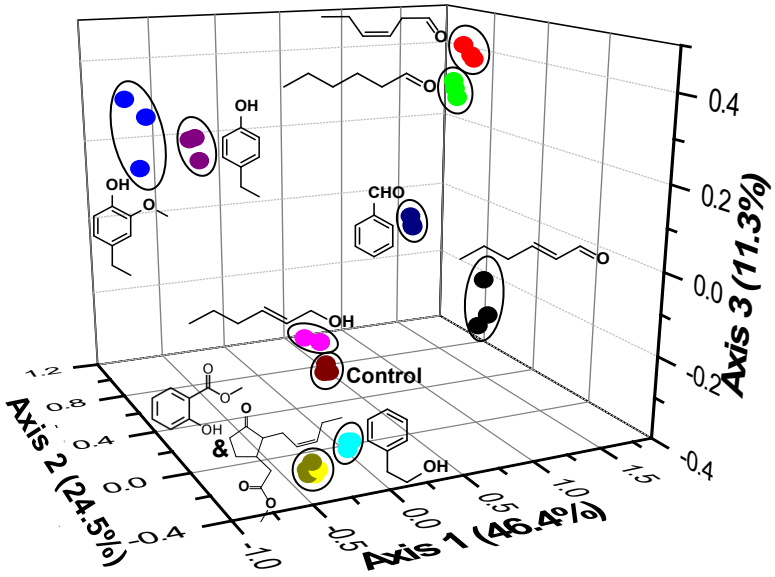
Plant VOCs

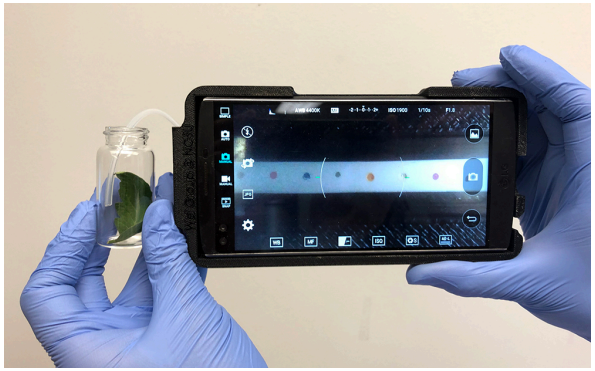


Mobile phone reader



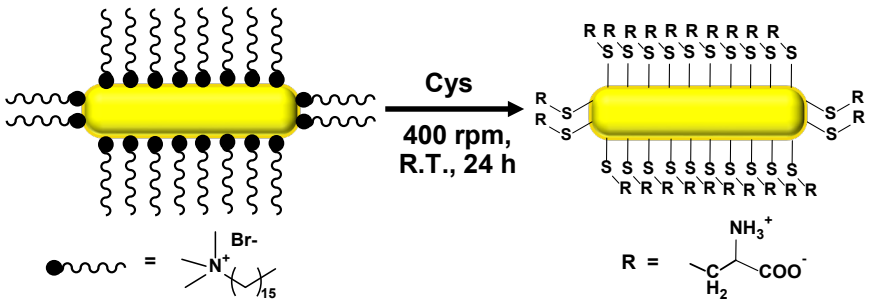
Chemical sensor array

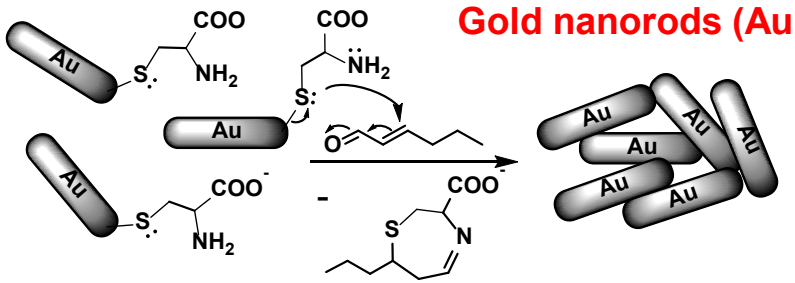




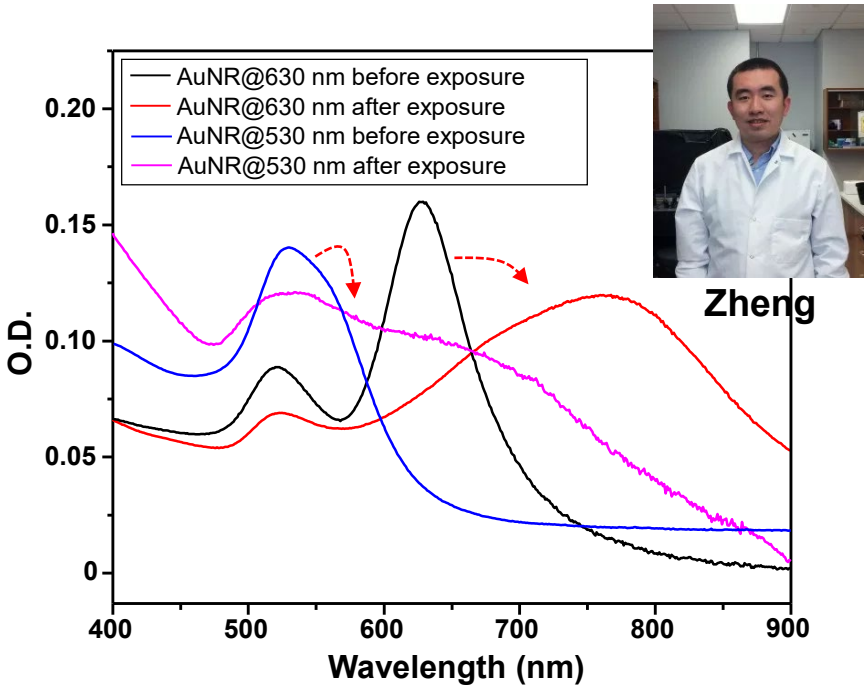
Collaborators:
Jean Ristaino (EPP)
Yong Zhu (MAE)

Nanoplasmonic Sensor for VOC Detection



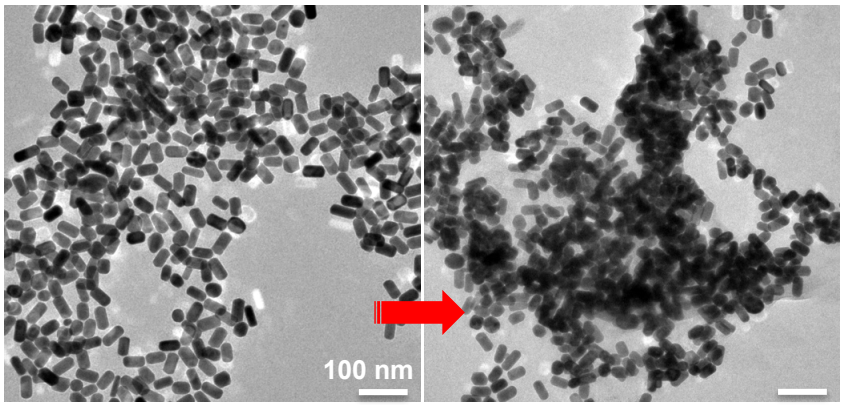


Gold nanorods (AuNRs)

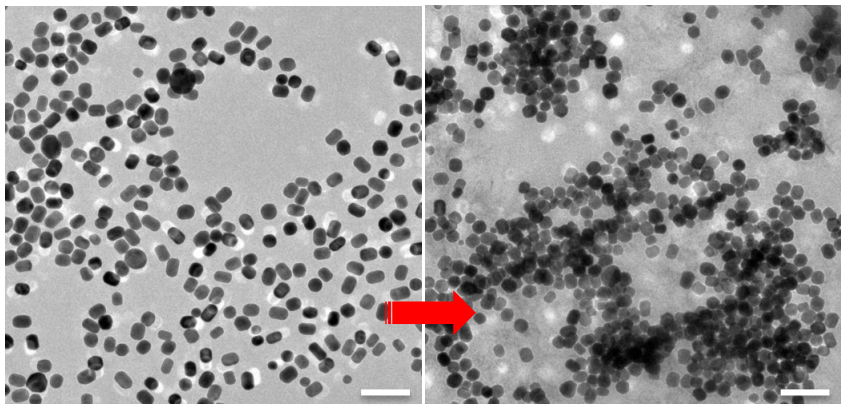


Zheng

- **630 nm AuNR (exposure to (*E*)-2-hexenal)**

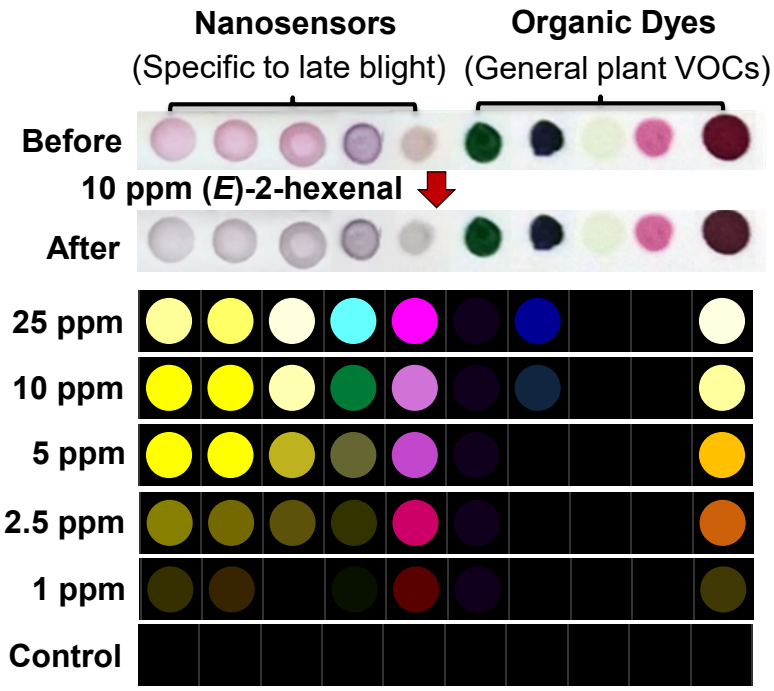


- **530 nm AuNR**



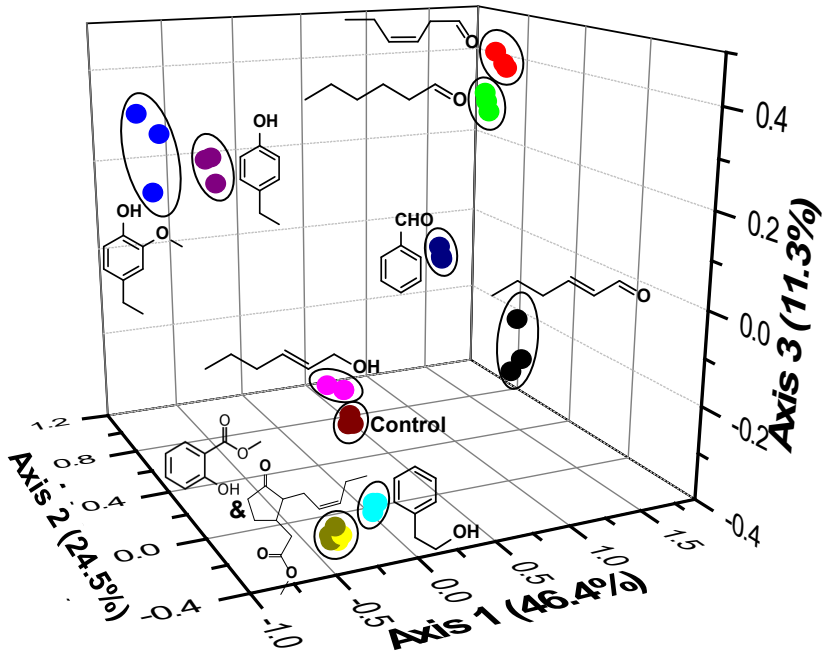
Li, Z. et al. ***Nature Plants***, 2019, 5, 856–866

Paper-Based Volatile Sensor Strips

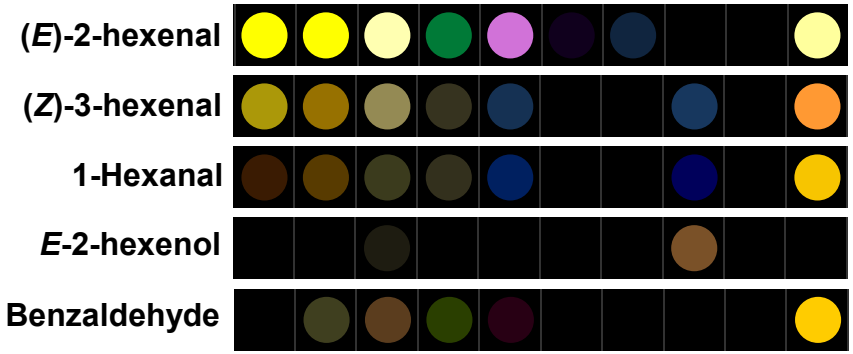


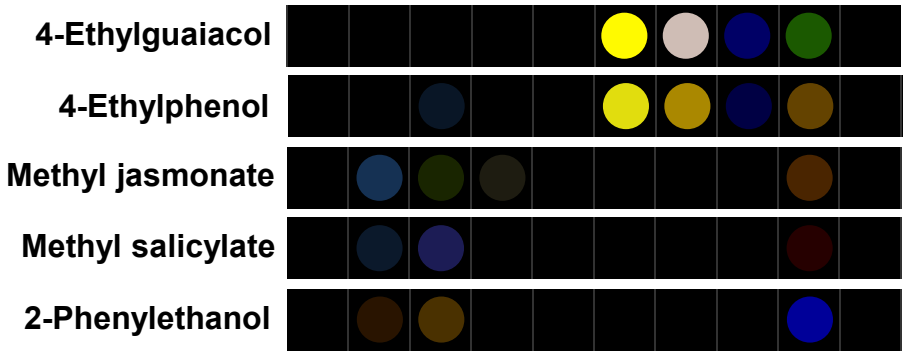
Cost: ~15 cents / test

- **Principal Component Analysis (PCA)**



- **10 ppm exposure (for 1 min)**





Early Detection of Late Blight (*P. Infestans*) After 2 Days of Inoculation

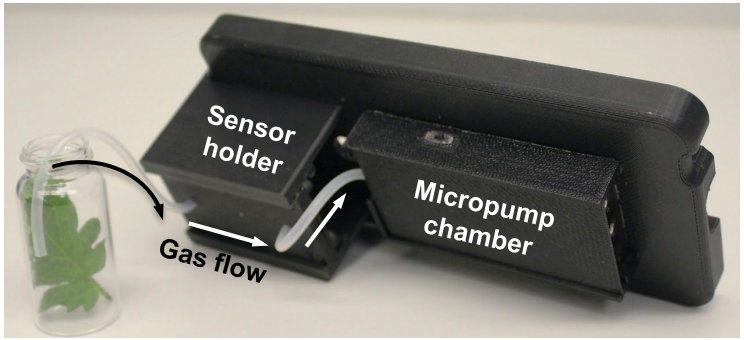
- **Experimental workflow**

Infected tomato leaf w/ *P. Infestans*

Accumulate headspace gas

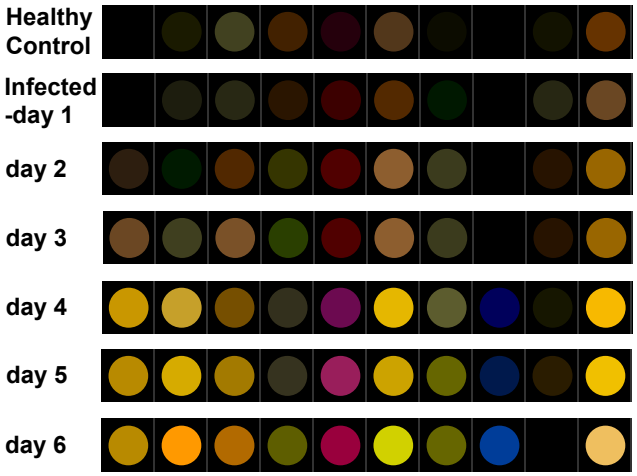
Leaf in 20 mL vial

Smartphone test for 1 min

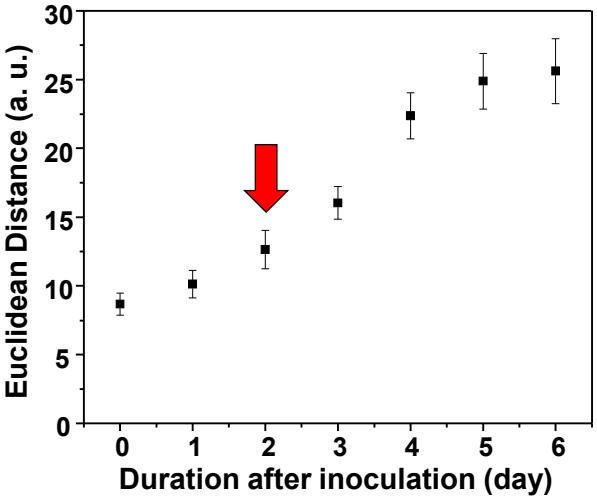


Smartphone VOC sensor

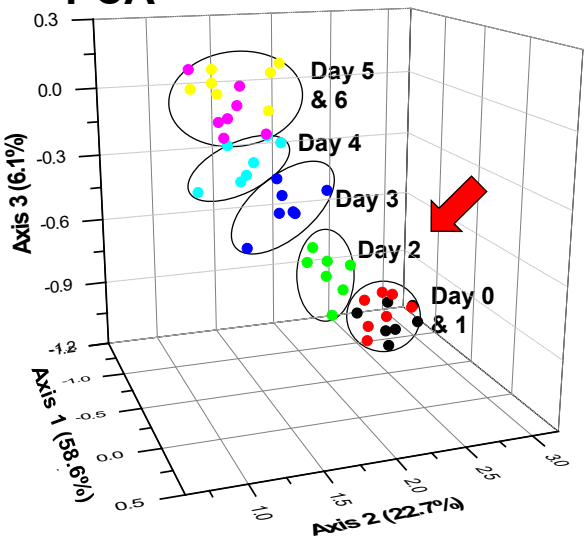
- **Response**



- **Quantification**

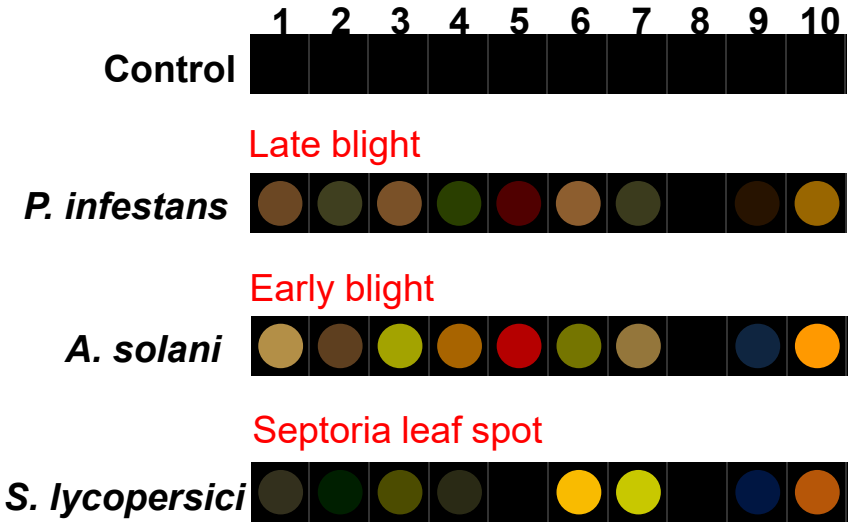


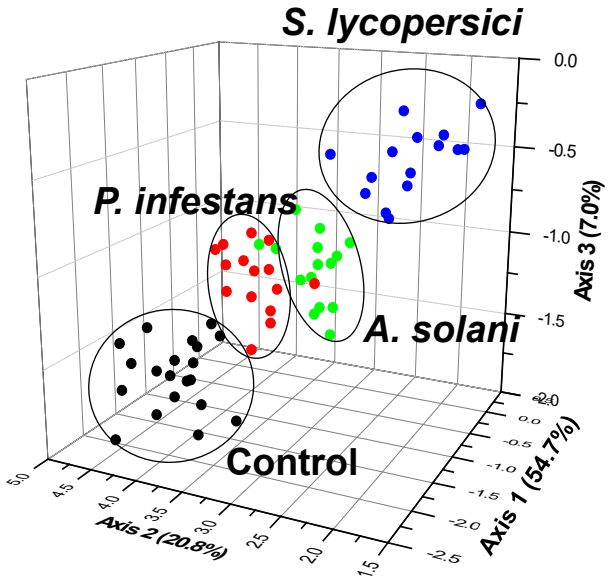
- **PCA**



Li, Z. et al. ***Nature Plants***, 2019, 5, 856–866

Differentiation of Other Infections With Similar Symptoms





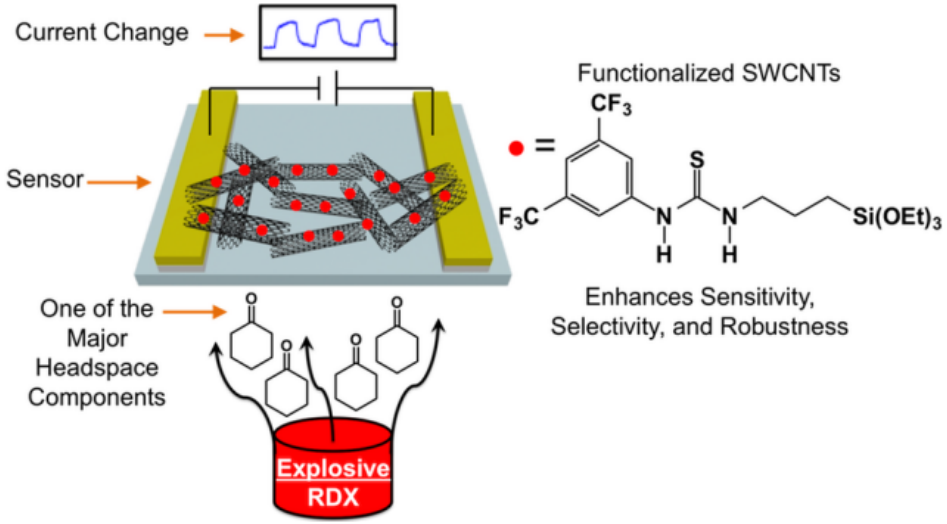
Classification accuracy: > 95%

(3 errors out of 65 samples tested in total)

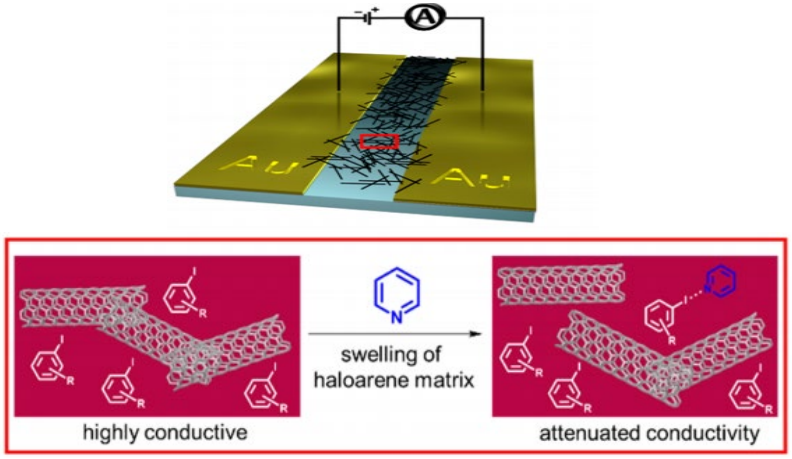
Li, Z. et al. ***Nature Plants***, 2019, 5, 856–866

Chemiresistive Plant Wearables for Long-Term Monitoring

Hydrogen Bonding Mechanism

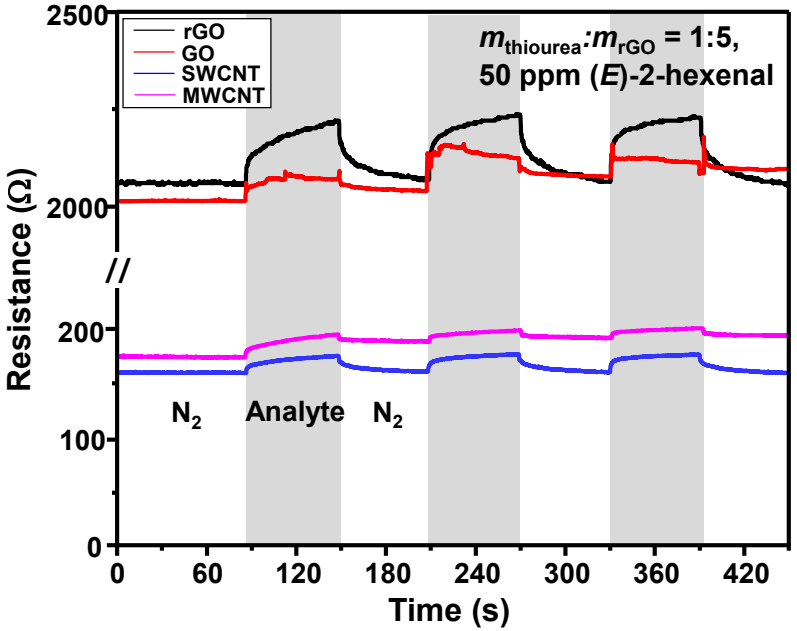


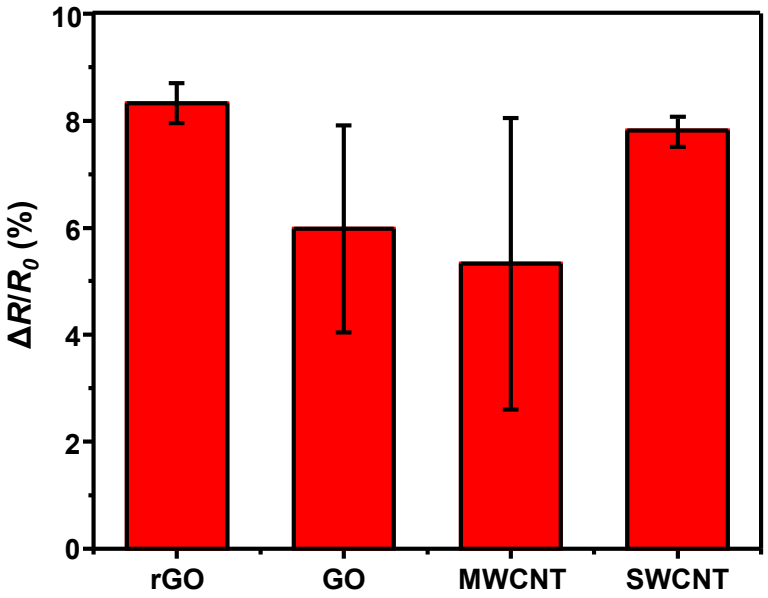
Halogen Bonding Mechanism

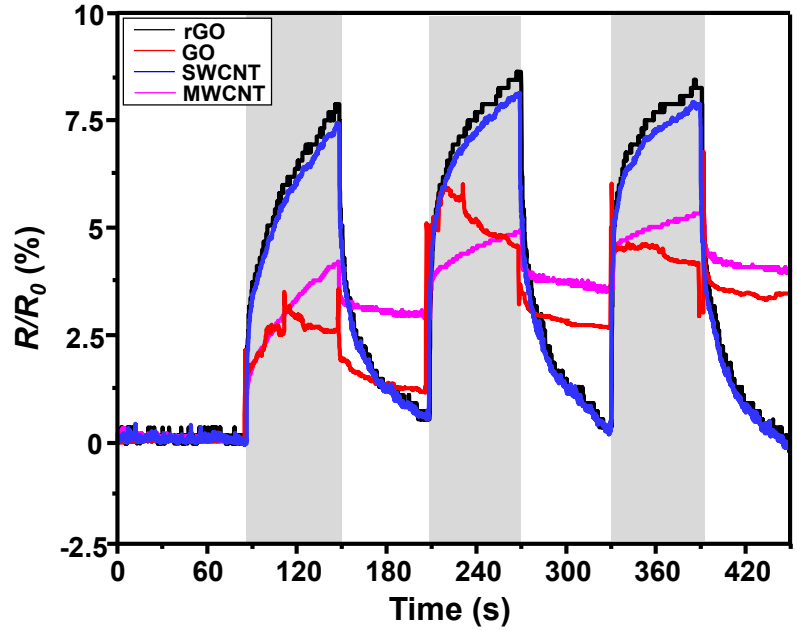


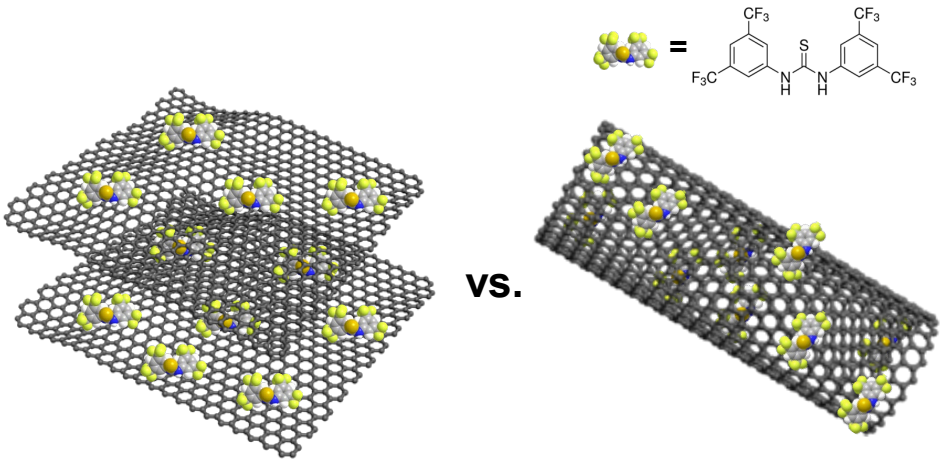
Frazier, K. M; Swager, T. M. *Anal. Chem.* **2013**, *85*, 7154.
Weis, J. G.; Ravnsbæk, J. B.; Mirica, K. A.; Swager, T. M. *ACS Sens.* **2016**, *1*, 115.

Sensing Materials





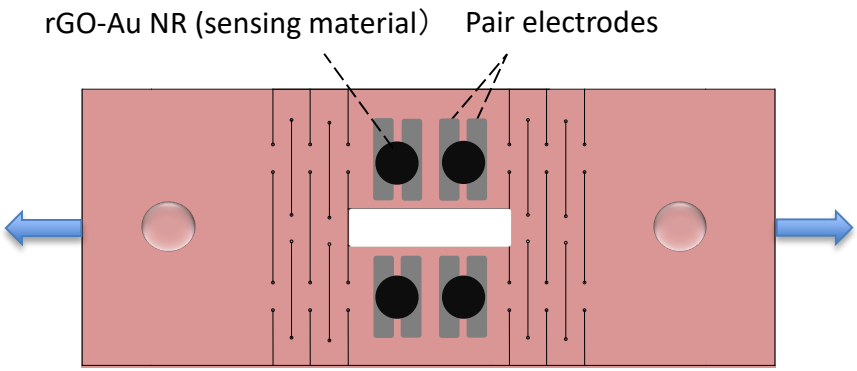


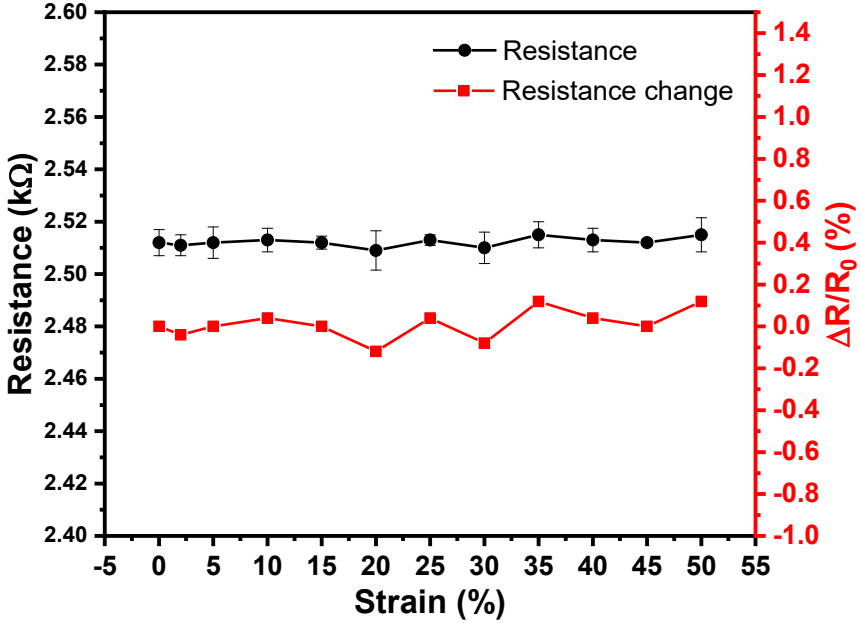


rGO (reduced graphene oxide)

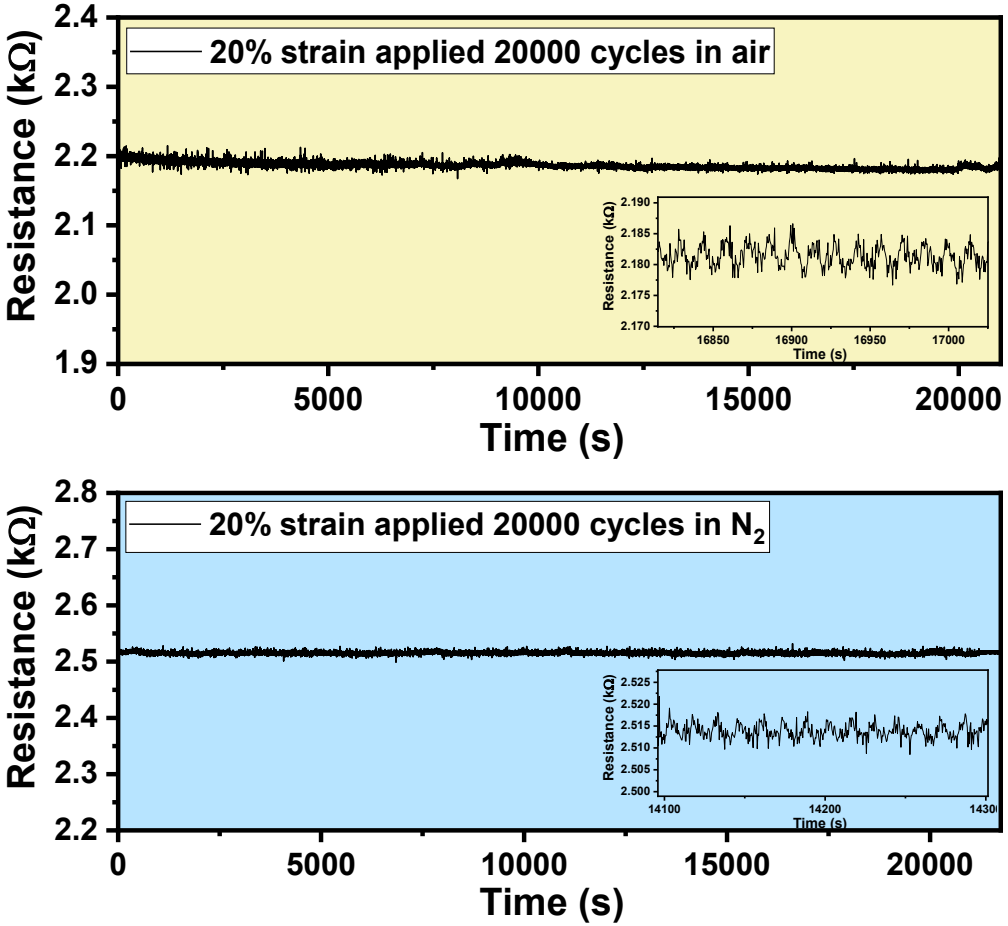
SWCNT (single-walled carbon nanotube)

Eliminating the strain effect on resistance change

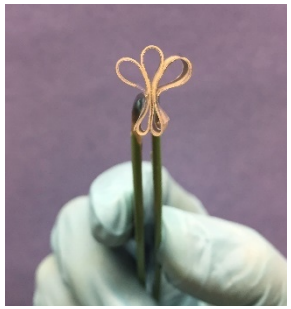


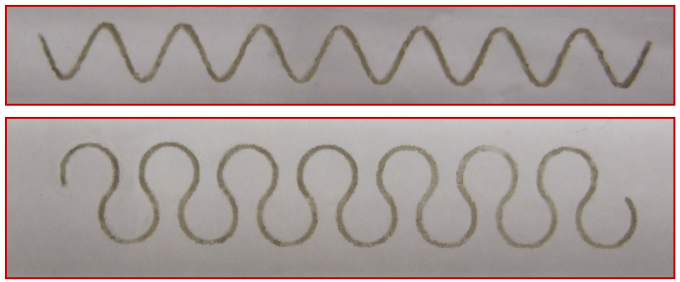


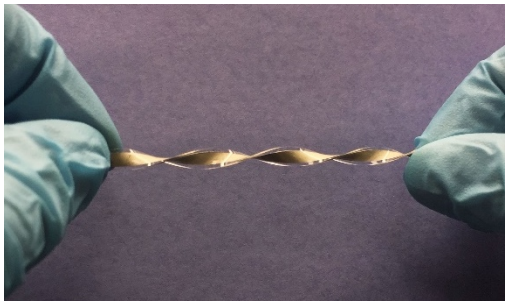
Cyclic test when applying 20% strain for rGO-Au NR(ITP)

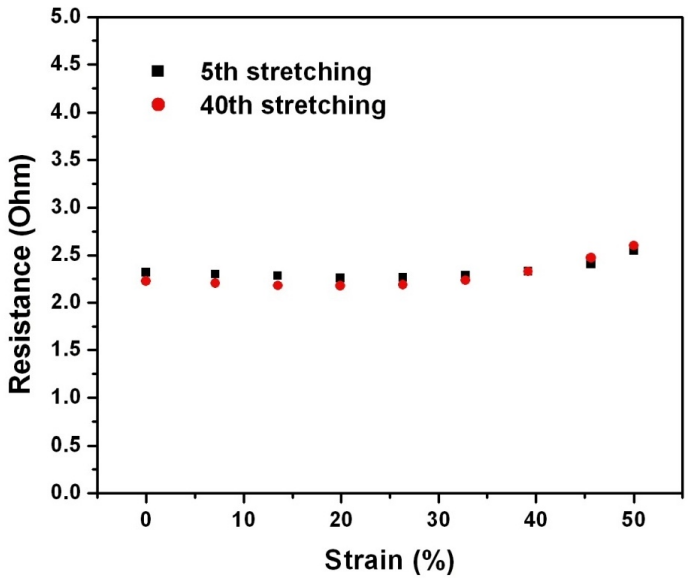


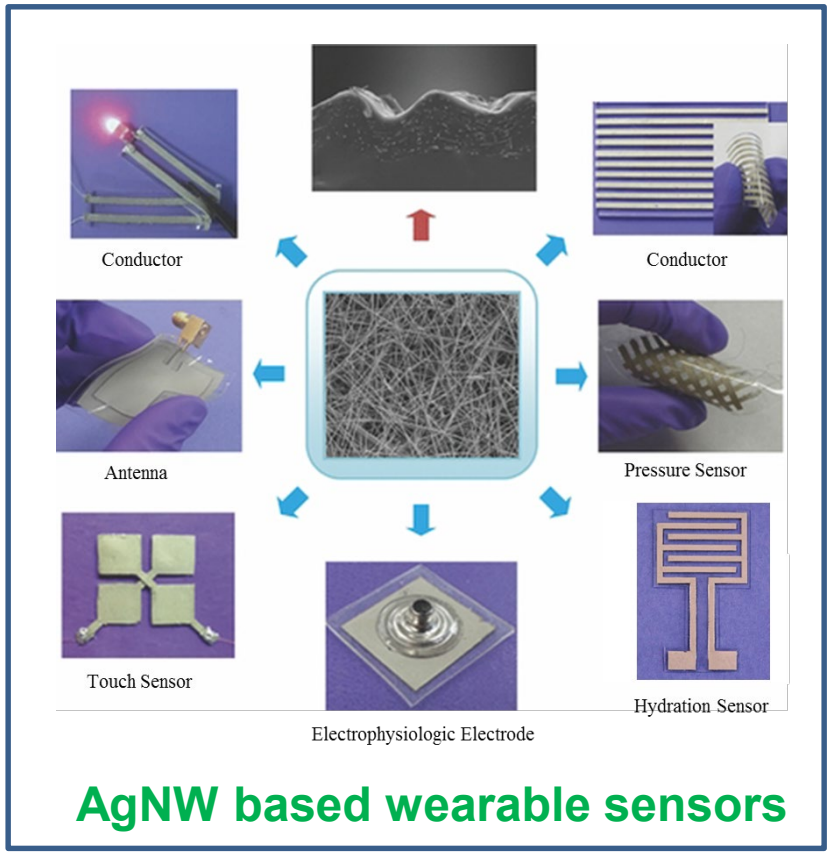
Highly Conductive & Stretchable Ag Nanowire Conductors





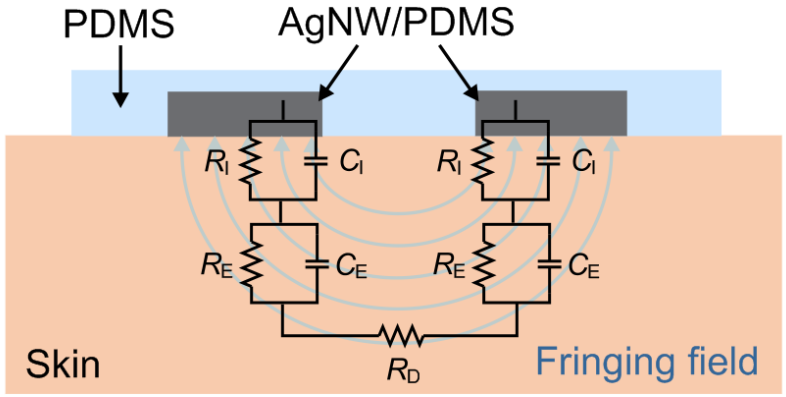


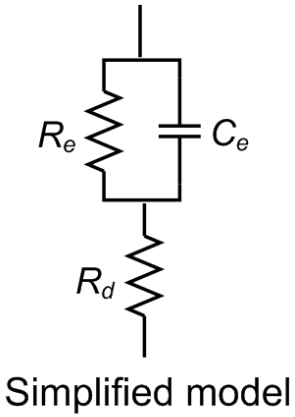




F. Xu and Y. Zhu, *Adv. Mater.* 24, 5117-5122 (2012).
S. Yao and Y. Zhu, *Adv. Mater.* 27, 1480-1511 (2015).

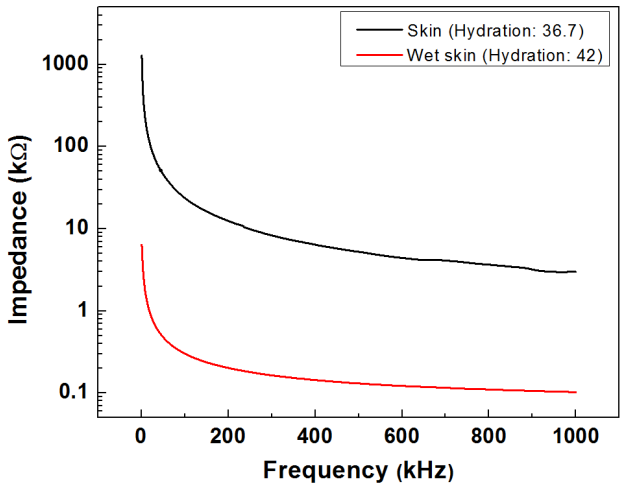
Hydration Sensors





Sensing Mechanism:

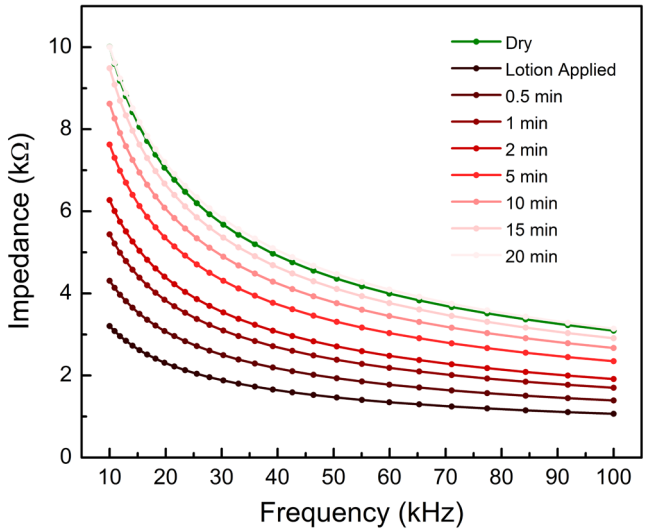
- **Electric field through the skin can measure skin impedance**
- **Water content increases**
  - — Permittivity ↑
  - — Conductivity ↑
  - — **Impedance** ↓

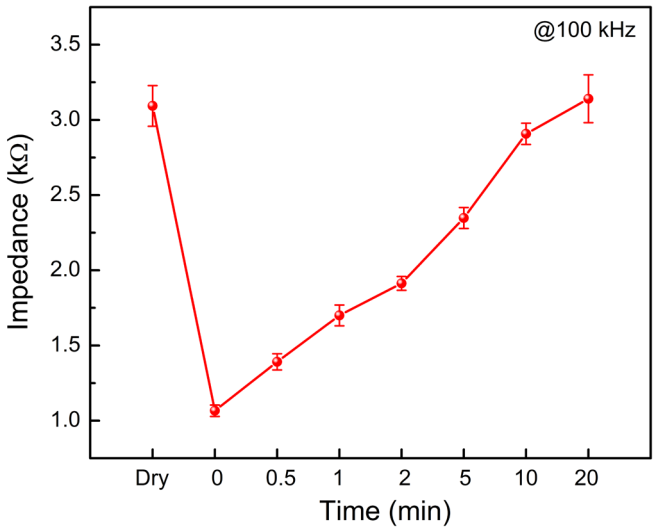


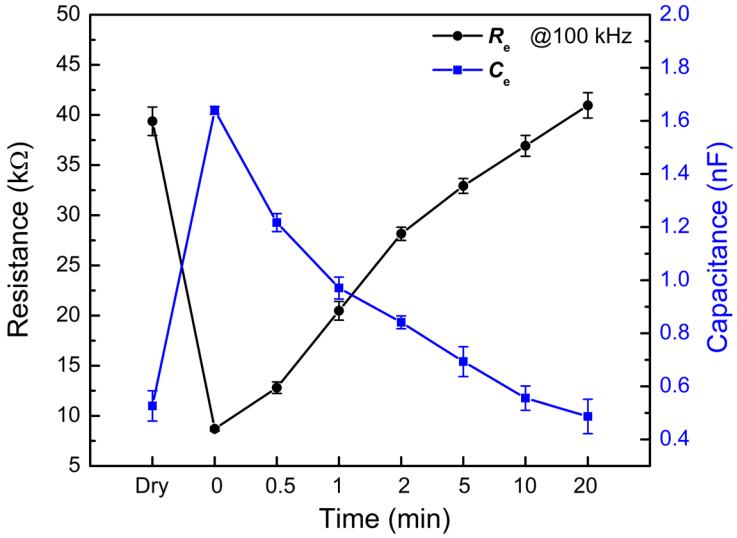
Parameters	Dry Skin	Moisturized Skin
R_e	9.81 MΩ	14.5 kΩ ↓
C_e	34.4 pF	55.7 nF ↑
R_d	Varies	Varies

S. Yao, et al., *Adv. Healthcare Mater.* 6, 1601159 (2017).

Hydration Sensors: Application



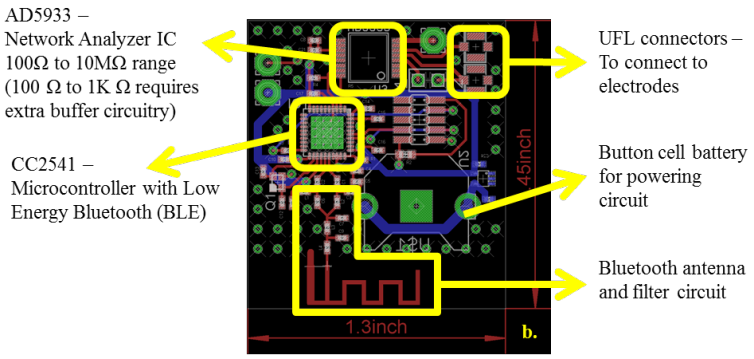


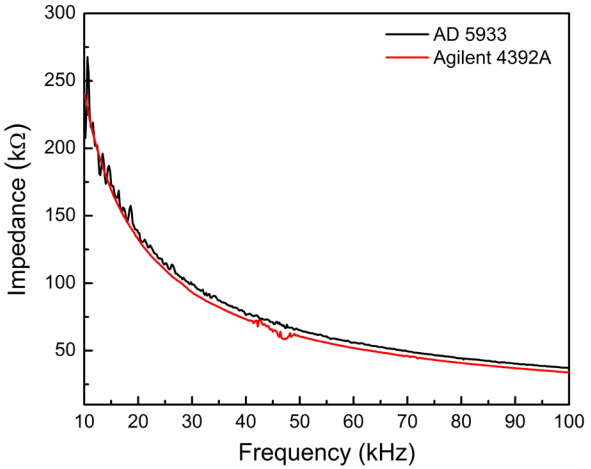


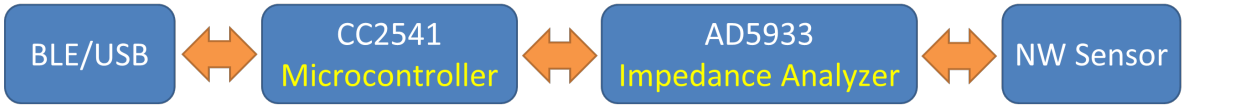
Sensor Integration for Wireless Monitoring

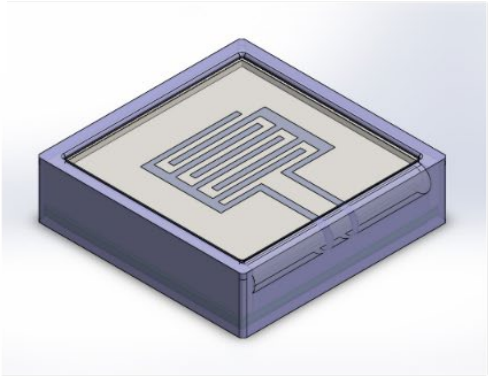
- **Wristwatch for Hydration Sensing**

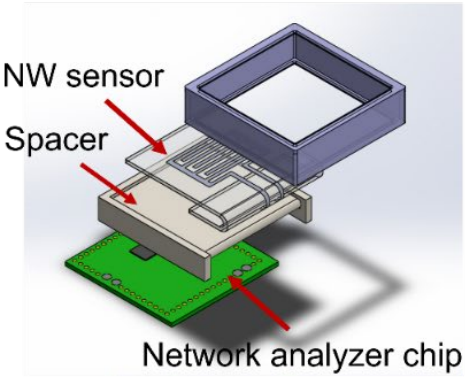
Collaborators:
John Muth (ECE, NCSU)



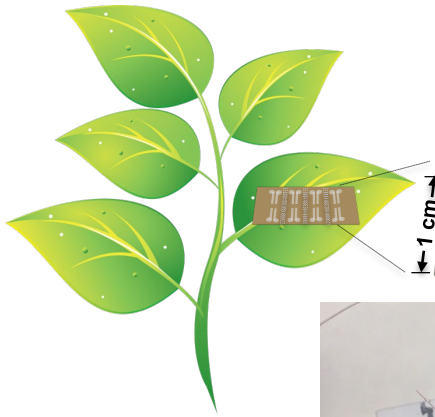


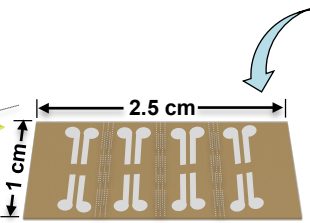


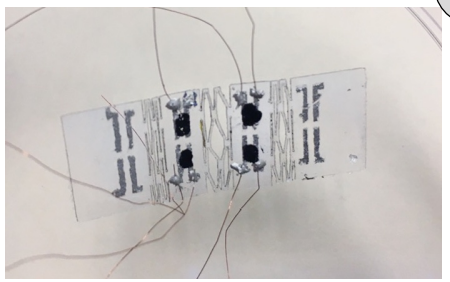


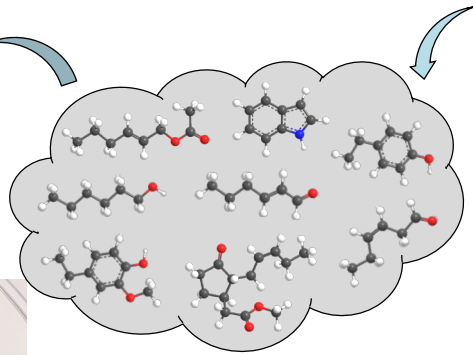


Wearable Plant VOC Sensor

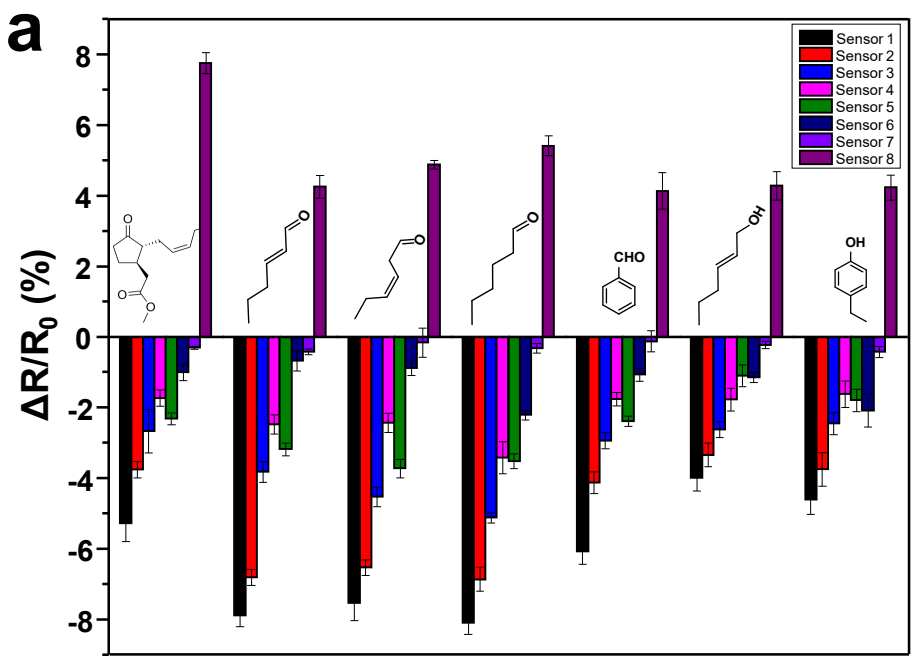


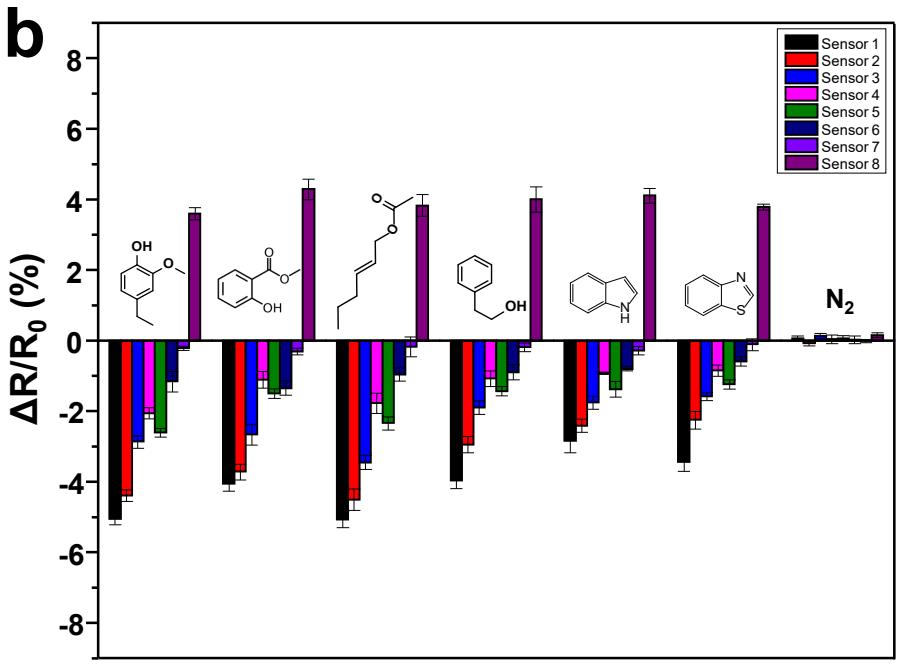






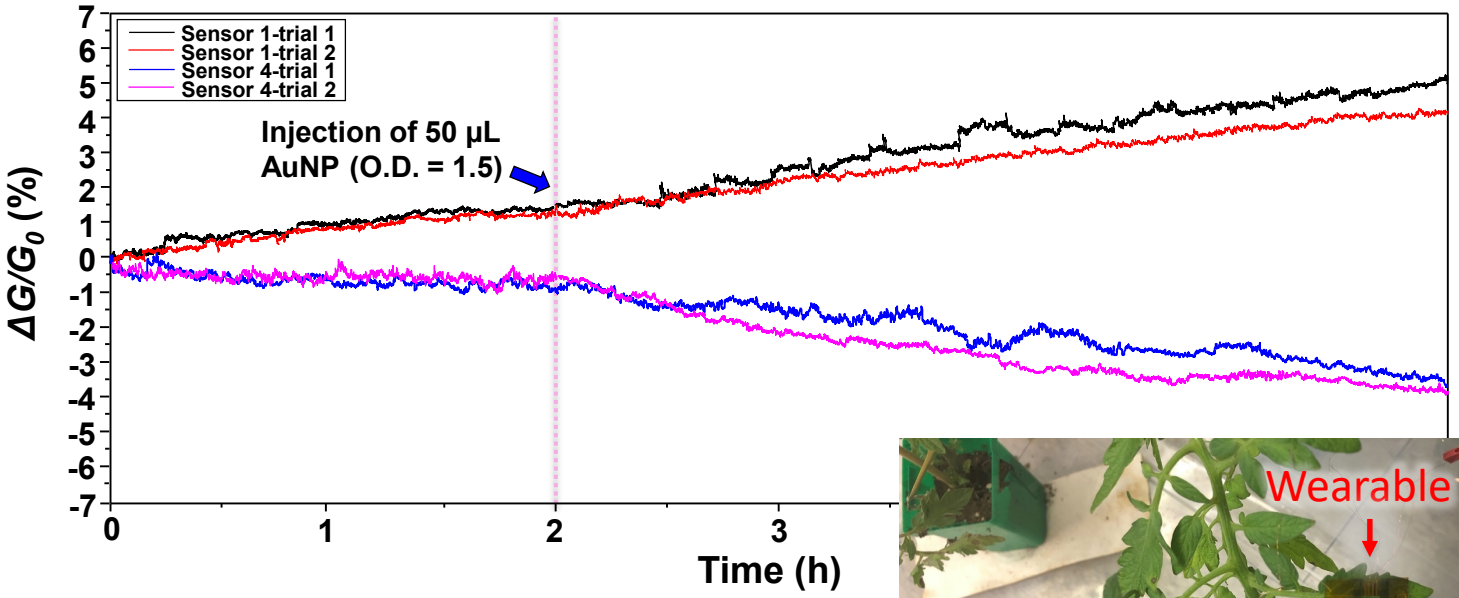
- ✓ Sunlight
- ✓ Humidity
- ✓ Physical damage
- ✓ Chemical injection
- ✓ Disease



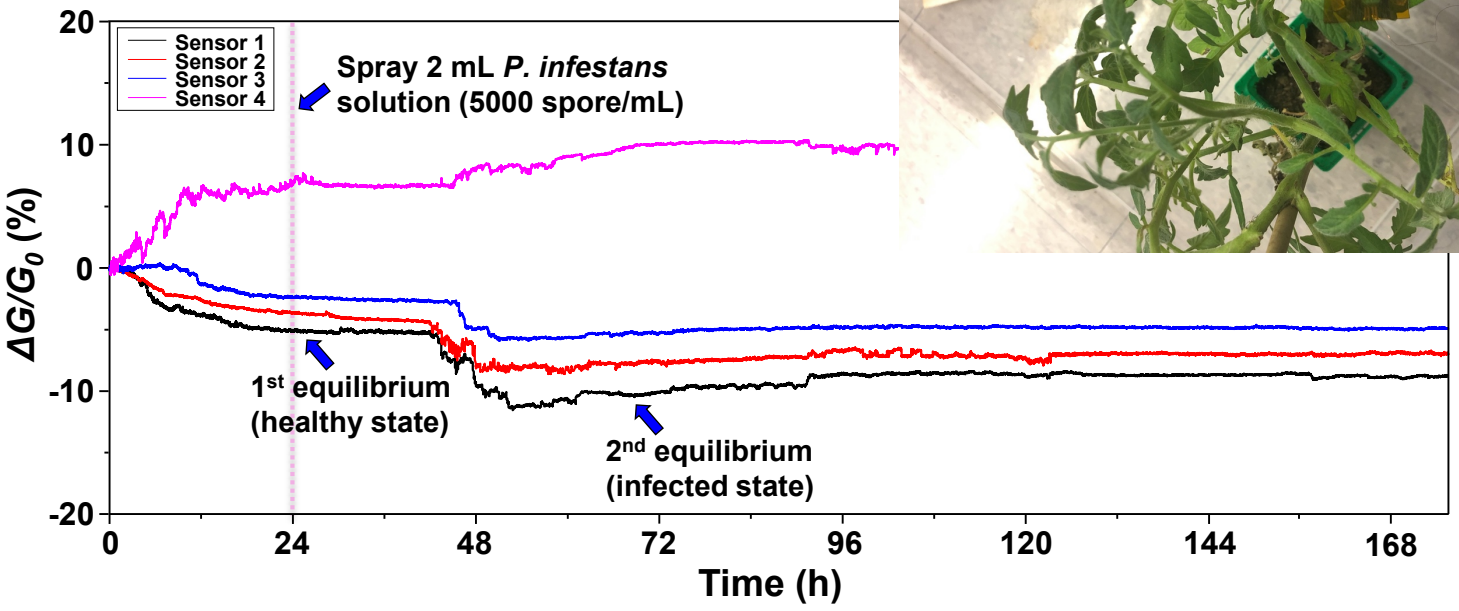


Real-Time Analysis of Plant Leaf VOC by Wearables

- **Injection of nanoparticles**



- **Pathogen infection**



Summary

- Plant disease surveillance requires new sensor technologies and devices that are cost-effective, miniaturized, and field-deployable.

- Three complementary sensor platforms (handheld molecular diagnostic system, smartphone VOC sensor, and plant wearables) are under development, which may impact the broad areas of plant science and AgBio.

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USDA NIFA

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ENGINEERING, TECHNOLOGY & SCIENCE
NC STATE UNIVERSITY