Project Notes:

Project Title: Modeling Sensitizer to Annihilator Ratios for Optimal Light Intensity in TTA Upconversion
Name: Ghosh, Aishani

Contents:

Knowledge Gaps:

This list provides a brief overview of the major knowledge gaps for this project, how they were resolved and where to find the information.

Knowledge Gap	Resolved By	Information is located	Date resolved
Plant model organism What are the types? Most common ones? How are they used?	Reading a journal article	Igor Cesarino, Raffaele Dello Ioio, Gwendolyn K Kirschner, Michael S Ogden, Kelsey L Picard, Madlen I Rast-Somssich, Marc Somssich, Plant science's next top models, *Annals of Botany*, Volume 126, Issue 1, 29 June 2020, Pages 1-23, https://doi.org/10.1093/aob/mcaa063	09/12/2025
How can bioluminescence be induced in bacteria?	Reading a journal article	Bernal, E., Deblais, L., Rajashekara, G., & Francis, D. M. (2021). Bioluminescent Xanthomonas Hortorum pv. Gardneri as a tool to quantify bacteria in planta, screen germplasm, and identify infection routes on leaf surfaces. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.667351	09/20/2025
How does TTA-UC work?	Reading a journal article	Wong, J., Wei, S., Meir, R., Sadaba, N., Ballinger, N. A., Harmon, E. K., Gao, X., Altin-Yavuzarslan, G., Pozzo, L. D., Campos, L. M., & Nelson, A. (2023). Triplet fusion upconversion for photocuring 3d-printed particle-reinforced composite networks. *Advanced Materials*,	11/23/2025

		35(11). https://doi.org/10.1002/adma.202207673	
What are the applications of TTA-UC?	Reading a journal article	Wong, J., Wei, S., Meir, R., Sadaba, N., Ballinger, N. A., Harmon, E. K., Gao, X., Altin-Yavuzarslan, G., Pozzo, L. D., Campos, L. M., & Nelson, A. (2023). Triplet fusion upconversion for photocuring 3d-printed particle-reinforced composite networks. *Advanced Materials*, *35*(11). https://doi.org/10.1002/adma.202207673	11/23/2025
What is self-quenching in TTA-UC, how does it work?	Reading a journal article	Olesund, A., Ghasemi, S., Moth-Poulsen, K., & Albinsson, B. (2023a). Bulky substituents promote triplet–triplet annihilation over triplet excimer formation in naphthalene derivatives. *Journal of the American Chemical Society*, *145*(40), 22168–22175. https://doi.org/10.1021/jacs.3c08115	12/10/2025

Literature Search Parameters:

These searches were performed between 08/25/2025 and XX/XX/2025.
List of keywords and databases used during this project.

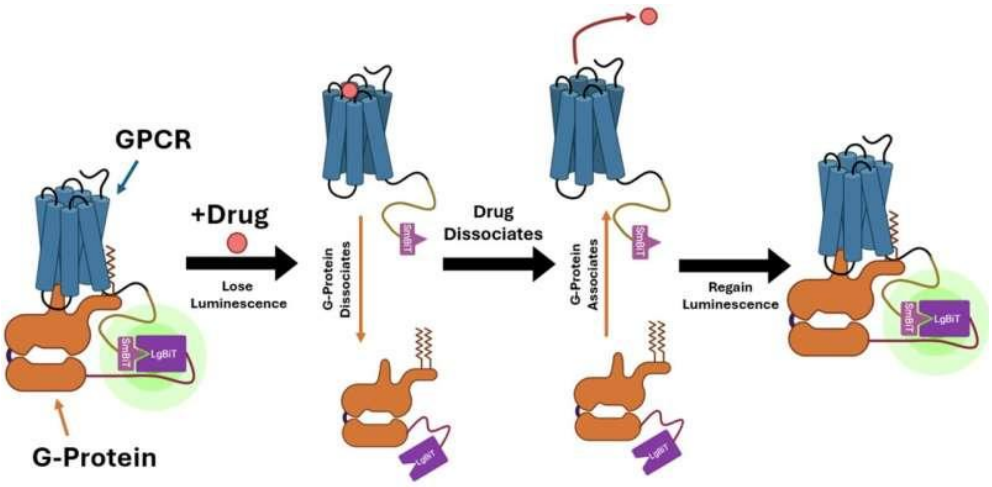
Database/search engine	Keywords	Summary of search
WPI Library Search	Bioluminescence AND plants	I found articles about bioluminescent imaging, bacteria, and multicolor imaging.
PubMed	Bioluminescence AND bacteria	I found lots of articles about using bioluminescent bacteria for imaging. Specifically, I found one about using bioluminescence to monitor lactic acid, which I think is very interesting.
PubMed	Biosensor AND plant	I found an article about prospective methods for plant disease detection describing biosensors as a potential tool.
PubMed	Nanomaterials	I found a lot of helpful articles about what nanomaterials are and their applications.
PubMed	TTA-UC	I found an article about using TTA-UC in curing hydrogels.

Tags:

Tag Name	
TTA-UC	Perylene
Quenching	PdTPBP
Upconversion	Hydrogel

Article #1 Notes: Glowing biosensor streamlines high-throughput drug screening

Source Title	Glowing biosensor streamlines high-throughput drug screening
Source citation (APA Format)	Smith, L. (2025, June 23). *Glowing biosensor streamlines high-throughput drug screening*. Phys.org. https://phys.org/news/2025-06-biosensor-high-throughput-drug-screening.html
Original URL	https://phys.org/news/2025-06-biosensor-high-throughput-drug-screening.html
Source type	Website Article
Keywords	GPCR, drug screening, Alzheimer's disease
#Tags	GCPR, bioluminescence, luciferase
Summary of key points + notes (include methodology)	Anne Robinson is a researcher at Carnegie Mellon University who is investigating a way to streamline drug screening. The article explains how testing different drugs for neurodegenerative diseases is expensive and takes a long time. For example, Alzheimer's disease has no cure yet, but it is known that the disease is connected to an upregulation of GPCRs (G-Protein Coupled Receptors). GPCRs are transmembrane proteins connecting the outside and inside of a cell. The G-protein is connected to the GPCR inside the cell. On the outside, a small-molecule drug can bind to the GPCR. When a drug binds, it causes the G-protein to disconnect from the other side of the GPCR. Researcher Sonbati created a biosensor to illuminate when the G-protein and GPCR are connected. Therefore, when a drug has properly bound to the outside of the GPCR, the GPCR and G-protein will disconnect and lose their light. It was created using the enzyme luciferase, the same one that gives fireflies their bioluminescence. With this, the Robinson Lab is now testing 700 different drugs on whether they can bind to the GPCR. Learning more about which drugs can affect GPCR regulation can one day lead to a cure for Alzheimer's disease. I read this article because I'm interested in biology, specifically bioluminescence. I'd like to learn more about the enzyme luciferase and how it can be applied to drugs/treatments in humans. The article shows an innovative way luciferase was employed in a biosensor to track drug efficacy.
Research Question/Problem/ Need	Can luciferase-based biosensors be used to speed up drug screening for GPCRs to help identify potential treatments for Alzheimer's disease?

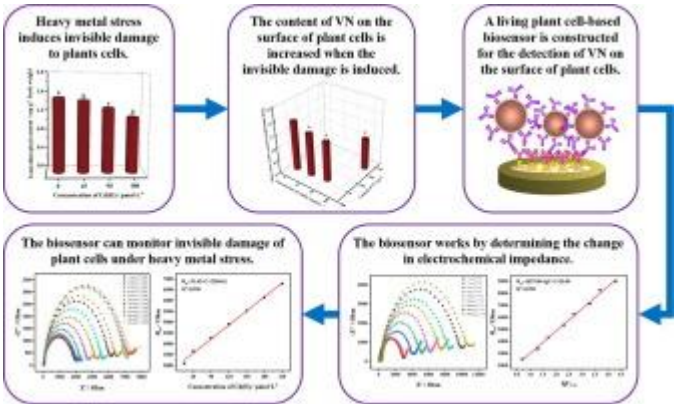
Important Figures	 Graphic of how G-Protein interacts with drug to lose luminescence
VOCAB: (w/definition)	GPCR: G-Protein Coupled Receptors; proteins that sit in the cell membrane, connect inside and outside of the cell Drug screening: technical analysis of a drug to see whether it fits the criteria needed
Cited references to follow up on	University of Basel. (2025, May 16). *GPS for proteins: Tracking the motions of cell receptors.* Phys.org. https://phys.org/news/2025-05-gps-proteins-tracking-motions-cell.html
Follow up Questions	Can this biosensor be used for diseases other than Alzheimer's? Is Alzheimer' the only disease linked to an upregulation of GCPRs? What was the methodology to accomplish this?

Notes:

- Anne Robinson is a researcher at Carnegie Mellon, studies ways to make drug screening faster and cheaper
- Testing drugs for diseases like Alzheimer's takes a long time + expensive
- Alzheimer's has no cure, but it's linked to GPCRs (G-Protein Coupled Receptors)
- GPCRs = proteins that sit in the cell membrane, connect inside and outside of the cell
- On the inside: GPCR is connected to a G-protein
- On the outside: a drug can bind to GPCR
- When a drug binds, the G-protein disconnects from GPCR
- She made a biosensor that lights up when GPCR and G-protein are connected
- If a drug works → GPCR + G-protein disconnect → light signal goes away
- Biosensor uses luciferase, the enzyme that makes fireflies glow
- Robinson's lab is now testing 700 drugs with this system
- Goal: find drugs that can change GPCR activity and maybe treat Alzheimer's

Article #2 Notes: A living plant cell-based biosensor for real-time monitoring invisible damage of plant cells under heavy metal stress

Source Title	A living plant cell-based biosensor for real-time monitoring invisible damage of plant cells under heavy metal stress
Source citation (APA Format)	Wang, X., Cheng, M., Yang, Q., Wei, H., Xia, A., Wang, L., Ben, Y., Zhou, Q., Yang, Z., & Huang, X. (2019). A living plant cell-based biosensor for real-time monitoring invisible damage of plant cells under heavy metal stress. *Science of The Total Environment*, *697*, 134097. https://doi.org/10.1016/j.scitotenv.2019.134097
Original URL	https://www.sciencedirect.com/science/article/abs/pii/S0048969719340744
Source type	Journal Article
Keywords	Heavy metals, VN protein, Arabidopsis, electron-transfer resistance, biosensor
#Tags	Heavy metals, Arabidopsis, biomarker, stress, antibodies
Summary of key points + notes (include methodology)	To monitor early plant damage, a plant cell-based biosensor was created to measure the invisible negative effect of cadmium and lead on VN proteins on the surface of plant cells using electrochemical impedance. The biosensor was created from a carbon electrode and modified with a VN-antibody, which allowed the electron-transfer resistance in the plant cells to be recorded. The sensor was tested on Arabidopsis and soybean, which both showed an increase in electron transfer resistance as VN increased (due to cadmium and lead induced stress), leading to a decrease in chlorophyll and plant health. From the data collected, a quantitative relationship between heavy metal stress and damage was established. This sensor can now serve as an early warning for metal pollution's effects on plants.
Research Question/Problem/ Need	How can we detect the invisible damage caused to plants by heavy metals to monitor plant health?

Important Figures	 Graphic of how biosensor detects heavy metal effects on plant health
VOCAB: (w/definition)	Arabidopsis: small, flowering plant in mustard family; used as a common model organism for plant biology due to rapid life cycle, small genome, and ease in genetic manipulation Antibody: a blood protein that specifically counteracts antigens (toxins) Biomarker: objective measure showing what is happening in a cell; used to diagnose and monitor health Electrochemical impedance: opposition to the flow of an alternating electric current; to measure, voltage is applied and resulting current is measured; useful in showing plant structure Electron-transfer resistance: any condition that slows down movement in the electron transport chain; can be caused by nutrient deficiency, drought, damage
Cited references to follow up on	Cheng, M., Wang, L., Yang, Q., & Huang, X. (2018). A detection method in living plant cells for rapidly monitoring the response of plants to exogenous lanthanum. *Ecotoxicology and Environmental Safety*, *158*, 94–99. https://doi.org/10.1016/j.ecoenv.2018.04.021 Baek, S. H., Kim, M. W., Park, C. Y., Choi, C.-S., Kailasa, S. K., Park, J. P., & Park, T. J. (2019). Development of a rapid and sensitive electrochemical biosensor for detection of human norovirus via novel specific binding peptides. *Biosensors and Bioelectronics*, *123*, 223–229.

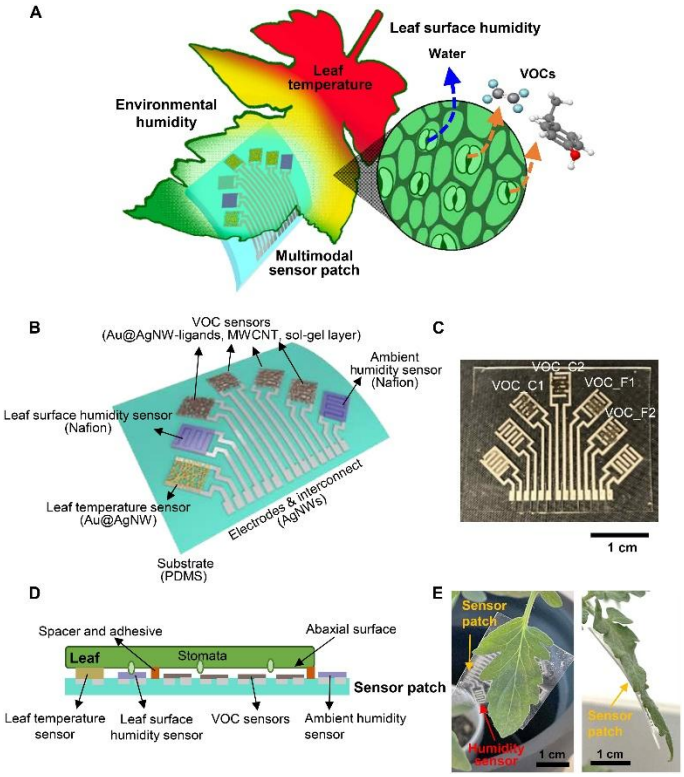
	https://doi.org/10.1016/j.bios.2018.08.064 Márquez, A., Jiménez-Jorquera, C., Domínguez, C., & Muñoz-Berbel, X. (2017). Electrodepositable alginate membranes for enzymatic sensors: An amperometric glucose biosensor for whole blood analysis. *Biosensors and Bioelectronics*, *97*, 136–142. https://doi.org/10.1016/j.bios.2017.05.051
Follow up Questions	1. How were antibodies used to modify living plant cells in the creation of the biosensor? 2. Can this method of plant cell-based biosensors be modified to detect other plant stressors or is it specific to heavy metals? 3. How was it initially found that heavy metals had a negative effect on VN proteins?

Notes:

- Heavy metals cause invisible damage to plants
- VN proteins = important biomarker on surface of plant cells
- VN proteins monitor damage under heavy metal stress --> how was this discovered?
- Living plant cell biosensor constructed to monitor damage
- Made from glassy carbon electrode, modified l-cysteine, modified anti-IgG-Au antibody, and living plant cell incubated with anti-VN
- Cadmium and Lead induced stress in Arabidopsis and soybean plants
- Arabidopsis is important plant model organism --> can I use this for my project?
- VN increase 20x --> electron transfer increased 35% --> chlorophyll decreased 17%
- Decrease in chlorophyll = damage to plant
- Relationship between heavy metal stress and invisible damage can now be measured
- Serves as “early-onset warning” for metal pollution to plant health

Article #3 Notes: Abaxial leaf surface-mounted multimodal wearable sensor for continuous plant physiology monitoring

Source Title	Abaxial leaf surface-mounted multimodal wearable sensor for continuous plant physiology monitoring
Source citation (APA Format)	Lee, G., Hossain, O., Jamalzadegan, S., Liu, Y., Wang, H., Saville, A. C., Shymanovich, T., Paul, R., Rotenberg, D., Whitfield, A. E., Ristaino, J. B., Zhu, Y., & Wei, Q. (2023). Abaxial leaf surface-mounted multimodal wearable sensor for Continuous Plant Physiology Monitoring. *Science Advances*, *9*(15). https://doi.org/10.1126/sciadv.ade2232
Original URL	https://doi.org/10.1126/sciadv.ade2232
Source type	Journal Article
Keywords	Volatile organic compounds (VOC), transpiration, abaxial, multimodal
#Tags	VOCs, abaxial, model organisms, wearable biosensor
Summary of key points + notes (include methodology)	Plant disease is a major contributor to crop loss annually, and continuous sensors to detect plant health can help decrease the response time and spread of the disease. In this study, a wearable biosensor for tomato plants was created. It is a thin, film-like material that attaches to the underside of a leaf in a tomato plant. It has 7 sensors on it, allowing it to continuously measure leaf VOCs (related to leaf volatile emissions), leaf surface temperature and humidity, and environmental humidity with accuracy. With this data, the plant's health can be monitored for biochemical and biophysical signs of disease. The team of scientists at North Carolina State University also developed a machine learning model to process the real-time data and analyze the health of the plants for disease risk assessment. The device itself has 4 sensors for measuring VOCs, 1 for leaf surface humidity, 1 for leaf temperature, and 1 for the environment's humidity. It utilizes nanotech and is made of Au@AgNWs, multiwalled carbon nanotubes, embedded in a hydrophobic sol-gel layer. To test the device a tomato plant was put through different abiotic stressors which were drought, overwatering, salinity, and darkness. The sensors showed similar data in the experiment's 3 trials and aligned with logical patterns (such as increased leaf humidity during excessive watering).

	The sensors were also tested on plants with the diseases TSWV and early blight. The machine learning model with the data from the sensors was able to catch the disease's presence earlier than traditional tests did. I read this article because I'm interested in biosensors and botany, and this study seemed like an interesting intersection of the two. I'm also curious about the large-scale impacts this type of technology can have in increasing agriculture efficiency as well as making home-gardening easier. I'd like to learn more about the kind of nanotechnology and tools required to build a biosensor for plants, similar to this one.
Research Question/Problem/ Need	How can plant health be continuously tracked in real time to allow early diagnosis of disease?
Important Figures	 Images of plant biosensor and components
VOCAB: (w/definition)	Volatile organic compounds (VOC): Low-molecular-weight carbon compounds with high vapor pressure that plants release into the atmosphere or soil, serving as signals for various functions Transpiration: process where plants absorb water through their roots and then release it as vapor through tiny pores in their leaves called stomata Abaxial: side of a plant organ that is positioned away from its central axis or stem Multimodal: several different modes of activity

Cited references to follow up on	Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., & Nelson, A. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecology & Evolution*, *3*(3), 430–439. https://doi.org/10.1038/s41559-018-0793-y Ristaino, J. B., Anderson, P. K., Bebber, D. P., Brauman, K. A., Cunniffe, N. J., Fedoroff, N. V., Finegold, C., Garrett, K. A., Gilligan, C. A., Jones, C. M., Martin, M. D., MacDonald, G. K., Neenan, P., Records, A., Schmale, D. G., Tateosian, L., & Wei, Q. (2021). The persistent threat of emerging plant disease pandemics to Global Food Security. *Proceedings of the National Academy of Sciences*, *118*(23). https://doi.org/10.1073/pnas.2022239118
Follow up Questions	1. How do the electrodes measure the VOCs? Through conductivity? 2. Can this patch be used on any plant leaf or is it only optimized for tomatoes? 3. How durable is the patch? Will it hold throughout different weather conditions outside?

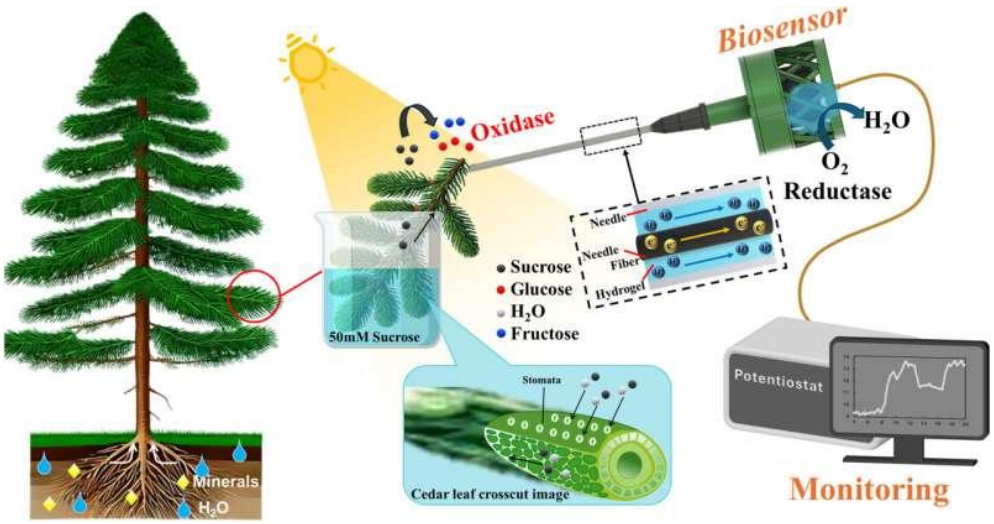
Notes:

- Plant diseases cause major crop loss every year
- Wearable biosensors can help detect disease early and reduce spread
- Scientists at NC State University made a thin, film-like biosensor for tomato plants
- The biosensor attaches to the underside of a tomato leaf (abaxial)
- 7 sensors total:
    - 4 for leaf VOCs (volatile organic compounds)
    - 1 for leaf surface humidity
    - 1 for leaf temperature
    - 1 for environment humidity
- Biosensor uses nanotech: Au@AgNWs + multiwalled carbon nanotubes in a hydrophobic sol-gel layer
- Purpose: monitor plant health for biochemical + biophysical signs of disease

- Data is processed by a machine learning model → analyzes health and predicts disease risk
- Testing:
    - Exposed plants to abiotic stress (drought, overwatering, salinity, darkness).
    - Sensor results were consistent across 3 trials.
    - Data matched expected patterns (ex: more leaf humidity with overwatering).
- Machine learning + sensors detected disease earlier than traditional tests.

Article #4 Notes: Novel biosensor allows real-time monitoring of sucrose uptake in plants

Source Title	Novel biosensor allows real-time monitoring of sucrose uptake in plants
Source citation (APA Format)	Waseda University. (2025, July 15). *Novel biosensor allows real-time monitoring of sucrose uptake in plants*. Phys.org. https://phys.org/news/2025-07-biosensor-real-sucrose-uptake.html
Original URL	https://phys.org/news/2025-07-biosensor-real-sucrose-uptake.html
Source type	Website (News from Phys.org)
Keywords	In vivo, sucrose, biosensor, enzyme, anode
#Tags	Biosensor, sucrose, real-time montioring
Summary of key points + notes (include methodology)	Sucrose is an essential molecule in plants, as it is the main sugar transported through a plant. It can reveal a lot about a plant's state of development and stress. However, there was no way to track sucrose in living plants in real time until now. Sucrose is always moving through the plant based on the time of day, which is what makes it difficult to measure. A flexible, needle-like biosensor has been created by a team at Waseda University. The sensor is inserted into the plant tissue to track sucrose concentrations. The sensor is created from a multi-enzyme anode (the enzymes being glucose oxidase, invertase, and mutarotase) and an agarose gel interface. The sensor measures sucrose through the stomata (plant openings in the leaf). It works efficiently with a response time of 90 seconds, and for 72 hours. Because of this, the sensor is not ready to be used in agricultural settings where extended monitoring is required. However, researchers hope to develop the biosensor so that it can work for longer periods of time, helping farmers with crop yield optimization, stress detection, and growth modeling. The researchers conducted an experiment to confirm the biosensor's accuracy. It measured a daily pattern in sucrose uptake, where levels peaked at night. This matches the known growth and transportation cycles of sucrose in plants. They also submerged cedar leaves in a sucrose solution in the light and dark. The sensor only measured sucrose levels rising in the light, which is when the stomata open. This suggests that sucrose can be absorbed through the leaves of a plant and transported. I chose this article because I'm interested in biosensors for plants. Specifically, I'm interested in their role in helping agricultural efforts in crop disease prevention. This biosensor is similar to the technology in my article #2, but only focuses on sucrose, whereas article #2 was a multi-sensor. I hope to learn

	more about this kind of biotechnology and what goes into developing these kinds of sensors. This biosensor is slightly different and seems less complex than the one in article #2, making me wonder if it may be feasible to create one for my STEM project.
Research Question/Problem/ Need	Tracking sucrose in real time within living plants is a challenge.
Important Figures	 Graphic of experiment setup and how biosensor monitors sucrose
VOCAB: (w/definition)	In vivo: performed or taking place in a living organism Sucrose: vital form of stored energy and transported sugar; disaccharide made of glucose and fructose Enzyme: protein that acts as a biological catalyst, accelerating reactions Anode: positively charged electrode by which the electrons leave a device
Cited references to follow up on	Boanares, D., Isaias, R. R., de Sousa, H. C., & Kozovits, A. R. (2018). Strategies of leaf water uptake based on anatomical traits. *Plant Biology*, *20*(5), 848–856. https://doi.org/10.1111/plb.12832 Chen, H., Zhou, S., Chen, J., Zhou, J., Fan, K., Pan, Y., & Ping, J. (2024). An integrated plant glucose monitoring system based on Microneedle-enabled electrochemical sensor. *Biosensors and Bioelectronics*, *248*, 115964. https://doi.org/10.1016/j.bios.2023.115964

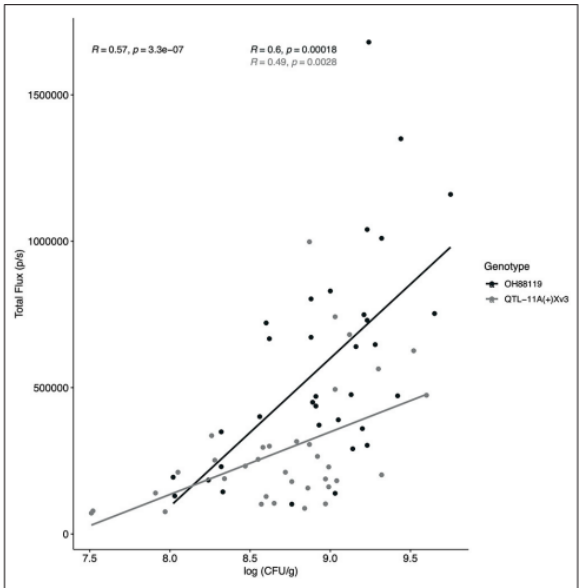
	Gavrilaș, S., Ursachi, C. Ștefan, Perța-Crișan, S., & Munteanu, F.-D. (2022). Recent trends in Biosensors for Environmental Quality Monitoring. *Sensors*, *22*(4), 1513. https://doi.org/10.3390/s22041513
Follow up Questions	What prevents the sensor from being used in a farm setting and how can it be overcome? How were the enzymes chosen and developed to track sucrose concentrations? How can the tracking be turned remote instead of having to be connected to a computer?

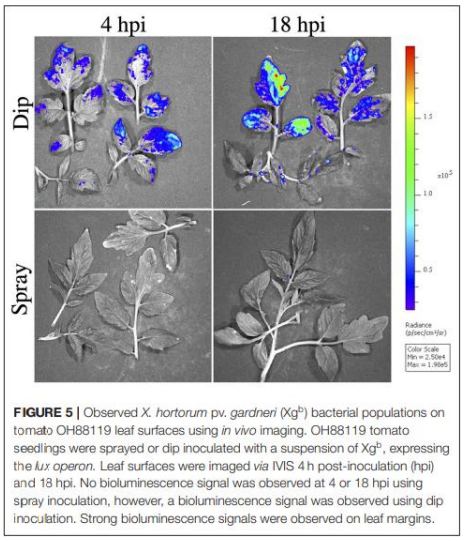
Notes:

- Sucrose = main sugar transported in plants, shows plant development + stress
- Hard to measure in real time because sucrose is always moving in the plant
- Waseda University team created a flexible, needle-like biosensor
- Sensor is inserted into plant tissue to track sucrose concentration
- Built from:
    - Multi-enzyme anode (glucose oxidase, invertase, mutarotase)
    - Agarose gel interface
    - Sensor works through the stomata (leaf openings)
- Response time = 90 seconds
- Works up to 72 hours → not yet long enough for farm use
- Goal: improve sensor for long-term monitoring → could help with crop yield, stress detection, growth modeling
- Experiments to test accuracy:
    - Tracked daily sucrose cycle → levels peak at night (matches known plant cycles).
    - Cedar leaves in sucrose solution (light vs. dark) → only absorbed sucrose in light (when stomata open).
- Shows sucrose can be absorbed through leaves and transported.

Article #5 Notes: Bioluminescent *Xanthomonas hortorum* pv. *gardneri* as a Tool to Quantify Bacteria *in Planta*, Screen Germplasm, and Identify Infection Routes on Leaf Surfaces

Source Title	Bioluminescent *Xanthomonas hortorum* pv. *gardneri* as a Tool to Quantify Bacteria *in Planta*, Screen Germplasm, and Identify Infection Routes on Leaf Surfaces
Source citation (APA Format)	Bernal, E., Deblais, L., Rajashekara, G., & Francis, D. M. (2021). Bioluminescent Xanthomonas Hortorum pv. Gardneri as a tool to quantify bacteria in planta, screen germplasm, and identify infection routes on leaf surfaces. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.667351
Original URL	https://doi.org/10.3389/fpls.2021.667351
Source type	Journal Article
Keywords	bacterial spot, phenotyping, tomato, Solanum lycopersicum, disease screening, heritability
#Tags	Bioluminescence, bacteria, tomato, plant disease, Xanthomonas hortorum pv. gardneri
Summary of key points + notes (include methodology)	The researchers created a bioluminescent strain of Xanthomonas hortorum pv. gardneri (Xg^b), which carries the luxCDABE operon plus a kanamycin resistance marker, to track bacterial growth in tomato plants without destroying the tissue. They used this strain to test if bioluminescence (light emission) correlates with actual bacterial numbers (measured by CFU counts), and found a significant positive correlation, r=0.57, indicating the luminescence is a good estimate for bacterial population size. The study compared resistant tomato genotypes (NIL QTL-11A) with susceptible control (OH88119), and found that resistant plants show lower light emission and lower CFU over time. They also compared how accurate the bioluminescence imaging method is versus traditional field disease ratings. Field ratings had higher heritability and reliability, but the IVIS method was much faster (30 days<90–120 days). Using SEM (scanning electron microscopy) plus IVIS, the researchers observed that bacteria tend to localize more at leaf edges near hydathodes (openings at edges, suggesting hydathodes are potential

	entry points. There are 2 inoculation methods: dip inoculation gives more rapid and uniform bacterial colonization, meanwhile spray inoculation led to slower detection. Hydathode pores are longer and wider than stomata which is how bacteria enter. The authors calculated heritability for the traits: field ratings had heritability ≈ 0.86, while bioluminescence imaging had heritability ≈ 0.58. This means genetic differences explain more of the variation in field disease severity than in bioluminescent signals. So, bioluminescence imaging is not very accurate for heritability, but it is much faster and can give a good quantification for bacteria colony count.
Research Question/Problem/ Need	How can bioluminescence be utilized to estimate bacterial populations i*n planta*?
Important Figures	 **FIGURE 2 |** Regression analysis between Total Flux (p/s) measured through IVIS and bacterial populations. An *X. hortorum* pv. *gardneri* strain, Xg^b, expressing the *lux operon* was developed to visualize and quantify bacteria *in planta*. Regression analysis was conducted to compare total flux (p/s) as measured through IVIS and $\log_{10}$ of bacterial populations in tomato leaf tissue (CFU/g). Bacterial colonies were counted at seven time points using resistant NIL, QTL-11A + *Xv3*, and the susceptible genotype OH88119. The regression experiment was conducted twice, the figure represents all data points. A significant and positive relationship was observed for combined data ($R = 0.57$, $p < -0.0001$) resistant NIL (gray line and points; $R = 0.49$, $p < -0.0028$) and susceptible, OH88119 (black line and points; $R = 0.6$, $p < -0.0002$). Graph of Total flux vs log (CFU/g) for wild type and resistant strain of tomatoes. Difference in slope is due to tomato strain's genetic differences p value <0.0002, significant data for both lines

	 **FIGURE 5 |** Observed *X. hortorum* pv. *gardneri* (Xg^b) bacterial populations on tomato OH88119 leaf surfaces using *in vivo* imaging. OH88119 tomato seedlings were sprayed or dip inoculated with a suspension of Xg^b, expressing the *lux operon*. Leaf surfaces were imaged *via* IVIS 4 h post-inoculation (hpi) and 18 hpi. No bioluminescence signal was observed at 4 or 18 hpi using spray inoculation, however, a bioluminescence signal was observed using dip inoculation. Strong bioluminescence signals were observed on leaf margins. Chart of plant luminescent 4 and 18 hours after inoculation for both spray and dip methods. Luminescence concentrates on leaf edges for dip while spray emits no light.
VOCAB: (w/definition)	Xgb: bioluminescent strain of *Xanthomonas hortorum* pv. *Gardneri* Horsfall-Barratt Scale: way to assess severity of plant disease using 12 intervals developed by James G. Horsfall and R.W. Barratt Spray and dip inoculation: Spray bacteria onto leaf or dip leaves into bacteria culture Hpi: hours past inoculation Inoculation: act of introducing pathogens into a living organism Pathogen: bacteria, virus, or other microorganism that causes disease Heritability: how much variation in a trait (disease resistance) is due to genetic differences rather than environmental/chance
Cited references to follow up on	Dane, F., & Dane, M. H. (1994). Growth of bioluminescent xanthomonas campestris pv. Vesicatoria in tomato cultivars. *HortScience*, *29*(9), 1037–1038. https://doi.org/10.21273/hortsci.29.9.1037
Follow up Questions	How can IVIS imaging increase the heritability of disease screening to make it more accurate? Can the bioluminescent signals be strengthened so IVIS imaging is not needed? Can the hydathodes be protected so the bacteria cannot enter, reducing risk of plant disease?

Notes:

Introduction

- Bioluminescence imaging is widely used to visualize cells

- *luxCDABE* (section of DNA from bacteria that codes for enzyme and substrate for luciferase)
- *luxCDABE* has 5 genes, creates blue/green light
- Bioluminescence signals are generally well-correlated with bacterial populations in planta = non-invasive technique to localize and measure the growth of pathogens in different pathosystems (system of host and parasite)
- Bioluminescence imaging can measure quantitative variation in bacterial growth
- So, it has been used to identify resistant and susceptible germplasm (parts that carry DNA: seeds, pollen, etc.)
- Past study measured bioluminescent *Xanthomonas campestris pv. Campestris* (bacteria that infects common crops, broccoli, arabdopsis) effects on cabbage
- Another past study shows growth differences in Xanthomonas campestris pv. vesicatoria (now X. euvesicatoria) (tomato pathogen) on resistant and susceptible tomatoes
- So, bioluminescence can be used to study plant-host interactions
- Hydathodes are referred to as water stomata due to their function in discharging water from the inner leaf, in a process known as guttation
- GOAL: to describe the infection process by X. hortorum pv. gardneri (formerly X. gardneri) on tomato through bioluminescence imaging technology
- The main objectives of this study were (i) to quantify bioluminescence signals as a function of bacterial growth in tomato seedlings, (ii) to determine whether bioluminescence can be used to differentiate between tomato lines resistant and susceptible to X. hortorum pv. gardneri, (iii) to compare the accuracy of field disease ratings and bioluminescence seedling screening assays, and (iv) to observe X. hortorum pv. gardneri colonization of the tomato leaf surface

Materials + Methods:

Plant Material and Greenhouse Conditions

- Germplasm in this study (tomato lines) bred to resist 3 bacteria pathogens (X. hortorum pv. Gardneri, X. perforans, X. euvesicatoria)
- They used wild tomatoes (PI 114490, LA2533), breeding lines (01-BR-7087, FG12-433E-43, OH087633), advanced NILs with QTL11, and a susceptible control (OH88119).
- The NILs are basically OH88119 with resistance genes/QTLs added in, making it easy to see the effect of just those resistance regions.
- Breeding line = a research tomato line with useful traits.
- NIL = a line that is the same as a susceptible tomato, except it has one resistance gene/QTL.
- QTL11 NILs = those NILs that carry resistance pieces from chromosome 11, carefully bred so we can study resistance clearly.
- Tomato seedlings grown at Biosafety Level 2 at Ohio State University, in greenhouse at 23-28 C, 14 h light, 10 h dark, in a 3ft pipe covered in plastic so that it stays 70-95% humidity (good for bacteria)

Construction of Bioluminescent X. hortorum pv. gardneri (Xgb)

- Goal: make *X. hortorum pv. gardneri* bacteria that glows (with lux operon) AND survive kanamycin antibiotic (with kanamycin resistance gene (kanR))

- Why? They insert lux operon and kanamycin resistance. Not all bacteria will pick up the lux operon. They spread bacteria onto agar plates with kanamycin. The plants that die are the ones that did not pick kanamycin resistance (and therefore also lux operon). Now you are left only with bacteria that picked up lux operon.
- How? Prepare bacteria for DNA uptake with centrifuge and suspend in glycerol. Then electroporation, allows DNA to enter cells. DNA (lux + kan cassette → kanR gene, promoter)) Adds SOC medium (food) for cells to recover after electroporation, incubated at 28 C and shaken for 3 hours. Plate bacteria on agar with kanamycin, only bacteria with lux-kan cassette survive, colonies grow after 72 hours. Check glowing colonies with pcr → band 1221 bp, confirmed

Bacterial Strain and Inoculum Preparation

- Prep and inoculated → apply (spray or dip) plants with Xgb (glowing bacteria)
- 1. Grow Bioluminescent Xgb in NBY medium (nutrient broth + yeast extract) with **50 μg/ml kanamycin** → keeps only the engineered bacteria alive (others die). Kept at 28 C
- Suspended bacteria in sterile water
- Spray inoculation: compressed air sprayer sprays bacteria suspension onto leaves to runoff (until liquid starts dripping). Mimics how bacteria spreads through rain (natural infection)
- Dip inoculation: Tomato seedlings upside down and dipped into bacteria for 30 seconds (bacteria can enter through pores or wounds all over, more controlled)

Bacterial Spot Evaluation in the Field

- Summers of 2016, 2017, 2018
- Bacteria strain of SM775-12 grown in NYB agar at 28 C for 2-3 days
- Plants inoculated with spray, transplanted to field after 1 week
- Used Horsfall-Barratt bacterial spot severity (1-12) rating
- Susceptible and resistant tomato controls
- Took ratings when ~80% of fruits mature green and when ~80% fruits ripe

Quantification of Bacterial Growth in planta:

- Tested Resistant and Susceptible lines of tomatoes
- 4 week old seedlings, placed in humidity chamber 2 days before inoculation
- Spray inoculated in morning with bioluminescent Xgb, kept in chamber for 48 hours to promote disease
- 2 experiments, first measured 3,4,5,8,9 days after; second measured 3,4,5,6,7,8,9 days after
- Collected 3 leaflets from each plant and recorded Total flux (p/sec) and Radiance, light per area per solid angle with camera (IVIS Lumina III system)
- After imaging, plants are weighed, macerated in water to release bacteria, water diluted, drops put on plates of agar + kanamycin so that only Xgb bacteria grows
- 26 hours after, bacteria colony counted measured by CFU per gram

Analysis of Tomato Germplasm With IVIS:

- Randomized seeds with NIL, wild, susceptible, spray inoculated, stayed in chamber for 48 h, imaged after 9 days

Scanning Electron Microscopy (microscope) Imaging of Leaf Natural Openings

- Goal: see how Xgb is distributed on leaves (could be top adaxial, bottom, abaxial, or edges)

- Used susceptible tomato line, spray and dip 4 seedlings each, humidity chamber, imaged at 4 and 18 hours to detect glowing bacteria
- Cut 1mm-1mm from leaf and uninfected leaf tissue for comparison
- Preserve tissue with chemicals
- Imaged with IVIS to see where bacteria sits
- Used FIJI to standardize images
- Overlaid grid on image and measured Number of natural openings (stomata, hydathodes), Size of openings, Density of bacteria within each grid square
- Gives precise, quantitative data about bacteria density

Bacterial Growth Analysis:

- They used the Log CFU/g (actual bacteria numbers per gram) and Total flux (light emitted)
- Linear model (Analysis of Variance) to see how genotype, experiment, day, and replicate affect bacterial growth

Plant Germplasm Screening

- They analyzed IVIS radiance and field disease ratings for each tomato genotype.
- Used ANOVA for NILs and BLUPs to normalize data across experiments and years.
- Calculated heritability → how much resistance is genetic.
- Calculated reliability → how consistent measurements are across experiments/years.

Analysis of Natural Openings and Bacterial Colonization

- They put grids over SEM images to measure openings and count bacteria systematically.
- Measured size of stomata/hydathodes using ANOVA.
- Counted bacteria in each grid and used chi-square tests to see if they are randomly spread or concentrated in certain areas.

Results:

Verification of Bioluminescent X. hortorum pv. gardneri Transformation:

- Bacteria glow and have the kanamycin gene.
- The inserted genes are **stable over generations**.
- Growth in lab media and plants is **unchanged** compared to normal bacteria.
- This confirms that using **bioluminescence is a valid way to track bacterial growth in tomatoes**.

Quantification of X. hortorum pv. gardneri Populations by IVIS and Dilution Plating:

- Susceptible line OH88119: higher bioluminescent signals → more bacterial growth.
- Resistant line QTL11A (+) Xv3: lower bioluminescent signals → less bacterial growth.
- Peak light levels (Total Flux) occurred on day 5–6 for both lines.
- CFU/g of leaf tissue also confirmed differences:
- Resistant line had fewer bacteria.
- Both IVIS Total Flux and CFU measurements show statistically significant differences between genotypes:
- Total Flux: $F(1,55) = 16.60$, $p \leq 0.001$
- CFU/g: $F(1,55) = 10.12$, $p \leq 0.002$

In vivo Imaging System vs. Field Screening of Genotypes

- Susceptible OH88119 had **higher average radiance** than resistant QTL11A only and QTL11A (+) Xv3
- Bioluminescence location: signal at leaf edges suggests bacteria may enter through hydathodes.
- IVIS average radiance:
- Genetics explained 25% of variance.
- Residual error explained 63%.
- Heritability = 0.58, reliability = 0.25
- Field ratings:
- Genetics explained 63% of variance.
- Residual error = 30%, year = 6%, within-field negligible.
- Heritability = 0.86, reliability = 0.63
- IVIS is not as accurate, but much faster (24 days) while Field Trials (rating 1-12, done in the field so you need to wait for plants to grow, get infected, ripen) is 90-120 days

The Tomato Leaf and Bacterial Colonization

- IVIS bioluminescence showed that bacteria often enter through leaf margins, likely via hydathodes (special openings that release water and are bigger than stomata).
- SEM (scanning electron microscopy) confirmed this and allowed them to measure natural openings.
- Spray inoculation:
    - Light detected after 3 days.
    - Symptoms were not visible for up to 9 days.
    - Light first appears at leaf margins.
- Dip inoculation with surfactant (Silwett L77):
    - Light detected very early (4 and 18 hours).
    - Light spreads across the whole leaf.
    - Symptoms appear necrotic at 48–72 hours in susceptible leaves.
- Dip → rapid, uniform infection.
- Spray → slower, concentrated at leaf edges.
- Bioluminescence detects infection before symptoms appear, allowing faster tracking than visual observation.
- Dip inoculation causes more bacteria to contact leaf with better entry points all over, faster infection

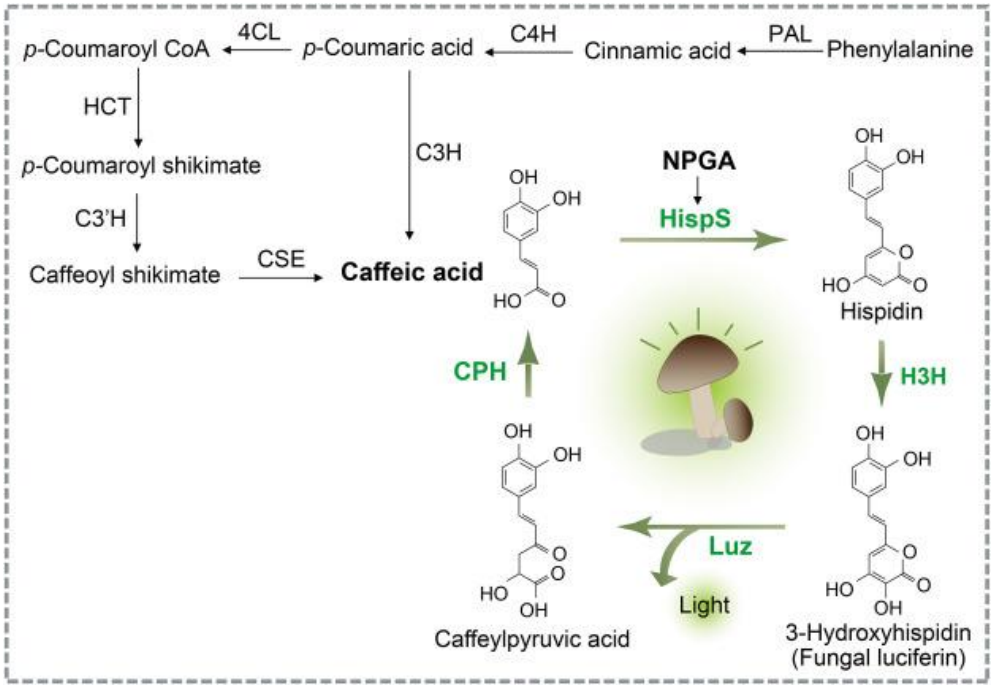
Discussion:

- In this study, we utilized an X. hortorum pv. gardneri strain expressing the lux operon, Xgb, to study infection and assess disease severity in resistant and susceptible tomato lines.
- A positive and significant correlation between bioluminescence signals and bacterial populations in planta has been observed in other plant-host interactions including R. solanacearum on pepper and potato, C. michiganesis subsp. michiganesis on tomato, and X. campestris pv. vesicatoria (now X. euvesicatoria) on tomato (Dane and Dane, 1994; Xu et al., 2010; Cruz et al., 2014; Du et al., 2017).

- We further explored the use of the bioluminescent X. hortorum pv. gardneri for rapid screening of germplasm.
- Screening based on total flux resulted in lower estimates of heritability and reliability relative to field screens, suggesting that the technique provided less accuracy in measuring genetic signals and for separating germplasm relative to classical field-based phenotyping.
- Next Steps: It may be possible to increase the heritability of disease screening using IVIS by accounting for morphological features and growth
- suggest that bacteria are adhering to all leaf surfaces when dipped, but when sprayed the bacteria showed greater density on the abaxial and adaxial sides compared to the leaf edge. However, at 18 hpi both spray and dip inoculation showed a higher density of bacteria on leaf edges.
- These water pores are longer and wider than stomata and tend to exude extracellular fluid containing sugars, vitamins, and other solutes that may promote a conducive environment for bacterial growth and colonization
- The distribution of bacteria as quantified by SEM and bioluminescence patterns suggest hydathode pores may be entry points for X. hortorum pv. gardneri.

Article #6 Notes: Advances and applications of the fungal bioluminescence pathway

Source Title	Advances and applications of the fungal bioluminescence pathway
Source citation (APA Format)	Li, Y., Xu, D., & Du, H. (2025a). Advances and applications of the fungal bioluminescence pathway. *Crop Design*, *4*(3), 100111. https://doi.org/10.1016/j.cropd.2025.100111
Original URL	https://doi.org/10.1016/j.cropd.2025.100111
Source type	Review Article
Keywords	Fungal bioluminescence pathway, Tracing technologies, Auto-bioluminescent plants, Biosensing, Artificial intelligence
#Tags	Review, Fungal bioluminescence pathway (FBP), luciferase
Summary of key points + notes (include methodology)	Bioluminescence is widely used in research but has constraints. Some are that it does not have enough light intensity and needs special imaging to view, and needs external substrates to work. Fungal bioluminescence pathway is a natural biological system that produces light in fungi. A 2018 discovery revealed the cyclic metabolic design of FBP with 4 enzymes (HispS (hispidin synthase), H3H (3-hydroxyhispidin hydrolase), Luz (luciferase), and CPH (caffeylpyruvic acid hydrolase)). Some benefits to FBP is that it is self-sustaining so it can be a great platform to create auto-luminescent plants. The output of light by FBP can also be increased by modifying conflicting pathways in the plant. With FBP, bioluminescent sensors can be created for non-invasive optical imaging. Some challenges of FBP include its large gene cluster size, complex host expression requirements, limited thermal stability, and suboptimal brightness. However, many advancements have looked at solutions to solve these problems to use FBP as a method for non-invasive monitoring tool.
Research Question/Problem/ Need	What has been accomplished in the study of the fungal bioluminescent pathway, and what might come in the future?

Important Figures	 Model of enzymes in caffeic acid cycle. This cycle produces light (bioluminescence)
VOCAB: (w/definition)	Fungal bioluminescence pathway: self-sustained, genetically encoded metabolic pathway that allows fungi and other organisms to produce light, converting caffeic acid into luciferin and then emitting green light via a luciferase enzyme Auto-bioluminescent plants: genetically modified plants that produce their own light through a biological process, without needing an external chemical or energy source Biosensing: process of using a biological recognition element with a physical transducer to detect and measure substances in a given sample, converting the interaction into a readable signal
Cited references to follow up on	Fleiss, A., Sarkisyan, K.S. A brief review of bioluminescent systems (2019*). Curr Genet 65*, 877–882 (2019). https://doi.org/10.1007/s00294-019-00951-5 Yeh, H.-W., & Ai, H.-W. (2019). Development and applications of bioluminescent and chemiluminescent reporters and biosensors. *Annual Review of Analytical Chemistry*, *12*(1), 129–150. https://doi.org/10.1146/annurev-anchem-061318-115027

	Khakhar, A., Starker, C. G., Chamness, J. C., Lee, N., Stokke, S., Wang, C., Swanson, R., Rizvi, F., Imaizumi, T., & Voytas, D. F. (2020). Building customizable auto-luminescent luciferase-based reporters in plants. *eLife*, *9*. https://doi.org/10.7554/elife.52786
Follow up Questions	1) How did FBP evolve in fungi? 2) Can FBP be applied to mammals? Do mammals share these same 4 enzymes? 3) How did previous bacterial systems of bioluminescence for plants work? Why were they ineffective? How is FBP a better choice?

Notes

- Bioluminescence is widely used in research but has constraints
- Constraints: not enough light intensity (need instruments to view), needs external substrate
- 2018 discovery revealed cyclic metabolic system involving four core enzymes: HispS (hispidin synthase), H3H (3-hydroxyhispidin hydrolase), Luz (luciferase), and CPH (caffeylpyruvic acid hydrolase) of FBP
- FBP can be enhanced through post-translational modification of HispS by NPGA (non-ribosomal peptide synthetase-type glutathione S-transferase) from Aspergillus nidulans (creates more light intensity)
- Pros to FBP: self-sustaining so it can be a great platform to create auto-luminescent plants
- FBP enabled development of autoluminescent Nicotiana tabacum and N. benthamiana plants exhibiting approximately tenfold greater brightness than previous bacterial systems
- FBP reporter system = luminescence-based approach for studying TF-promoter interactions through co-expression of FBP enzymes in plant cells coupled with placement of the Luz reporter gene downstream of target promoters
- FRET, BRET - Non-invasive optical imaging techniques based on Förster resonance energy transfer
- FBP-based BRET biosensor created by coupling the fungal Neonothopanus nambi nnLuz luciferase with fluorescent proteins

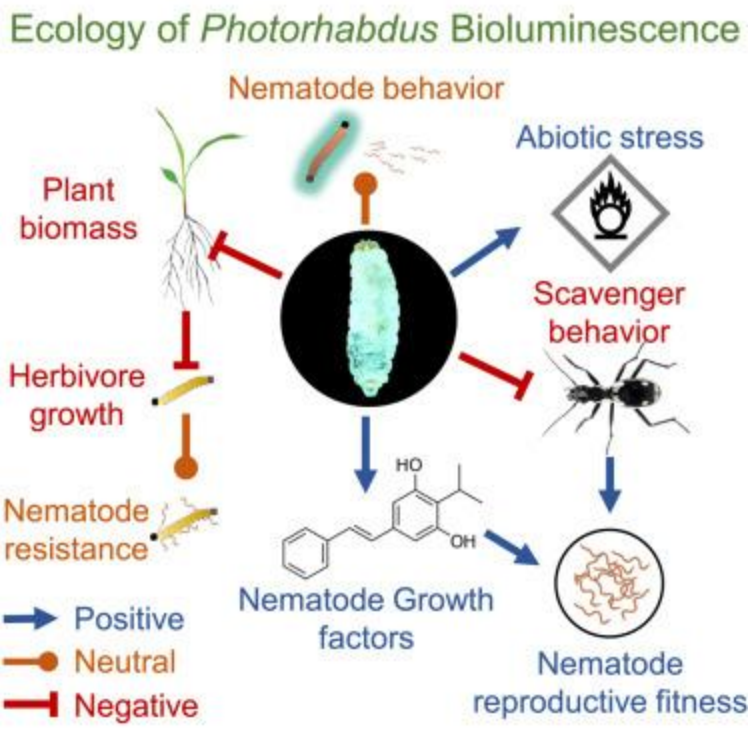
Challenges + Future

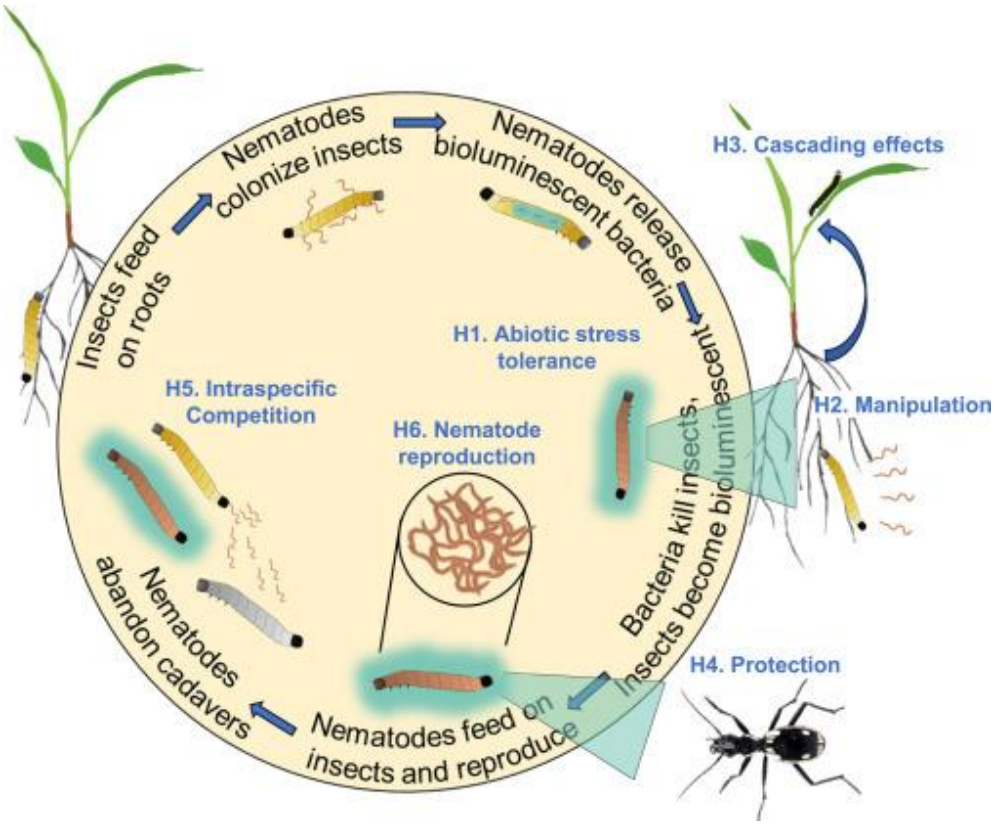
- FBP: large gene cluster size, complex host expression requirements, limited thermal stability, and suboptimal brightness
- Many advances have addressed solutions to this
- AI is advancing protein design

- Computationally designed fluorescence-activating transmembrane proteins overcomes traditional limitations
- Enables faster protein modification, creation

Article #7 Notes: Bacterial bioluminescence is an important regulator of multitrophic interactions in the soil

Source Title	Bacterial bioluminescence is an important regulator of multitrophic interactions in the soil
Source citation (APA Format)	Muller, A., Morales-Montero, P., Boss, A., Hiltmann, A., Castaneda-Alvarez, C., Bhat, A. H., Arce, C. C. M., Glauser, G., Joyce, S. A., Clarke, D. J., & Machado, R. A. R. (2024). Bacterial bioluminescence is an important regulator of multitrophic interactions in the soil. *Cell Reports*, *43*(10), 114817. https://doi.org/10.1016/j.celrep.2024.114817
Original URL	https://doi.org/10.1016/j.celrep.2024.114817
Source type	Research Article
Keywords	chemical and molecular ecology, entomopathogenic nematodes, Photorhabdus bacteria, plants, root herbivores, scavenger insects
#Tags	entomopathogenic nematodes, Photorhabdus bacteria, root herbivores, scavenger insects
Summary of key points + notes (include methodology)	- Bioluminescence relevance to soil ecosystems not been studied - Entomopathogenic Nematode = parasites of insects that serve as biological control agents - Photorhabdus bacteria = only known bioluminescent soil bacteria; pathogen of insects that forms a mutualistic relationship with nematodes of the Heterorhabditis family, colonizing the nematode's gut and facilitating the insect's death to support nematode growth and development. - Some earthworms, potworms release bioluminescent substances upon stimulation, bioluminescence may act as an anti-predator defense - Photorhabdus bacteria used as a model

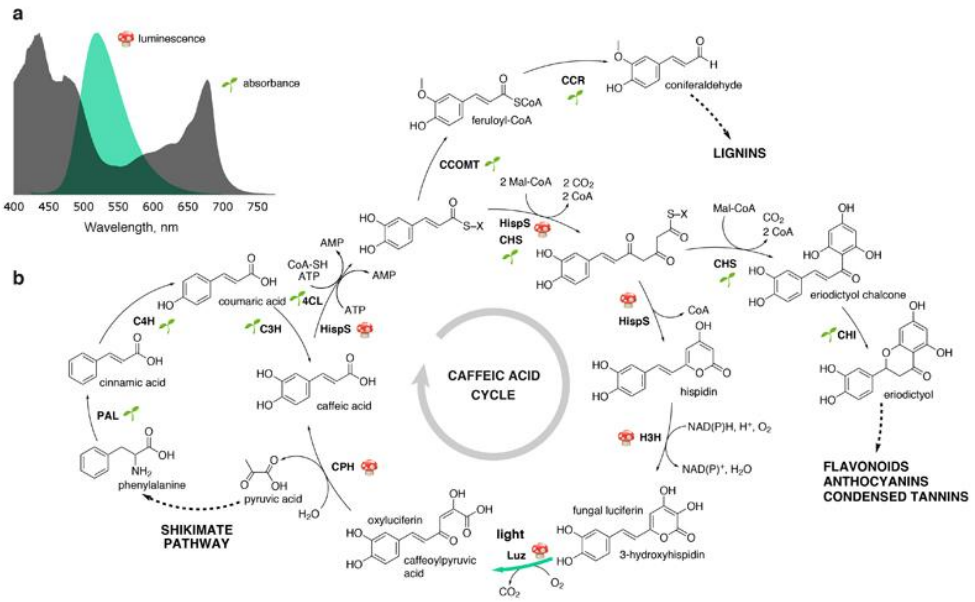
	- Nematodes transport bacteria into soil insects → bacteria produce toxins that kill insect → during this bacteria is bioluminescent (and makes insect bioluminescent) → nematodes feed on insect tissues and reproduce → bacteria colonize intestine of developing nematode → Pair goes to find new host - Studied 59 strains of bacteria - Measured its light produced in vivo and in vitro (lab cultures) - Lots of variability between species and in same species - Differences persisted even after they standardized bacterial density - Related species had similar levels of bioluminescence, but age of species does not correlate to bright or dim
Research Question/Problem/ Need	How does bioluminescence affect the soil ecosystem?
Important Figures	 Graphic of ecology of *Photorhabdus Bioluminescence* and its affects on ecosystem

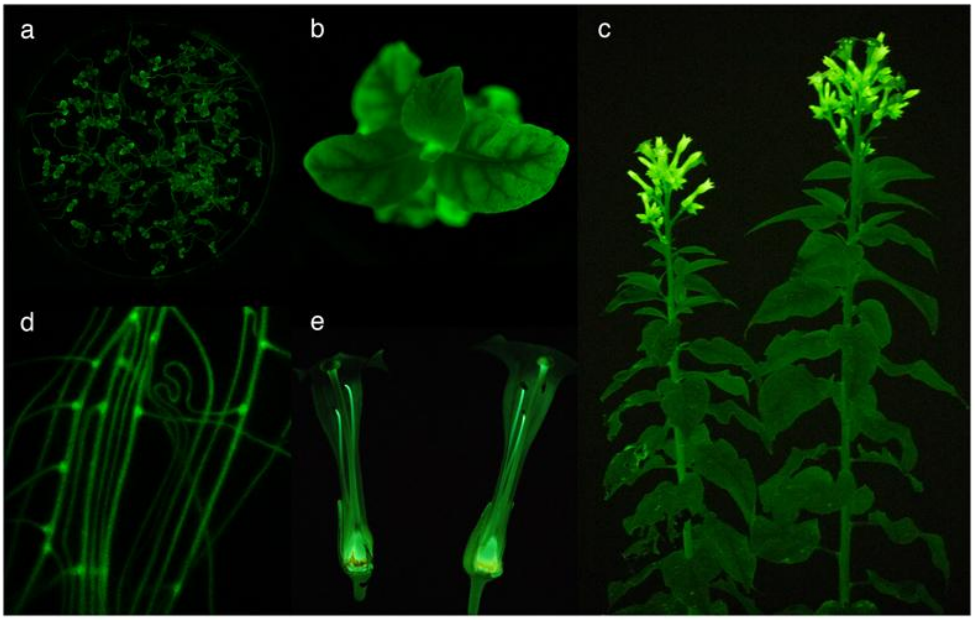
	 Cyclical model of Nematode life cycle and how they infect plants
VOCAB: (w/definition)	entomopathogenic nematodes: microscopic, non-segmented roundworms that naturally parasitize and kill insects by releasing symbiotic bacteria from their gut once inside the host Photorhabdus bacteria: The bioluminescent bacteria which the nematodes release from their gut root herbivores: soil-dwelling animals, particularly invertebrates like wireworms and root-feeding nematodes, that feed on plant roots, damaging plants and influencing the composition of the below-ground soil ecosystem scavenger insects: organisms that consume dead plants, animals, waste, or decaying organic matter
Cited references to follow up on	Lau, E. S., & Oakley, T. H. (2020). Multi-level convergence of complex traits and the evolution of bioluminescence. *Biological Reviews*, *96*(2), 673–691. https://doi.org/10.1111/brv.12672

	Nealson, K. H., & Hastings, J. W. (1979). Bacterial bioluminescence: Its control and ecological significance. *Microbiological Reviews*, *43*(4), 496–518. https://doi.org/10.1128/mr.43.4.496-518.1979 Delroisse, J., Duchatelet, L., Flammang, P., & Mallefet, J. (2021). Leaving the dark side? Insights into the evolution of Luciferases. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.673620
Follow up Questions	- How did the bioluminescence of *Photorhabdus* evolve? - How would the soil ecosystem be affected if *Photorhabdus* was not bioluminescent? - What enzymes do *Photorhabdus* use? Can those enzymes be extracted and manipulated from them?

Article #8 Notes: Plants with genetically encoded autoluminescence

Source Title	Plants with genetically encoded autoluminescence
Source citation (APA Format)	Mitiouchkina, T., Mishin, A. S., Somermeyer, L. G., Markina, N. M., Chepurnyh, T. V., Guglya, E. B., Karataeva, T. A., Palkina, K. A., Shakhova, E. S., Fakhranurova, L. I., Chekova, S. V., Tsarkova, A. S., Golubev, Y. V., Negrebetsky, V. V., Dolgushin, S. A., Shalaev, P. V., Shlykov, D., Melnik, O. A., Shipunova, V. O., … Sarkisyan, K. S. (2020). Plants with genetically encoded autoluminescence. *Nature Biotechnology*, *38*(8), 944–946. https://doi.org/10.1038/s41587-020-0500-9
Original URL	https://doi.org/10.1038/s41587-020-0500-9
Source type	Research Article
Keywords	Autoluminescence, *Nicotiana tabacum*, Agrobacterium-mediated transfer, luciferin, caffeic acid cycle
#Tags	Autoluminescence, Agrobacterium-mediated transfer, caffeic acid cycle
Summary of key points + notes (include methodology)	- Plants with genetically autoluminescence due to low light output - Authors used natural caffeic acid in plant and turned into luciferin - Mimics process of bioluminescent fungi - Done on *Nicotiana tabacum* and *benthamiana* - Benefit: no external substrate needed (so it can be useful for plants grown in soil instead of lab setting) - Engineered via random-site genome integration using Agrobacterium-mediated transformation - Light emissions were visible at all stages, but flowers emitted the most - Bright luminescence developed instantly following injections of luciferin or hispidin - lower intensity was produced more slowly with caffeic acid - Increased light emission at injured leaves - Aging leaves gradually lose light emission with decreasing caffeic acid

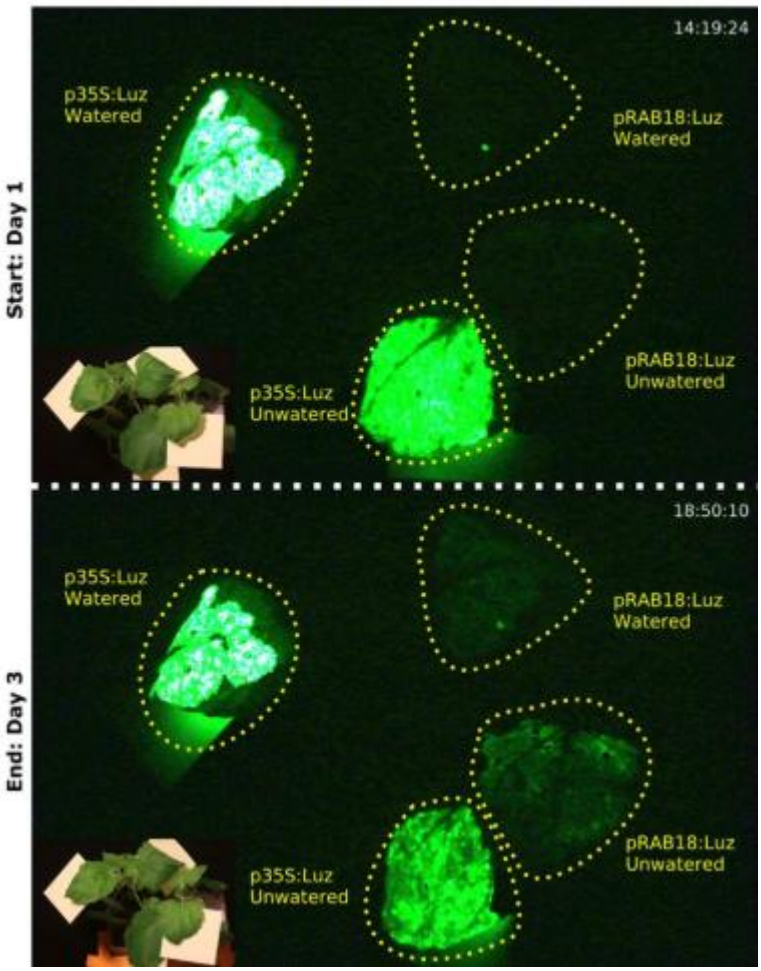
	- Dramatically increased light when plant treated with ethylene (ripe banana skin) → causes more enzyme production - Agrobacterium-mediated transfer: Bacteria grown overnight, diluted in liquid medium Leaf explants cut from 2 week old plants incubated with bacteria culture for 20 minutes Leaves placed on filter paper on MS medium Transferred to medium after 2 days Regeneration shoots grown on MS medium with antibiotics
Research Question/Problem/ Need	How can plants be engineered to produce self-sustained light without an external substrate?
Important Figures	 Diagram of caffeic acid cycle. Mushroom represents enzymes present in mushrooms, plants represent enzymes present in plants.

	 Light emission of engineering *N. tabacum* at all stages of growth
VOCAB: (w/definition)	Agrobacterium-mediated transfer: method where genetically modified Agrobacterium tumefaciens bacteria transfer a segment of their DNA, called T-DNA, containing desired foreign genes, into a plant's genome, enabling the creation of transgenic plants Autoluminescence: spontaneous emission of light from a substance due to internal energy, rather than from an external excitation source like heat or an external light or substrate Caffeic acid cycle: biological process involving the cyclic conversion of caffeic acid into a luciferin (a light-emitting compound), followed by its breakdown and regeneration. This metabolic pathway is the chemical basis for the green light produced by bioluminescent fungi.
Cited references to follow up on	Krichevsky, A., Meyers, B., Vainstein, A., Maliga, P., & Citovsky, V. (2010). Autoluminescent plants. *PLoS ONE*, *5*(11). https://doi.org/10.1371/journal.pone.0015461 Kotlobay, A. A., Sarkisyan, K. S., Mokrushina, Y. A., Marcet-Houben, M., Serebrovskaya, E. O., Markina, N. M., Gonzalez Somermeyer, L., Gorokhovatsky, A. Y., Vvedensky, A., Purtov, K. V., Petushkov, V. N.,

	Rodionova, N. S., Chepurnyh, T. V., Fakhranurova, L. I., Guglya, E. B., Ziganshin, R., Tsarkova, A. S., Kaskova, Z. M., Shender, V., … Yampolsky, I. V. (2018). Genetically encodable bioluminescent system from fungi. *Proceedings of the National Academy of Sciences*, *115*(50), 12728–12732. https://doi.org/10.1073/pnas.1803615115 Gaquerel, E., Gulati, J., & Baldwin, I. T. (2014). Revealing insect herbivory-induced phenolamide metabolism: From single genes to metabolic network plasticity analysis. *The Plant Journal*, *79*(4), 679–692. https://doi.org/10.1111/tpj.12503
Follow up Questions	1) Is it disruptive to the plant's natural caffeic cycle to use it to create luminescence 2) How did the Agrobacterium for Agrobacterium-mediated transfer obtain the necessary genes to give the plants? 3) Why did fungi evolve bioluminescent capabilities with caffeic acid but not plants?

Article #9 Notes: Building customizable auto-luminescent luciferase-based reporters in plants

Source Title	Building customizable auto-luminescent luciferase-based reporters in plants
Source citation (APA Format)	Khakhar, A., Starker, C. G., Chamness, J. C., Lee, N., Stokke, S., Wang, C., Swanson, R., Rizvi, F., Imaizumi, T., & Voytas, D. F. (2020a). Building customizable auto-luminescent luciferase-based reporters in plants. *eLife*, *9*. https://doi.org/10.7554/elife.52786
Original URL	https://doi.org/10.7554/eLife.52786
Source type	Research Article
Keywords	Fungal Bioluminescence Pathway, hormone signaling, *AtRAB18* promoter, plant hormone abscisic acid (ABA)
#Tags	*AtRAB18* promoter (pRAB18), hormone signaling, Agrobacterium infiltration, CPH, ABA, Luz
Summary of key points + notes (include methodology)	- Bioluminescence = powerful biological signal - scientists repurpose as reporter for gene expression - Cons: high cost + non-uniform tissue penetration - Paper induces FBP in planta using "composable toolbox", works in broad range of plans, w/o external substrate - Also can use FBP for autoluminescent reporters - Firefly luciferin is water soluble, can be topically applied to whole plants through watering - uniform substrate delivery is challenging - so, difficult to understand if absence of bioluminescent signal is due to low luciferase expression or poor substrate delivery - plus high cost of luciferin Methodology: - Infused FBP in N. benthamiana with Agrobacterium infiltration - caffeylpyruvate hydrolase (CPH) is an enzyme in FBP which recycles spent luciferin - scientists re-induced luminescence with additional expression cassette for CPH for stronger bioluminescent output - Also tested this in A thaliana and Solanum lycopersicum (tomato) - Observed robust auto-luminescence

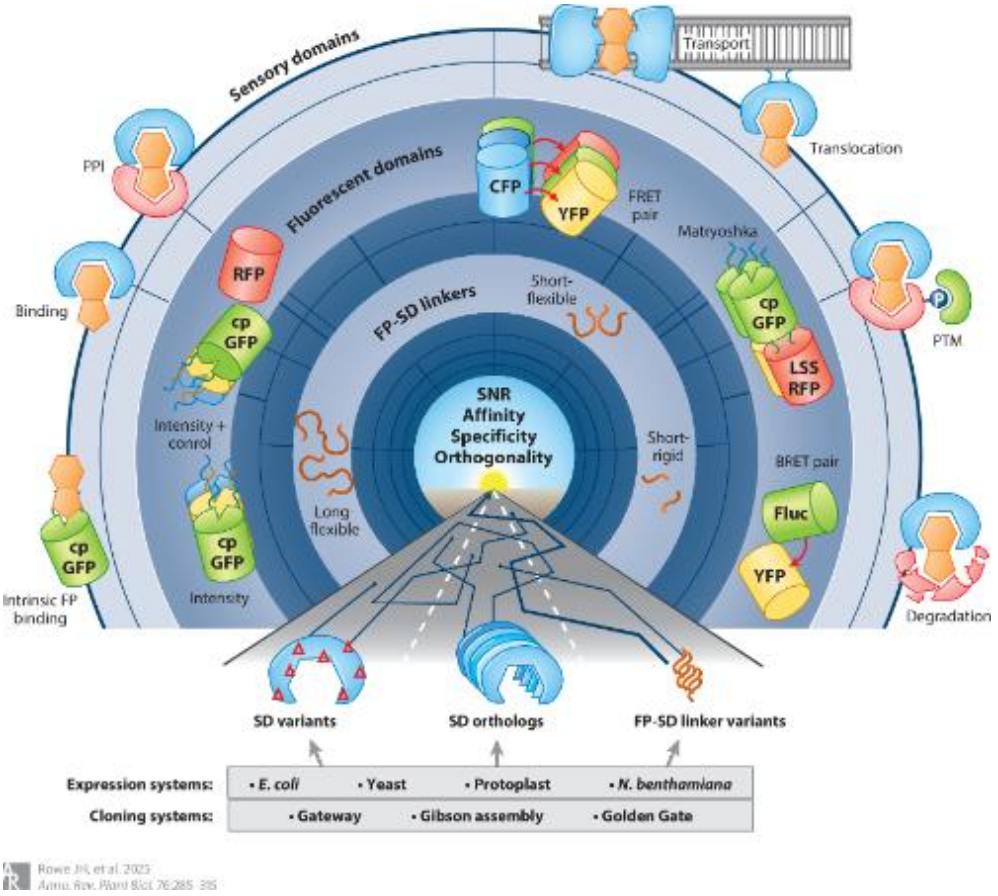
	- Created a hormone reporter from FBP - Used *AtRAB18* promoter to drive expression of *Luz* - promoter previously characterized as strong expression increase in response to the plant hormone abscisic acid (ABA) - Bioluminescent leaves watered with ABA over 3 days, light got stronger
Research Question/Problem/ Need	How can auto-luminescence be used as a reporter in plants?
Important Figures	**Video Figure 1 still images**  Images from promoter experiment with bioluminescence respone Article figure caption: one leaf each on two *N. benthamiana* plants were agro-infiltrated with FBPs that had either a 35S or pRAB18 driven *Luz*. One plant was allowed to desiccate (bottom two leaves labeled unwatered) while the other was kept watered (top two leaves labeled watered). The infiltrated leaves are highlighted with a dashed yellow line. A paired bright field image is inset in corner of each image.

VOCAB: (w/definition)	Fungal Bioluminescence Pathway: metabolic pathway found in some fungi that generates light by converting caffeic acid into luciferin, a high-energy intermediate, which then yields green light upon decomposition Hormone signaling biosensor: detect and quantify hormone-induced changes in a cell or organism, transforming a hormone binding event into an easily measurable signal like fluorescence or luminescence *AtRAB18* promoter: upstream regulatory DNA sequence for the *Arabidopsis thaliana RAB18* gene. Responsiveness to stress hormones and abiotic stresses plant hormone abscisic acid (ABA): primarily regulates responses to environmental stress, such as drought, cold, and salinity, by closing stomata to conserve water
Cited references to follow up on	Čermák, T., Curtin, S. J., Gil-Humanes, J., Čegan, R., Kono, T. J. Y., Konečná, E., Belanto, J. J., Starker, C. G., Mathre, J. W., Greenstein, R. L., & Voytas, D. F. (2017). A multipurpose toolkit to enable Advanced Genome Engineering in plants. *The Plant Cell*, *29*(6), 1196–1217. https://doi.org/10.1105/tpc.16.00922 Engler, C., Youles, M., Gruetzner, R., Ehnert, T.-M., Werner, S., Jones, J. D., Patron, N. J., & Marillonnet, S. (2014). A Golden Gate Modular Cloning Toolbox for plants. *ACS Synthetic Biology*, *3*(11), 839–843. https://doi.org/10.1021/sb4001504 Kim, T.-H., Hauser, F., Ha, T., Xue, S., Böhmer, M., Nishimura, N., Munemasa, S., Hubbard, K., Peine, N., Lee, B., Lee, S., Robert, N., Parker, J. E., & Schroeder, J. I. (2011). Chemical Genetics reveals negative regulation of abscisic acid signaling by a plant immune response pathway. *Current Biology*, *21*(11), 990–997. https://doi.org/10.1016/j.cub.2011.04.045
Follow up Questions	1) What are the reporters for various plant stressors?

	2) Can the same method be applied to other hormones by just changing the reporter? 3) How did FBP evolve in fungi, and can plants be genetically engineered to contain genes for caffeic acid cycle? Will the plants pass it down to offspring?

Article #10 Notes: Quantifying Plant Biology with Fluorescent Biosensors

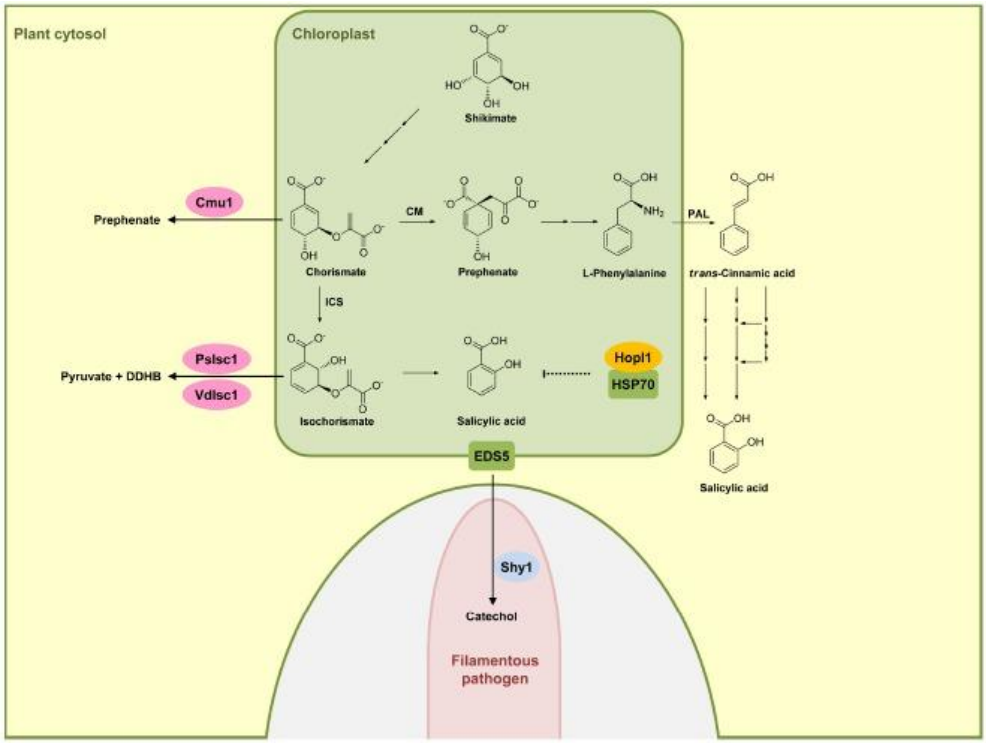
Source Title	Quantifying Plant Biology with Fluorescent Biosensors
Source citation (APA Format)	Rowe, J. H., Josse, M., Tang, B., & Jones, A. M. (2025). Quantifying plant biology with fluorescent biosensors. *Annual Review of Plant Biology*, *76*(1), 285–315. https://doi.org/10.1146/annurev-arplant-061824-090615
Original URL	https://doi.org/10.1146/annurev-arplant-061824-090615
Source type	Review Article
Keywords	genetically encoded fluorescence biosensors, quantitative plant biology, live imaging, molecular dynamics
#Tags	GFP, imaging, biosensor, genetically encoded fluorescence biosensors
Summary of key points + notes (include methodology)	- Need to correlate single-cell methods with the dynamics of key small molecules and molecular events (metabolites, hormones, etc.) - Fluorescent biosensors = direct, specific, genetically encoded + minimally invasive to quantify live cellular dynamics Signaling Pathways (Especially in Stomata) - Biosensors for: H_2O_2, Ca^{2+}, ABA, glutamate, CPK, SnRK2 - Yellow Cameleon (YC2.1) detect Ca spikes during closure (stimulated by ABA or CO2) - R-GECO1-mTurquoise show Ca transients amplify ABA-induced closure - only some stomata respond: - Ca^{2+} transients = ROS- + RBOH-dependent; signaling gated - ABA primes Ca^{2+} receptors for activation. - CPK21 & ABI1 phosphatase interaction explains another ABA–Ca^{2+} crosstalk mechanism - Different CPK21/23 Ca^{2+} affinities = distinct signal processing across tissues - Fluorescent biosensors show energy flow, redox signaling, metabolite transport, and stress responses in plants - Scientists recreated stress with ABA translocation from roots to leaves during water stress - Direct biosensors (ABAleons, ABACUS) = non-destructive, live imaging of ABA movement in Arabidopsis

Research Question/Problem/ Need	What has been accomplished in the study of the fluorescent biosensors in quantifying plant biology, and what might come in the future?
Important Figures	 Rowe JH, et al. 2023 Annu. Rev. Plant Biol. 74:285–315 The path to engineering a fluorescent biosensor. Selection of sensory domain, fluorescent domain, protoype with bacteria/plants, optimize Abbreviations: • **FP:** Fluorescent protein (e.g., GFP, RFP, CFP, YFP) • **SD:** Sensory domain • **PTM:** Posttranslational modification • **PPI:** Protein–protein interaction • **Fluc:** Firefly luciferase
VOCAB: (w/definition)	genetically encoded fluorescence biosensors: proteins made through genetic engineering that emit fluorescent light in response to specific biological changes live imaging: observe biological processes in living organisms in real time molecular dynamics: computer simulations that model how move and interact. In biosensor design, molecular dynamics helps refine the shape, flexibility,

	interaction of fluorescent + sensory domains direct biosensor: Sensors that bind analytes directly and change fluorescence = no need for cellular signaling components
Cited references to follow up on	Aratani, Y., Uemura, T., Hagihara, T., Matsui, K., & Toyota, M. (2023). Green leaf volatile sensory calcium transduction in Arabidopsis. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-41589-9 Ast, C., Foret, J., Oltrogge, L. M., De Michele, R., Kleist, T. J., Ho, C.-H., & Frommer, W. B. (2017). Ratiometric matryoshka biosensors from a nested cassette of green- and orange-emitting fluorescent proteins. *Nature Communications*, *8*(1). https://doi.org/10.1038/s41467-017-00400-2 Beltrán, J., Steiner, P. J., Bedewitz, M., Wei, S., Peterson, F. C., Li, Z., Hughes, B. E., Hartley, Z., Robertson, N. R., Medina-Cucurella, A. V., Baumer, Z. T., Leonard, A. C., Park, S.-Y., Volkman, B. F., Nusinow, D. A., Zhong, W., Wheeldon, I., Cutler, S. R., & Whitehead, T. A. (2022). Rapid biosensor development using plant hormone receptors as reprogrammable scaffolds. *Nature Biotechnology*, *40*(12), 1855–1861. https://doi.org/10.1038/s41587-022-01364-5
Follow up Questions	1) How can you induce the promoter of ABA into N. benthamiana? 2) Why do scientists test biosensors in both E. coli and N. benthamiana? Why is benthamiana more optimal? 3) Which bacteria can be best modified for use of a biosensor? E. coli?

Article #11 Notes: Microbial effectors target multiple steps in the salicylic acid production and signaling pathway

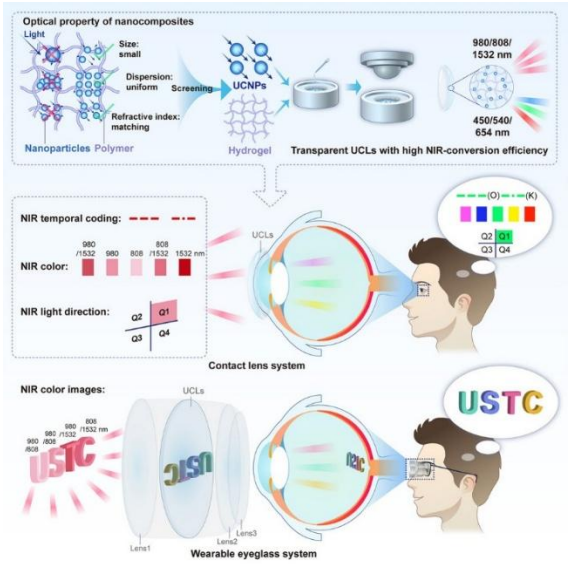
Source Title	Microbial effectors target multiple steps in the salicylic acid production and signaling pathway
Source citation (APA Format)	Tanaka, S., Han, X., & Kahmann, R. (2015). Microbial effectors target multiple steps in the salicylic acid production and signaling pathway. *Frontiers in Plant Science*, *6*. https://doi.org/10.3389/fpls.2015.00349
Original URL	https://doi.org/10.3389/fpls.2015.00349
Source type	Journal Article
Keywords	virulence effector, salicylic acid, bacterial plant pathogens, fungal plant pathogens, oomycete plant pathogens
#Tags	salicylic acid, pathogens, signaling pathway
Summary of key points + notes (include methodology)	- Microbes attempting to colonize plants recognized through plant immune surveillance system - salicylic acid (SA) signaling = important pathway bc of ability to trigger plant cell death - Some diseases have evolved strategies to downregulate SA signaling - SA = crucial player in pathogen associated molecular pattern (PAMP)-triggered immunity (PTI) + effector-triggered immunity (ETI) - AKA, SA is a big factor in PIT and ETI which are types of immunity - PTI = plant defense reaction where pathogens recognized through conserved molecular patterns - PAMP-induced defense responses = calcium spiking, the production of reactive oxygen species, callose deposition which interferes with pathogen spread, the production of antimicrobial compounds, accumulation of the plant hormone SA - ETI = detect pathogen through secreted protein effectors + mount highly effective defense response, associated with programmed cell death at site of infection - SA = key plant hormone for triggering systemic acquired resistance (SAR) - SAR = induced defense elicited by an avirulent pathogen involving the entire plant and providing protection against a broad spectrum of pathogens

	- SA = important for immunity against biotrophs, Jasmonic acid + Ethylene (different signaling molecules) important for immunity against necrotrophs - Since SA is important in immunity, some biotrophic pathogens evolved to downregulate SA levels to efficiently cause disease - Article covers methods of how these biotrophs accomplish this - Two pathways for biosynthesis of SA - Both start with chorismate (end product of shikimate pathway) - Isochorismate pathway (IC) = prime source of SA - Chorismate is converted to isochorismate by isochorismate synthase (ICS) - A. thaliana has two ICS genes (ICS1 and ICS2) - If ICS1 is defective, SA levels drop 90% - Second pathway for SA is phenylalanine ammonia-lyase (PAL) pathway - phenylalanine is converted by PAL to *trans*-cinnamic acid - precursor for various routes of SA biosynthesis - This pathway is very minor
Research Question/Problem/ Need	How is salicylic acid produced in plants and what role does it play in plant immunity?
Important Figures	 Diagram of Salicylic Acid pathway
VOCAB: (w/definition)	virulence effector: a molecule secreted by a pathogen, such as a bacterium, fungus, or oomycete, that manipulates host cells to promote infection oomycete: group of fungus-like eukaryotic organisms, many of which are destructive pathogens to plants, animals, and other microorganisms Biotrophs: obligate parasite, meaning it can only live and multiply on a living host

	Necrotrophs: parasitic organism that kills its host and then feeds on the dead tissue
Cited references to follow up on	Anderson, R. G., Casady, M. S., Fee, R. A., Vaughan, M. M., Deb, D., Fedkenheuer, K., Huffaker, A., Schmelz, E. A., Tyler, B. M., & McDowell, J. M. (2012). Homologous RXLR effectors from hyaloperonospora arabidopsidis and phytophthora sojae suppress immunity in distantly related plants. *The Plant Journal*, *72*(6), 882–893. https://doi.org/10.1111/j.1365-313x.2012.05079.x Aravind, L., & Koonin, E. V. (1999). Fold prediction and evolutionary analysis of the POZ domain: Structural and evolutionary relationship with the potassium channel tetramerization domain 1 1edited by F. Cohen. Journal of Molecular Biology, 285(4), 1353–1361. https://doi.org/10.1006/jmbi.1998.2394 Asai, S., Rallapalli, G., Piquerez, S. J., Caillaud, M.-C., Furzer, O. J., Ishaque, N., Wirthmueller, L., Fabro, G., Shirasu, K., & Jones, J. D. (2014). Expression profiling during Arabidopsis/downy mildew interaction reveals a highly-expressed effector that attenuates responses to salicylic acid. *PLoS Pathogens*, *10*(10). https://doi.org/10.1371/journal.ppat.1004443
Follow up Questions	1. Does salicylic acid leak out of plant cells? 2. What is the average quantity of salicylic acid production in plants after infection? 3. How does Jasmonic acid and ethylene compare to salicylic acid levels after infection?

Article #12 Notes: Near-infrared spatiotemporal color vision in humans enabled by upconversion contact lenses

Source Title	Near-infrared spatiotemporal color vision in humans enabled by upconversion contact lenses
Source citation (APA Format)	Ma, Y., Chen, Y., Wang, S., Chen, Z.-H., Zhang, Y., Huang, L., Zhang, X., Yin, F., Wang, Y., Yang, M., Li, Z., Huang, K., Fang, X., Li, Z., Wang, M., Liu, W., Li, J.-N., Li, L., Zhao, H., … Xue, T. (2025). Near-infrared spatiotemporal color vision in humans enabled by upconversion contact lenses. *Cell*, *188*(13). https://doi.org/10.1016/j.cell.2025.04.019
Original URL	https://doi.org/10.1016/j.cell.2025.04.019
Source type	Journal Article
Keywords	near-infrared light, color vision, upconversion nanoparticle, nanocomposites, contact lenses, spectrum, visual behavior
#Tags	NIR, upconversion nanoparticle, contact lenses
Summary of key points + notes (include methodology)	- Humans cannot perceive infrared light due to the physical thermodynamic properties of photon-detecting opsins - >700nm is not visible to mammals - Current methods of night vision require external energy - NIR = Near Infrared Light - Paper explores wearable polymeric materials for non-invasive NIR vision, assisting humans in perceiving and transmitting temporal, spatial, and color dimensions of NIR light - Tested on mice first, they could distinguish based on space and time with light - Separated NIR light into three different spectral bands in visible light - This technology can be applied for enhanced vision in devices for search & rescue - Polymeric nanocomposites developed for human eyes - Monomers + UCNPs molded into contact lens - UNCPs = upconversion nanoparticles = materials to absorb NIR and emit visible light, multiple low-energy photons are converted into a single high-energy photon

	- Mice tested to see if they could differentiate light based on location, color, and time - Worked on both mice and humans! - UNCPs contacts were biocompatible (no irritation) to mice over 7 days - The scattering of nanoparticles in the polymer had to be uniform (spaced out evenly) for light to pass through correctly without changing direction
Research Question/Problem/ Need	How can a non-invasive way to view near infrared light in humans be created with nanoparticles?
Important Figures	 Graphic of how NIR light is separated into three color spectrums
VOCAB: (w/definition)	near-infrared light: part of the electromagnetic spectrum with wavelengths just beyond the visible red light, making it invisible to the human eye(751-1400nm) upconversion nanoparticle: nanoscale materials that absorb two or more low-energy photons and emit a single, higher-energy photon, convert NIR to visible light nanocomposites: hybrid materials made by mixing a base material with nanoscale particles (less than 100 nanometers) to create enhanced properties SEM: Scanning Electron Microscope, a powerful instrument that uses a beam of electrons to scan a sample's surface and create highly magnified, detailed image
Cited references to follow up on	Rao, T., Chen, M., Mu, G., & Tang, X. (2022). Infrared-to-visible upconversion devices. *Coatings*, *12*(4), 456. https://doi.org/10.3390/coatings12040456

	Kim, D. Y., Song, D. W., Chopra, N., De Somer, P., & So, F. (2010). Organic Infrared Upconversion device. *Advanced Materials*, *22*(20), 2260–2263. https://doi.org/10.1002/adma.200903312 Loste, J., Lopez-Cuesta, J.-M., Billon, L., Garay, H., & Save, M. (2019). Transparent polymer nanocomposites: An overview on their synthesis and advanced properties. *Progress in Polymer Science*, *89*, 133–158. https://doi.org/10.1016/j.progpolymsci.2018.10.003
Follow up Questions	1) How was TTA-UC incorporated into the contacts? 2) What pairing of TTA-UC molecules were used? 3) How durable are the contacts? One-time use?

Article #13 Notes: The Role of Nanomaterials in the Treatment of Diseases and Their Effects on the Immune System

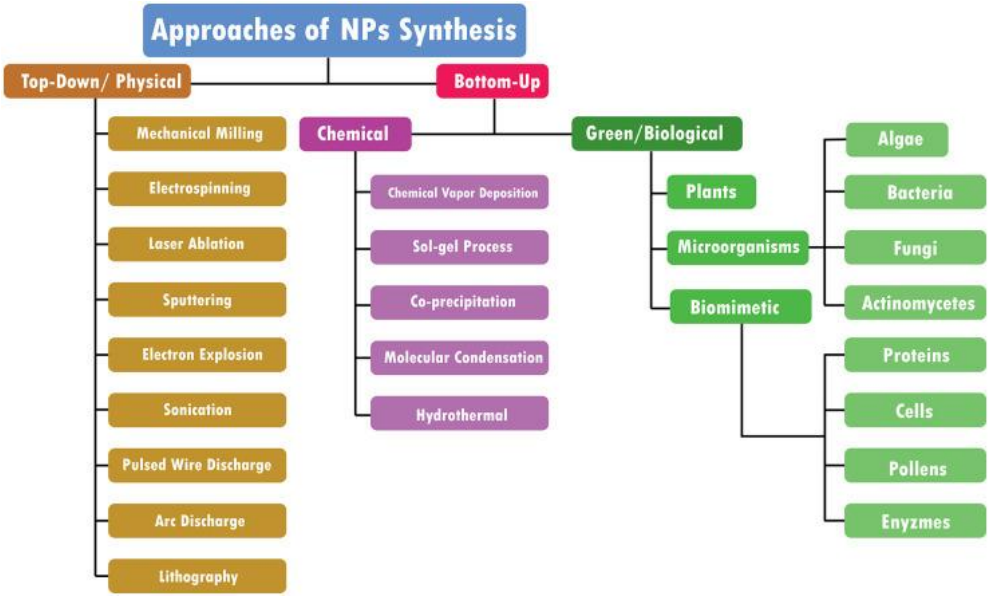
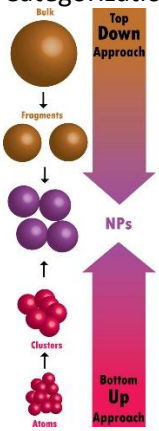
Source Title	The Role of Nanomaterials in the Treatment of Diseases and Their Effects on the Immune System
Source citation (APA Format)	Rezaei, R., Safaei, M., Mozaffari, H. R., Moradpoor, H., Karami, S., Golshah, A., Salimi, B., & Karami, H. (2019). The role of nanomaterials in the treatment of diseases and their effects on the immune system. *Open Access Macedonian Journal of Medical Sciences*, *7*(11), 1884–1890. https://doi.org/10.3889/oamjms.2019.486
Original URL	https://doi.org/10.3889/oamjms.2019.486
Source type	Review Article
Keywords	Nanomedicine, Nanomaterials, Immune system, Autoimmune diseases, Nanotoxicology
#Tags	Nanoparticles, Immune system, disease, nanotechnology
Summary of key points + notes (include methodology)	- Nanotechnology widely used in recent years - Engineered nanomaterials can: - stimulate the inhibition or enhancement of immune responses - prevent the detection ability of the immune system - little info on the toxicological and biological effects of nanomaterials - Nanomaterials = structures <100 nm - most common materials = silicates, non-oxide ceramics and metal oxides - Nanotechnology used in the fields of prevention, diagnosis and treatment of various diseases - nanomaterials can cause excitation or suppression of immune responses through binding to blood proteins - affect the interaction of nanoparticles (NPs) with other blood components - widely used to improve targeted immune responses to the prevention and treatment of diseases - nanomaterials used to direct drugs to the target cells and delivered to the desired site (might help treat cancer) - small size of nanomaterials allows them to penetrate into deeper areas of biological systems that are inaccessible to larger particles (like past cell

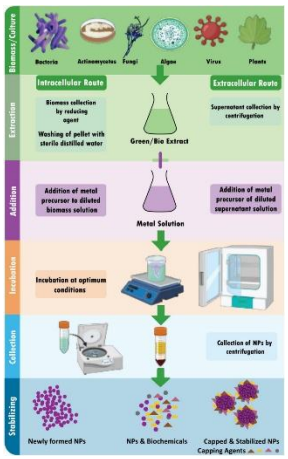
	barriers)
Research Question/Problem/ Need	How are nanomaterials used in the treatment of diseases?
Important Figures	N/A No figures included in this review article
VOCAB: (w/definition)	Nanomaterials: substances between 1 and 100 nanometers, possessing unique optical, electronic, and mechanical properties due to their small size Nanotoxicology: study of the potential harmful effects of nanomaterials on living organisms and the environment Nanoparticles: extremely small particles between 1 and 100 nanometers. Their minuscule size gives them unique properties, such as a high surface area to volume ratio, making them useful in various applications like medicine for drug delivery Blood proteins: vital molecules in the blood that perform various functions, such as transporting substances, maintaining fluid balance, fighting infection, and clotting
Cited references to follow up on	Zhang, L., Jiang, Y., Ding, Y., Povey, M., & York, D. (2006). Investigation into the antibacterial behaviour of suspensions of zno nanoparticles (zno nanofluids). *Journal of Nanoparticle Research*, *9*(3), 479–489. https://doi.org/10.1007/s11051-006-9150-1 Safaei, M., & Taran, M. (2017). Optimal conditions for producing bactericidal sodium hyaluronate-tio2 bionanocomposite and its characterization. *International Journal of Biological Macromolecules*, *104*, 449–456. https://doi.org/10.1016/j.ijbiomac.2017.06.016 Morigi, V., Tocchio, A., Bellavite Pellegrini, C., Sakamoto, J. H., Arnone, M., & Tasciotti, E. (2012). Nanotechnology in medicine: From

	inception to market domination. *Journal of Drug Delivery*, *2012*, 1–7. https://doi.org/10.1155/2012/389485
Follow up Questions	1) How are nanoparticles initially designed? 2) What process is used to create nanoparticles? 3) How are nanoparticles tested? How can it be confirmed that they are safe for humans?

Article #14 Notes: A review on nanoparticles: characteristics, synthesis, applications, and challenges

Source Title	A review on nanoparticles: characteristics, synthesis, applications, and challenges
Source citation (APA Format)	Altammar, K. A. (2023). A review on nanoparticles: Characteristics, synthesis, applications, and challenges. *Frontiers in Microbiology*, *14*. https://doi.org/10.3389/fmicb.2023.1155622
Original URL	https://doi.org/10.3389/fmicb.2023.1155622
Source type	Review Article
Keywords	green synthesis, nanoparticles, nanotechnology, biological synthesis, microbial nanotechnology, bionanotechnology
#Tags	green synthesis, nanoparticles, nanotechnology, biological synthesis, microbial nanotechnology, bionanotechnology
Summary of key points + notes (include methodology)	- Frequently synthesized by reducing metal ions into uncharged nanoparticles (NP) using hazardous reducing agents - Recently, green methods used to safely create nanoparticles - Green methods = biological ways to synthesize NP = eco-friendly, clean, safe, cost-effective, uncomplicated, and highly productive - NP used in many industries (food additive, antimicrobial agent, waste water treatment, medicine) - NP found throughout history in pottery, Roman glassware - NPs classified into Carbon-based, Metal (Silver, Zinc, Copper, Gold, Aluminum, Iron), Ceramics, Lipid-based, Semiconductor, Polymeric - 3 approaches for NP synthesis: physical (top down), chemical (bottom up), biological aka green systems (bottom up) - Mechanical Milling: balls inside containers carried out in various mills, typically planetary and shaker mills, impact process with high energy - Electrospinning: used to create nanofibers from various materials, most often polymers; draws charged threads from polymer melts or solutions - Laser Ablation: produces nanoparticles by striking the target material with an intense laser beam. - Sputtering: when the solid substance is assaulted by intense plasma or gas particles, microparticles are expelled, “sputtered”, off - And many more Top-Down methods - Sol-gel: widely used. metal precursors in solution are condensed, hydrolyzed, and thermally decomposed, results in stable solution. the

	unstable chemical ingredients are separated to create NPs. - Different microorganisms can be employed to create nanoparticles. This is the most environmentally friendly method. - AuNPs can be used in cancer treatment, biological imaging, and drug delivery. - NPs can delivery drugs to specific sites, allowing targeted treatment - Some NPs have strong antimicrobial properties, can be used in medical devices + dressings (Ag + Cu)
Research Question/Problem/ Need	What are nanoparticles, how are they used and created?
Important Figures	 Categorization of different approaches to synthesis of nanoparticles  Visualization of Top-Down and Bottom-Up approaches to nanoparticle synthesis

	 Graphic of steps for biological synthesis of nanoparticles
VOCAB: (w/definition)	green synthesis: Another name for the biological synthesis of nanoparticles biological synthesis: using microorganisms to create nanoparticles microbial nanotechnology: using microbes to produce, manipulate, and apply nanomaterials for various applications, such as environmental cleanup
Cited references to follow up on	Abdulle, A., & Chow, J. C. (2019). Contrast enhancement for portal imaging in nanoparticle-enhanced radiotherapy: A Monte Carlo Phantom evaluation using flattening-filter-free photon beams. *Nanomaterials*, *9*(7), 920. https://doi.org/10.3390/nano9070920 Ago, H. (2015). CVD growth of high-quality single-layer graphene. *Frontiers of Graphene and Carbon Nanotubes*, 3–20. https://doi.org/10.1007/978-4-431-55372-4_1 Ahmad, T., Wani, I. A., Ahmed, J., & Al-Hartomy, O. A. (2013). Effect of gold ion concentration on size and properties of gold nanoparticles in tritonx-100 based inverse microemulsions. *Applied Nanoscience*, *4*(4), 491–498. https://doi.org/10.1007/s13204-013-0224-y

Follow up Questions	1) Which method of synthesis is most used for medicinal applications? 2) What method of synthesis is fastest? 3) How are nanomaterials manipulated to get the desired results? Are they designed first, and how?

Article #15 Notes: Triplet Fusion Upconversion for Photocuring 3D-Printed Particle-Reinforced Composite Networks

Source Title	Triplet Fusion Upconversion for Photocuring 3D-Printed Particle-Reinforced Composite Networks
Source citation (APA Format)	Wong, J., Wei, S., Meir, R., Sadaba, N., Ballinger, N. A., Harmon, E. K., Gao, X., Altin-Yavuzarslan, G., Pozzo, L. D., Campos, L. M., & Nelson, A. (2023). Triplet fusion upconversion for photocuring 3d-printed particle-reinforced composite networks. *Advanced Materials*, *35*(11). https://doi.org/10.1002/adma.202207673
Original URL	https://doi.org/10.1002/adma.202207673
Source type	Research Article
Keywords	3D printing, hydrogel, TiO2, TTA-UC systems
#Tags	TTA-UC systems, hydrogel, upconversion
Summary of key points + notes (include methodology)	- In Additive manufacturing, 3D printing prints layer by layer using liquid polymers - Photopolymerization is using light to cure the liquid into a solid. - It can be done fast at room temperature with precise control - This uses high energy light (wavelengths below 405 nm) to generate radicals that initiate polymerization - When objects are too thick or opaque, the light cannot penetrate it and cure it - TiO2 (basically white paint) is often added to 3D materials to strengthen it - But this makes it opaque - How can we cure it? TTA-UC - Triplet–triplet annihilation upconversion (TTA-UC) is a process that effectively converts low energy photons (long wavelength) into high-energy excitons, which can then emit short-wavelength irradiation or undergo energy transfer processes. - Long wavelengths (red light) can penetrate deep into the materials - But short wavelengths (blue light) are needed to cure it and turn it into a solid - TTA-UC involves two chromophores, a sensitizer and an annihilator, and

benefits from the high extinction coefficient of the sensitizers to achieve excitation at a relatively low light fluence.

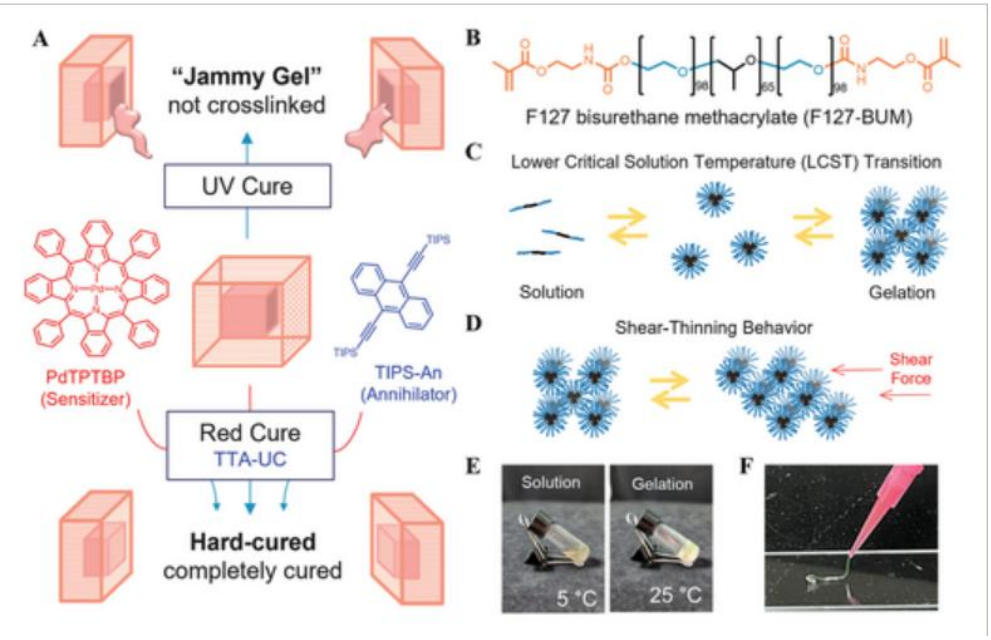
- TTA-UC to initiate polymerizations is rapidly gaining traction due to the versatility of the systems used, especially in molding and printing 3D polymeric objects.

Study:

- used F127 bisurethane methacrylate (F127-BUM), which is a triblock copolymer that forms a versatile temperature responsive and shear-thinning hydrogel ink for DIW 3D printing
- Liquid below 17C and gel above
- Sensitizer: PdTPTBP
- Annihilator: TIPS-anthracene
- These are a pair of TTA-UC molecules
- Dissolved in THF and soybean oil → oil is an oxygen scavenger (removes oxygen) to prevent quenching of triplet excitons
- This system mixed with 30%wt. F127-BUM hydrogel
- Mixed by vortexing
- Researchers made sure that the addition of TTA-UC system did not change the properties of the hydrogel
- Made sure that it was still viscoelastic, and shearthinning behavior
- The hydrogel is cured using red (660 nm) light
- compared to a control hydrogel (no annihilator → so it shouldn't cure)
- Result: the control hydrogel stayed jammy in the center, but the hydrogel cured all the way
- Many inorganic fillers are added to hydrogels to reinforce mechanical properties (strength, durability)
- Added TiO_2 into the hydrogel, makes it strong and opaque
- Added varying amounts of TiO_2 particles, reduced transparency
- Gels were cured and cut in half to observe how well it cured
- Tried this on a TTA-UC hydrogel and a Eosin Y hydrogel (it cured directly with UV light, can't penetrate far)
- samples cured with UV, blue or green light have uncured material in the center (more with increasing wt.% of TiO_2 particles), all samples cured with red light were entirely cross-linked through the center
- any material not cross-linked into the network was extracted with acetone. (so remaining mass/original mass is the mass fraction)
- mass fractions for samples cured with 660 nm light = very close to each other, between 81.83 ± 0.87%(1 wt.% TiO_2) and 76.91 ± 0.96% (5 wt.% TiO_2)
- similar mass fractions mean samples cured using red light not affected by addition of particles that reduce transparency, allowing the hydrogels to cure consistently throughout the structure

Another test they did is:

- printed a clear hydrogel layer sandwiched between 2 opaque hydrogel layers followed by irradiation with the light source above the opaque layer
- UV light did not cure it all the way, but TTA-UC did
- Shows that TTA-UC can penetrate deep and through different opacity levels while regular UV can't

	Conclusion: - Low energy light can penetrate into visibly opaque hydrogels laden with TiO2 particles - TTA-UC system converts the low energy light into blue light to initiate free radicals to harden the gel. - 3D printing hydrogels did not lose their mechanical properties with the addition of TTA-UC system and were still able to be 3D printed in all three directions - future utility as inks for DIW 3DP to produce complex multi-material objects with low optical transparency for use in tissue engineering and soft robotics and modeling biological tissues
Research Question/Problem/ Need	How can opaque and thick hydrogels be fully cured using TTA-UC systems?
Important Figures	 Diagram of cured vs uncured gel

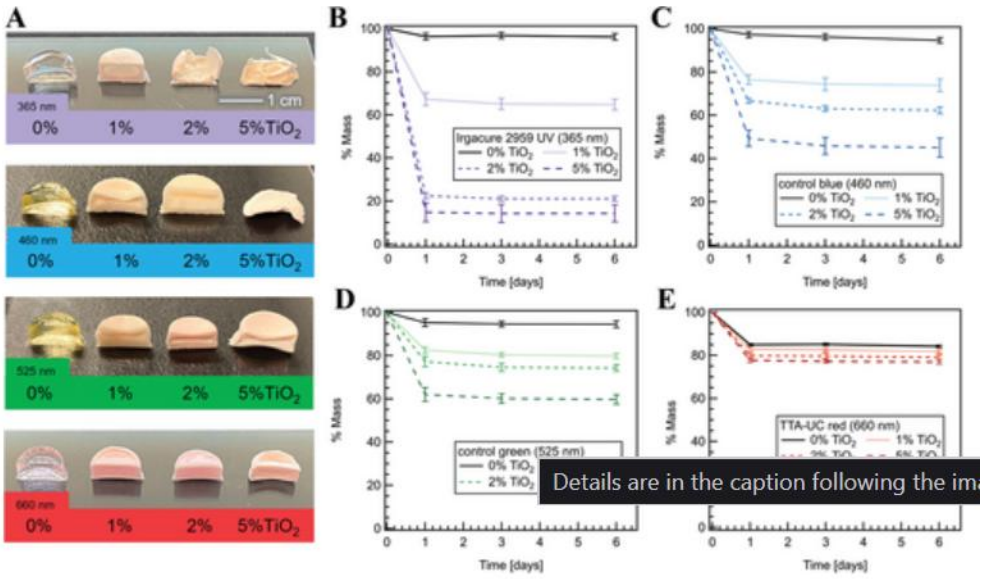
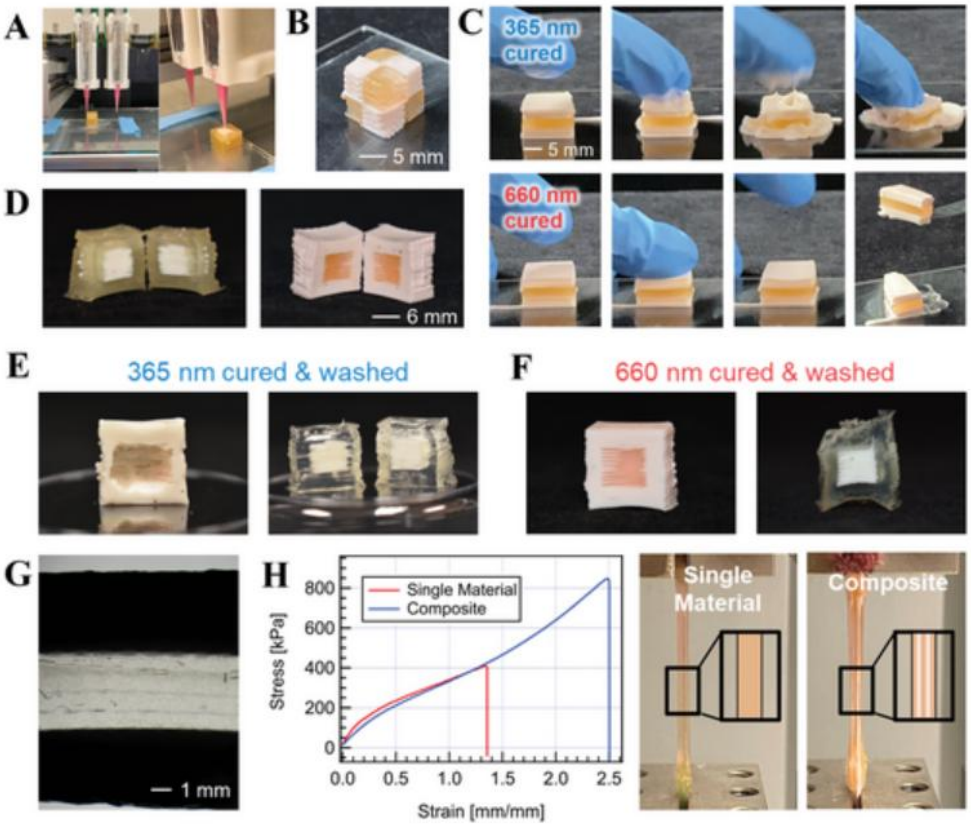


Diagram and graphs of different opacities of hydrogels



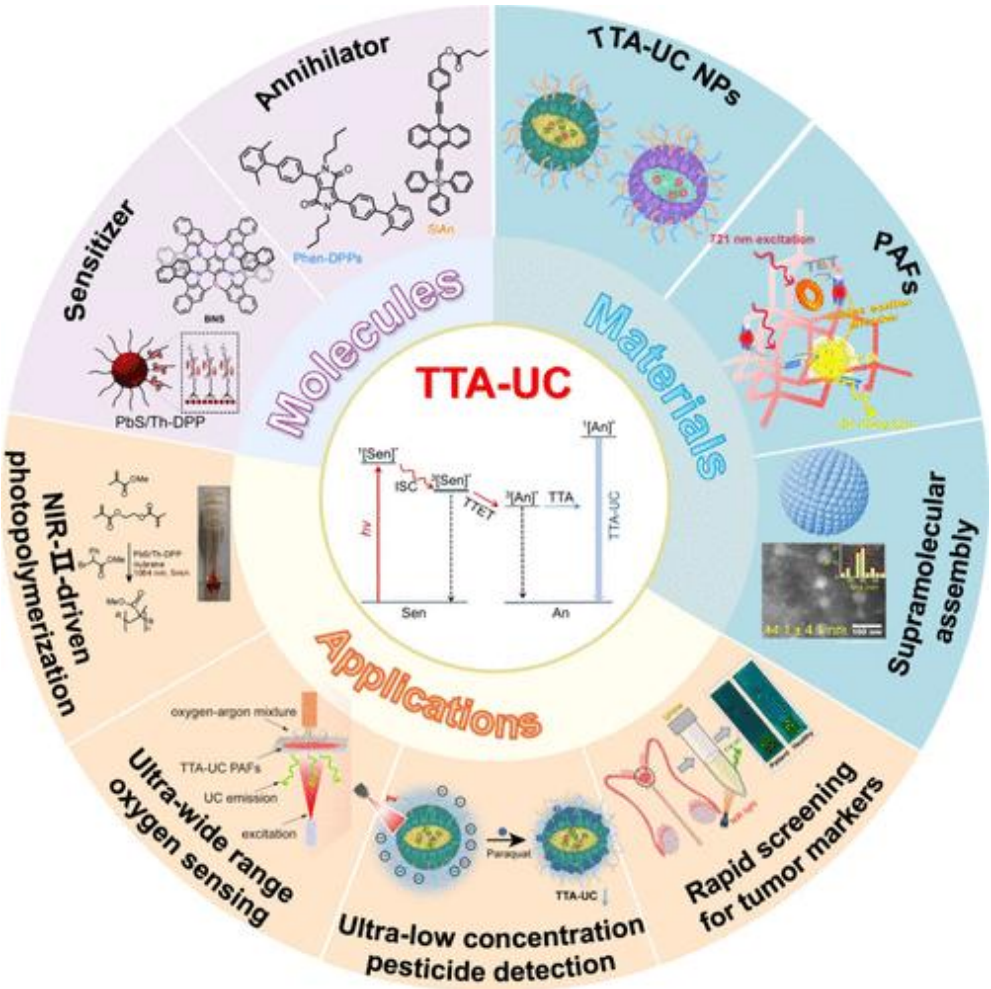
Images of integrity of different opacity layered hydrogels cured by UV and TTA-UC

VOCAB: (w/definition)	Hydrogel: crosslinked polymer chains with three-dimensional (3D) network structures, has high water content TiO2: Basically a white paint, added to make the material stronger

	TTA-UC systems: The sensitizer, annihilator, and the solvent Sensitizer: molecules that absorb the initial low-energy light (red) and transfer their energy to annihilator molecules. Annihilator: molecules which, after receiving energy, undergo triplet–triplet annihilation to reach a high-energy singlet excited state, which then emits upconverted light (blue) Triplet-triplet annihilation (TTA): Once two annihilator molecules are both in their triplet T1 excited states, they collide. Through the TTA process, the energy from these two triplet states is combined onto a single annihilator molecule, promoting it to a higher-energy excited singlet state S1 and returning the other to its ground state. Emission of high-energy photon: The annihilator in the high-energy S1 state then relaxes back to its ground state, emitting a single photon with higher energy than the initial absorbed photons. This results in an upconverted light (blue) emission.
Cited references to follow up on	Lopes, L. R., Silva, A. F., & Carneiro, O. S. (2018). Multi-material 3D printing: The Relevance of Materials Affinity on the boundary interface performance. *Additive Manufacturing*, *23*, 45–52. https://doi.org/10.1016/j.addma.2018.06.027 Pinho, A. C., & Piedade, A. P. (2022). Stimuli-responsive smart materials for Additive Manufacturing. *Nanotechnology-Based Additive Manufacturing*, 249–276. https://doi.org/10.1002/9783527835478.ch9 Zheng, Y., Zhang, W., Baca Lopez, D. M., & Ahmad, R. (2021). Scientometric analysis and systematic review of multi-material additive manufacturing of polymers. *Polymers*, *13*(12), 1957. https://doi.org/10.3390/polym13121957
Follow up Questions	1) What concentration of sensitizer and annihilator was used? 2) How long were the hydrogels cured for? 3) What was the intensity of the blue and red lights used?

Article #16 Notes: Triplet–Triplet Annihilation Upconversion: From Molecules to Materials

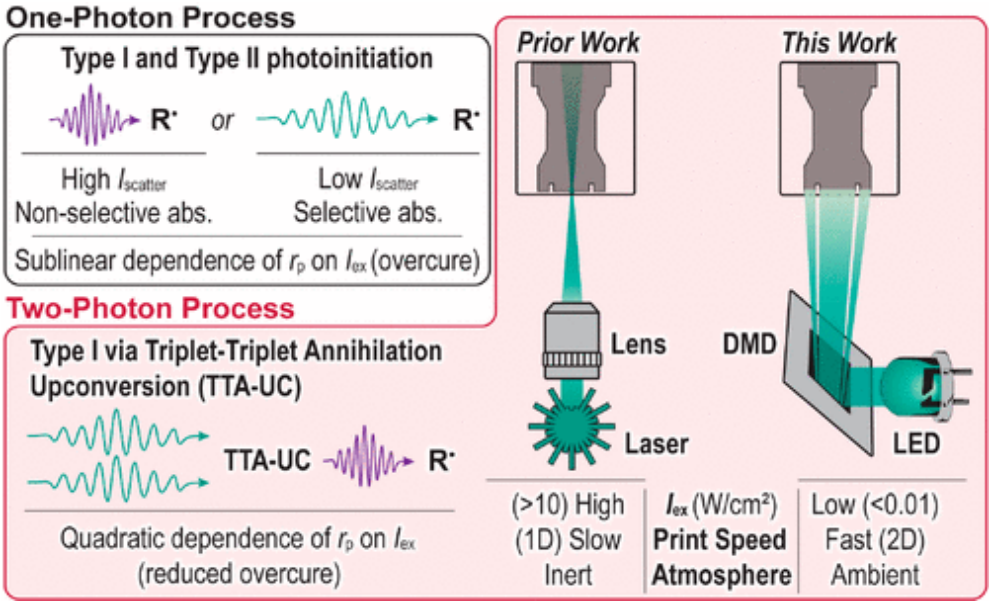
Source Title	Triplet–Triplet Annihilation Upconversion: From Molecules to MaterialsClick to copy article link
Source citation (APA Format)	Feng, H.-J., Zhang, M.-Y., Jiang, L.-H., Huang, L., & Pang, D.-W. (2025). Triplet–triplet annihilation upconversion: From molecules to materials. *Accounts of Chemical Research*. https://doi.org/10.1021/acs.accounts.5c00403
Original URL	https://pubs.acs.org/doi/10.1021/acs.accounts.5c00403
Source type	Review Article
Keywords	TTA-UC, Challenges, molecules, TADF, photoredox, applications
#Tags	TTA-UC, Challenges, molecules, TADF
Summary of key points + notes (include methodology)	- TTA-UC converts low-energy photons into higher-energy ones through multiphoton fusion - promise in biosensing, biomedicine, photoredox catalysis, and solar energy harvesting - highly efficient upconversion performance in oxygen-depleted organic solvents when exposed to light irradiation - photosensitizer absorbs a photon to generate a singlet excited state, transfers to triplet excited state (T1) - Sensitizer passes energy to annihilator via ISC - Two excited triplets combine energy, release higher energy photon - ideal photosensitizer requires a high triplet quantum yield, long triplet lifetime, and impressive absorbance - molecules with thermally activated delayed fluorescence (TADF) properties are the most common types of photosensitizers Challenges with TTA-UC - rubrene = primary annihilator in use, molecule exhibits poor photostability - majority of polymerization processes rely on UV or blue light as excitation source, limited penetration Applications for TTA-UC - Polymerization initiated with UV light - Increasing efficiency in solar energy harvesting
Research Question/Problem/	What has been learned through current research on TTA-UC and what are its

Need	challenges faced and future applications?
Important Figures	 Diagram of molecules, materials, and applications of TTA-UC
VOCAB: (w/definition)	TADF: Thermally Activated Delayed Fluorescence, allowing almost 100% efficiency by converting non-emissive triplet excitons into light-emitting singlet states using minimal thermal energy Photoredox: branch of photochemistry that uses single-electron transfer Rubrene: tetraphenyl derivative of tetracene that is used as an organic semiconductor Solar Energy harvesting (how does TTA-UC apply): allows solar cells to capture otherwise wasted sunlight and potentially break efficiency limits
Cited references to follow up on	Feng, H.-J., Zeng, L., Li, J.-Y., Lin, W.-Y., Qi, F., Jiang, L.-H., Zhang, M.-Y., Zhao, Y., Huang, L., & Pang, D.-W. (2024). Natural protein photon upconversion supramolecular assemblies for background-free biosensing. *Journal of the*

	American Chemical Society, *146*(31), 21791–21805. https://doi.org/10.1021/jacs.4c06012 Jiang, L.-H., Miao, X., Zhang, M.-Y., Li, J.-Y., Zeng, L., Hu, W., Huang, L., & Pang, D.-W. (2024). Near infrared-II excited triplet fusion upconversion with anti-stokes shift approaching the theoretical limit. *Journal of the American Chemical Society*, *146*(15), 10785–10797. https://doi.org/10.1021/jacs.4c00936 Peng, Y., Li, J.-Y., Qi, F., Guo, D.-X., Li, Y.-Z., Feng, H.-J., Jiang, L.-H., Zhang, M.-Y., Liu, Y.-X., Zeng, L., & Huang, L. (2025). Highly effective near-infrared to blue triplet–triplet annihilation upconversion nanoparticles for reversible photobiocatalysis. *Nano Letters*, *25*(13), 5291–5298. https://doi.org/10.1021/acs.nanolett.5c00117
Follow up Questions	1) When will these applications become widespread technology? 2) How would the TTA-UC system be incorporated into solar panels? 3) How would the TTA-UC system be durable enough to survive in the environment with solar panels?

Article #17 Notes: Triplet Upconversion under Ambient Conditions Enables Digital Light Processing 3D Printing

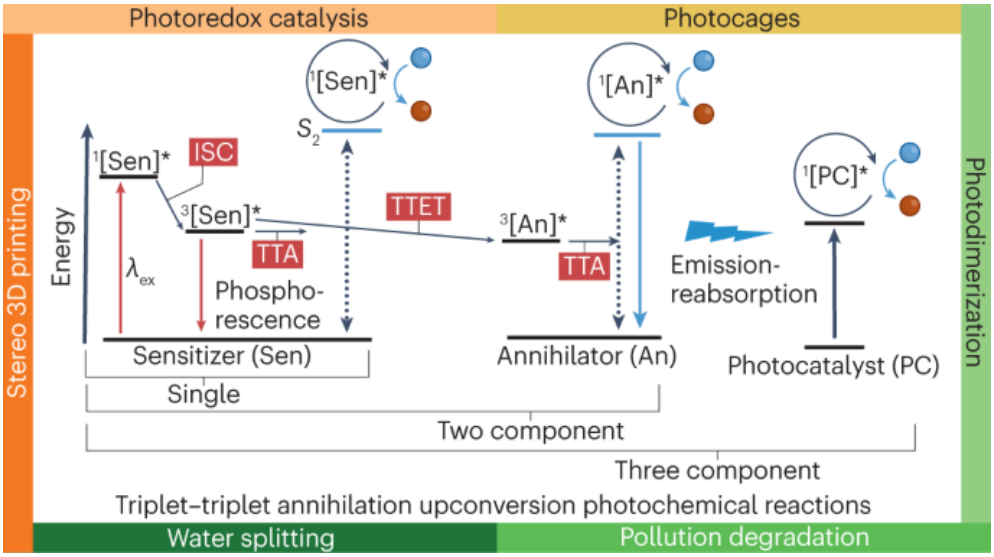
Source Title	Triplet Upconversion under Ambient Conditions Enables Digital Light Processing 3D Printing
Source citation (APA Format)	O'Dea, C. J., Isokuortti, J., Comer, E. E., Roberts, S. T., & Page, Z. A. (2024). Triplet upconversion under ambient conditions enables digital light processing 3D printing. *ACS Central Science*, *10*(2), 272–282. https://doi.org/10.1021/acscentsci.3c01263
Original URL	https://doi.org/10.1021/acscentsci.3c01263
Source type	Journal Article
Keywords	Type 1 photopolymerization, Type 2 photopolymerization, TTA-UC, PtOEP, DPA, BAPO, One-Photon vs Two-Photon process
#Tags	Photopolymerization, TTA-UC
Summary of key points + notes (include methodology)	- industrialized photocurables unable to be cured by high-energy UV light (cannot penetrate through) - develop a photosystem based on triplet–triplet annihilation upconversion efficiently drives a Type I photocuring process using green light at low power density (<10 mW/cm^2) and low oxygen. - first-time integration of TTA-UC in an inexpensive, rapid, and high-resolution manufacturing process - method results in improved cure depth confinement and resin shelf stability - used broadly in the dental + medical industries to create items like teeth alignment devices + surgical tools - light gives precise spatial and temporal control - Current problem: reliance on high-energy photons (<400 nm, UV) and/or high light exposure intensity (>100 mW/cm2) - objective = make upconversion-based 3D-printing more accessible by "constructing a TTA-UC-driven photopolymerization system that achieves the desired superlinear (∼quadratic) intensity dependence (and hence high spatial resolution) upon exposure to low-intensity (<10 mW/cm2) visible light from an inexpensive LED source under ambient conditions" (O'Dea et al., 2024) - paper's design couples two processes: TTA-UC and Type I photoinitiation - TTA-UC absorbs 525 nm (green light) with PtOEP

	- Annihilator = DPA emits 420–440 nm, violet-blue light - Photointiator = BAPO - low sensitivity to oxygen because DPA acts as a singlet oxygen scavenger
Research Question/Problem/ Need	How can TTA-UC be efficiently used for low-cost photopolymerization in ambient conditions?
Important Figures	 Diagram of One-Photon vs Two-Photon process of experiment
VOCAB: (w/definition)	Ambient oxygen: refers to the about 21% concentration of oxygen in the Earth's air Type I photopolymerization: light-activated process, a photoinitiator molecule absorbs light and breaks apart (homolytic cleavage) into highly reactive free radicals, starts a chain reaction to polymerize monomers into solid polymers One-Photon process: one-photon excitation directly boosts molecule to high singlet state (S1) with one UV/blue photon Two-Photon process: TTA-UC uses long-wavelength light absorbed by a sensitizer, transferring to triplets, and then annihilating two triplets to form one high-energy singlet for emission
Cited references to follow up on	Corrigan, N., Yeow, J., Judzewitsch, P., Xu, J., & Boyer, C. (2019). Seeing the light: Advancing Materials Chemistry through photopolymerization. *Angewandte Chemie*, *131*(16), 5224–5243. https://doi.org/10.1002/ange.201805473

	Dadashi-Silab, S., Doran, S., & Yagci, Y. (2016). Photoinduced electron transfer reactions for macromolecular syntheses. *Chemical Reviews*, *116*(17), 10212–10275. https://doi.org/10.1021/acs.chemrev.5b00586 Bao, Y. (2022). Recent trends in advanced photoinitiators for VAT photopolymerization 3D printing. *Macromolecular Rapid Communications*, *43*(14). https://doi.org/10.1002/marc.202200202
Follow up Questions	1) Since this article has found a way for TTA-UC polymerization to occur in a low-cost effective way, will it start to be used commercially? 2) How does quadratic dependence work? 3) What is the span/area of the LED light's effect?

Article #18 Notes: Triplet–triplet annihilation photon upconversion-mediated photochemical reactions

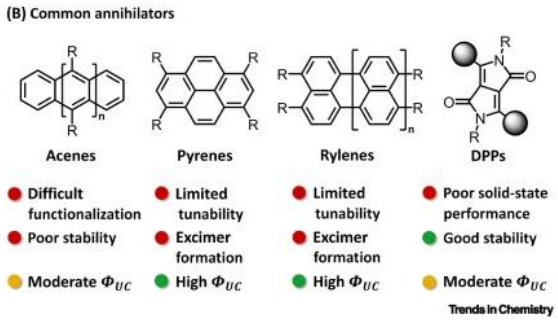
Source Title	Triplet–triplet annihilation photon upconversion-mediated photochemical reactions
Source citation (APA Format)	Huang, L., & Han, G. (2024). Triplet–triplet annihilation photon upconversion-mediated photochemical reactions. *Nature Reviews Chemistry*, *8*(4), 238–255. https://doi.org/10.1038/s41570-024-00585-3
Original URL	https://doi.org/10.1038/s41570-024-00585-3
Source type	Review Article
Keywords	TTA-UC, component, photocatalyst, photoresponse, photosensitizers
#Tags	TTA-UC, component upconversion, catalyst
Summary of key points + notes (include methodology)	- red + near-infrared wavelength = penetrate tissue deeply, more efficient large-scale reactions + in vivo phototherapy - TTA-UC = high upconversion efficiencies + low excitation power densities + tunable absorption and emission wavelengths Advancements in TTA-UC - new types of photosensitizers (metal clusters, noble-free metallic complexes and heavy atom-free photosensitizers) - expanding absorption wavelengths to cover NIR + blue-light ranges - library of annihilators for TTA-UC created by chemically modifying perylene + anthracene + DPP + BODIPY - three-component TTA-UC = absorption redshift + extending the photoresponse wavelength of the photocatalyst, not in photocatalytic reaction - two component = photosensitizer + annihilator; annihilator = both a triplet acceptor & photocatalyst - changes taken into consideration – lots of energy required to convert light amounts - materials designed suppress oxygen-mediated photon upconversion quenching - Red-light TTA-UC good for photopolymerization of transparent & manufacturing of opaque hydrogels
Research Question/Problem/	What are the recent advancements and challenges in TTA-UC research?

Need	
Important Figures	 Diagram of single, two and three component light upconversion and its components
VOCAB: (w/definition)	Photocatalyst: material, often a semiconductor, that speeds up a chemical reaction when it absorbs light energy Photoresponse: refers to how TTA-UC systems react to light (efficiency and environmental factors) Photosensitizers: different name for the sensitizer molecule
Cited references to follow up on	Tao, W., & Farokhzad, O. C. (2022). Theranostic nanomedicine in the NIR-II window: Classification, fabrication, and biomedical applications. *Chemical Reviews*, *122*(6), 5405–5407. https://doi.org/10.1021/acs.chemrev.2c00089 Chen, Y., Wang, S., & Zhang, F. (2023). Near-infrared luminescence high-contrast in vivo biomedical imaging. *Nature Reviews Bioengineering*, *1*(1), 60–78. https://doi.org/10.1038/s44222-022-00002-8 Ravetz, B. D., Tay, N. E., Joe, C. L., Sezen-Edmonds, M., Schmidt, M. A., Tan, Y., Janey, J. M., Eastgate, M. D., & Rovis, T. (2020).

	Development of a platform for near-infrared photoredox catalysis. *ACS Central Science*, *6*(11), 2053–2059. https://doi.org/10.1021/acscentsci.0c00948
Follow up Questions	1) What are some of the steps being taken to mitigate challenges of TTA-UC? 2) Why does oxygen affect TTA-UC reactions? 3) What affects the reaction rate of TTA-UC systems?

Article #19 Notes: Design and optimization of triplet–triplet annihilation upconversion annihilators

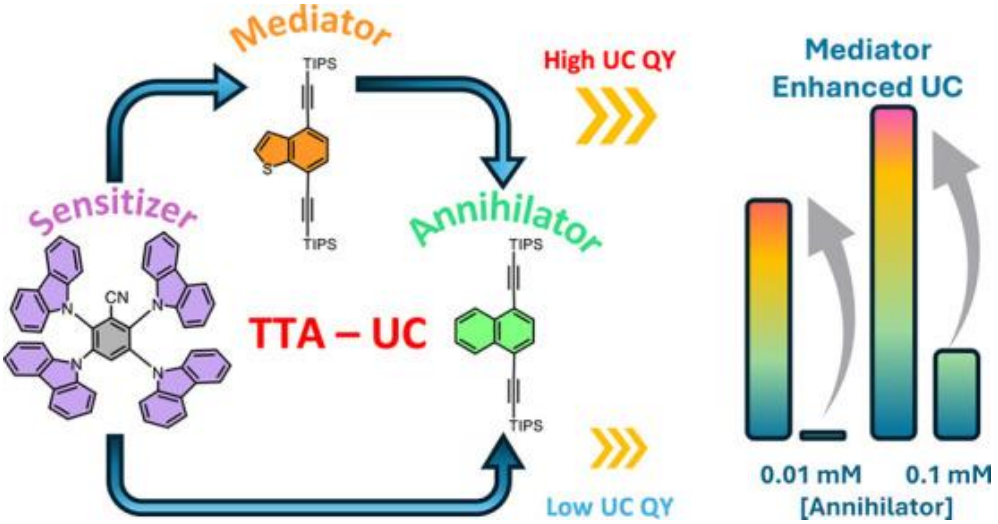
Source Title	Design and optimization of triplet–triplet annihilation upconversion annihilators
Source citation (APA Format)	Naimovičius, L., & Pun, A. B. (2025). Design and optimization of triplet–Triplet Annihilation Upconversion Annihilators. *Trends in Chemistry*, *7*(4), 171–174. https://doi.org/10.1016/j.trechm.2025.02.002
Original URL	https://doi.org/10.1016/j.trechm.2025.02.002
Source type	Review Article
Keywords	TTA-UC, energy, TTET, steric effects, Excimer, challenges
#Tags	TTA-UC, review, energy, TTET, steric effects
Summary of key points + notes (include methodology)	- lack of efficient annihilators limits TTA-UC application - Reviews progress of new/optimized annihilators - Most work tries to optimize systems with common annihilators - Difference in energy excitations between sensitizer and annihilator affect performance - To tune this, some techniques are aryl, nitrile, TIPS - TIPS lowered the energy of one from 3.9 to 2.6 eV - Lowering this allowed using lower sensitizers (more efficient + better performance) - These methods are used to tune existing annihilators, not create from scratch - Efficiency can be diminished by excimer formation (called steric effects) - Excimer = unwanted side reaction, two excited annihilator molecules form short-lived excimer that emits lower-energy light or decays non-radiatively reduces overall efficiency - Bulky substituents used to eliminate excimer formation in naphthalene-based annihilator - Used TPhS + TIPS - But, bulkier substituents also make energy transfer slower + inefficient - That means there has to be an ideal, optimized area where it is best Future steps: - Energy + steric effects are main factors in annihilator optimizing - Optimizing annihilators (most ineffecient part of TTA-UC system) will help it be used commercially and be cheaper - Most common annihilators work best in visible light range - But the uses of TTA-UC usually want UV light

	- So, annihilators must be optimized to get this UV light
Research Question/Problem/ Need	How can annihilators be optimized for a more efficient TTA-UC system?
Important Figures	 Diagram of common annihilators and their positives/drawbacks
VOCAB: (w/definition)	Excimer: an unwanted side reaction, where two excited annihilator molecules form short-lived excimer that emits lower-energy light or decays non-radiatively; reduces overall efficiency TET: Triplet Energy Transfer, excited sensitizer transfers triplet energy to annihilator molecule, while sensitizer returns to ground state Steric effects: influence of the physical size and spatial arrangement of atoms or groups on the efficiency and performance of the upconversion process Excimer formation is a category of this
Cited references to follow up on	Naimovičius, L., Zhang, S. K., & Pun, A. B. (2024). Impact of steric effects on the statistical probability factor in triplet–triplet annihilation upconversion. *Journal of Materials Chemistry C*, *12*(45), 18374–18380. https://doi.org/10.1039/d4tc03269a Fallon, K. J., Churchill, E. M., Sanders, S. N., Shee, J., Weber, J. L., Meir, R., Jockusch, S., Reichman, D. R., Sfeir, M. Y., Congreve, D. N., & Campos, L. M. (2020). Molecular engineering of chromophores to enable triplet–triplet annihilation upconversion. *Journal of the American Chemical Society*, *142*(47), 19917–19925. https://doi.org/10.1021/jacs.0c06386

	Olesund, A., Ghasemi, S., Moth-Poulsen, K., & Albinsson, B. (2023). Bulky substituents promote triplet–triplet annihilation over triplet excimer formation in naphthalene derivatives. *Journal of the American Chemical Society*, *145*(40), 22168–22175. https://doi.org/10.1021/jacs.3c08115
Follow up Questions	1) How are the bulky substituents incorporated into the TTA-UC system? 2) How much does oxygen affect annihilator efficiency? 3) Can presence of oxygen be mitigated without removing oxygen and instead adding/fixing annihilator?

Article #20 Notes: Improving Triplet–Triplet Annihilation Upconversion Output by a Triplet Mediator Approach: Mechanistic Insights on Homo and Hetero-Annihilation in Three-Component Systems

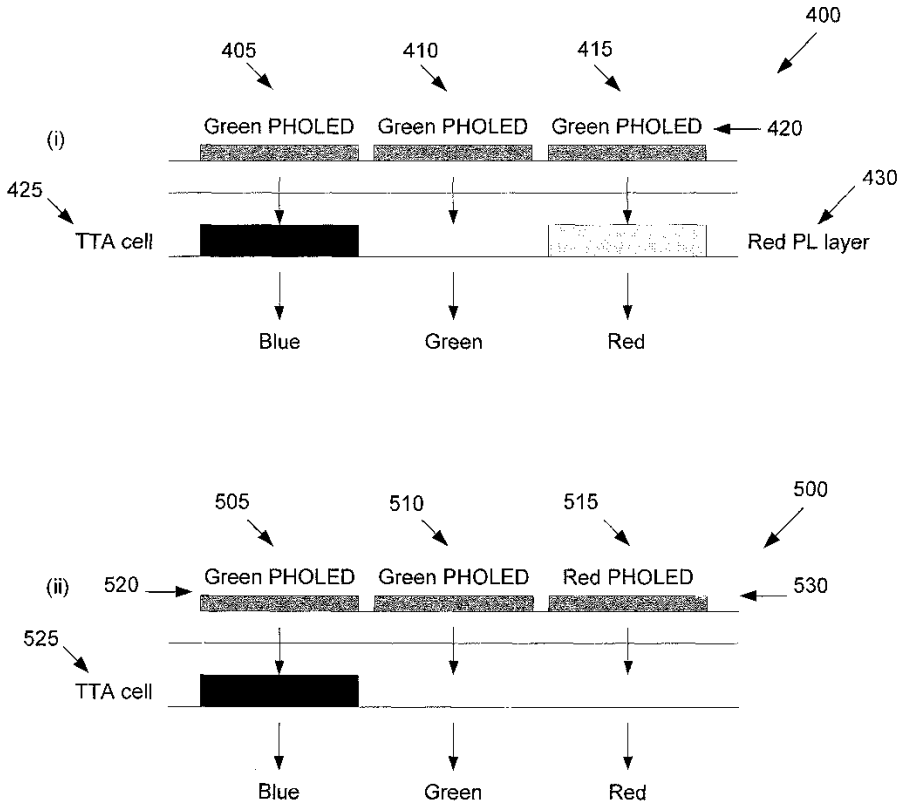
Source Title	Improving Triplet–Triplet Annihilation Upconversion Output by a Triplet Mediator Approach: Mechanistic Insights on Homo and Hetero-Annihilation in Three-Component Systems
Source citation (APA Format)	Kandappa, S. K., & Gray, V. (2025a). Improving triplet-triple annihilation upconversion output by a triplet mediator approach: Mechanistic insights on homo and hetero-annihilation in three component systems. *ChemRxiv*. https://doi.org/10.26434/chemrxiv-2025-6sf3f-v2
Original URL	https://doi.org/10.26434/chemrxiv-2025-6sf3f-v2
Source type	Research Article
Keywords	TET, concentration, mediator, BT, TIPS
#Tags	TTA-UC, TET, review, concentration
Summary of key points + notes (include methodology)	- Challenge in tta-uc is minimizing reabsorption of upconverted photons by annihilator molecules (happens when there are too many annihilator molecules) - Paper presents "mediator-assisted TTA-UC approach utilizing a neutral mediator molecule to facilitate upconversion in the ultraviolet (UV) and visible regions" Previous work + Background: - Typical system has sensitizer molecule that donate energy to annihilator molecule which accepts it - Lowering concentration of annihilator minimizes reabsorption but also decreases TET - Mediator is a molecule, helps energy transfer between sensitizer and annihilator - In solid state TTA-UC systems, a third component called singlet acceptor/singlet sink will take in "extra" energy Paper's work: - Paper used BT as mediator - Annihilator = TIPS-Nap emits UV light

	- Sensitizer = 4CzBN - BT energy is in between sensitizer and annihilator - Resulted in more efficient energy transfer - Resulted in 10 fold increase of quantum yield
Research Question/Problem/ Need	How can a third component be used to reduce annihilator reabsorption in a TTA-UC system?
Important Figures	 Diagram of how paper's new process incorporates mediator into TTA-UC
VOCAB: (w/definition)	Mediator: molecule between sensitizer and annihilator to assist with energy transfer BT: Benzothiophene, facilitates energy transfer in TTA-UC by accepting triplet energy from a sensitizer and passing it to an annihilator, improving efficiency TIPS: Triisopropylsilyl, bulky chemical group added to the annihilator molecule, emits UV light, widely used
Cited references to follow up on	Gray, V., Moth-Poulsen, K., Albinsson, B., & Abrahamsson, M. (2018). Towards efficient solid-state triplet–triplet annihilation based photon upconversion: Supramolecular, macromolecular and self-assembled systems. *Coordination Chemistry Reviews, 362, 54–71.* https://doi.org/10.1016/j.ccr.2018.02.011 Trupke, T., Shalav, A., Richards, B. S., Würfel, P., & Green, M. A. (2006). Efficiency enhancement of solar cells by luminescent up-conversion of

	sunlight. *Solar Energy Materials and Solar Cells*, *90*(18–19), 3327–3338. https://doi.org/10.1016/j.solmat.2005.09.021 Schulze, T. F., & Schmidt, T. W. (2015). Photochemical upconversion: Present status and prospects for its application to Solar Energy Conversion. *Energy & Environmental Science*, *8*(1), 103–125. https://doi.org/10.1039/c4ee02481h
Follow up Questions	1) What are some requirements that make a good/efficient mediator? 2) Is the mediator incorporated into the system normally, or is it first prepped? 3) What concentration is the mediator compared to the sensitizer and annihilator?

Patent #1 Notes: Triplet-Triplet annihilation up conversion (TTA-UC) for display and lighting applications

Source Title	Triplet-Triplet annihilation up conversion (TTA-UC) for display and lighting applications
Source citation (APA Format)	Xia, C., Weaver, M. S., & Brooks, J. (2014). *Triplet–triplet annihilation up conversion (TTA-UC) for display and lighting applications* (U.S. Patent No. 8,742,657 B2). United States Patent and Trademark Office. https://patents.google.com/patent/US8742657B2
Original URL	https://patents.google.com/patent/US8742657B2
Source type	Patent
Keywords	Patent, lighting, commercial, OLED
#Tags	Patent, lighting, commercial
Summary of key points + notes (include methodology)	Patent Claims: - Patent for a device that layers a OLED light and a TTA-UC layer on top - OLED provides an excitation light source - TTA-UC system absorbs the light + convert to shorter wavelength emission - Ex. blue emission created by using a green/red OLED - Long device operational lifetime will be achieved from the TTA-UC layer saving it energy from having to produce blue light. Uses: - “organic materials, such as their flexibility, may make them well suited for particular applications such as fabrication on a flexible substrate” - Wants to use the organic TTA-UC layer to help create flexible devices Image: - The primary images shows how the OLED and TTA-UC will be layered. - Green PHOLED can have a TTA cell on top which light will pass through - When light passes through, TTA cell upconverts it to blue, green, or red. - Red is a lower wavelength than green, this happens from the red PL layer. - Patent Information: - Patent submitted by in 2010, still active - Patent granted in 2014 - Set to expire in 2031 - Assigned to Universal Display Corp

	- Inventors are Chuanjun Xia, Michael S Weaver, Jason Brooks
Research Question/Problem/ Need	How can TTA-UC systems be used to transform light for devices, allowing a longer lifetime?
Important Figures	 Image from patent depicting layering of OLED and TTA cell
VOCAB: (w/definition)	OLED: light-emitting diode with thin flexible sheets of an organic electroluminescent material, mainly used in digital display screens. Optoelectronic: electronic components that interact with light, convert electrical energy to light (like LEDs) PHOLED: Phosphorescent Organic Light-Emitting Diode, highly efficient type of OLED technology, uses phosphorescent materials to convert almost 100% of electrical energy into light
Cited references to follow up on	N/A
Follow up Questions	1) How effective is this? 2) What are the costs of this? Which is costlier: producing blue light from the device itself or having the TTA-UC system do it? 3) Will everyday users have this technology on their home devices, or is it only for high-power devices?

Patent #2 Notes: Molecular photon upconversion using organic-inorganic hybrid interfaces

Source Title	Molecular photon upconversion using organic-inorganic hybrid interfaces
Source citation (APA Format)	Hanson, K., Hill, S., & Dilbeck, T. (2016). *Molecular photon upconversion using organic-inorganic hybrid interfaces* (WO 2016039976 A1). World Intellectual Property Organization. https://patents.google.com/patent/WO2016039976A1/en
Original URL	https://patents.google.com/patent/WO2016039976A1/en
Source type	Patent
Keywords	Multilayer, TTA-UC, Perylene + PdTPBP
#Tags	Multilayer, device, TTA-UC, patent, Perylene + PdTPBP
Summary of key points + notes (include methodology)	Patent Claims: - multilayer structure with - a substrate with a metal oxide surface and a bulk region - self-assembled bilayer film - the bilayer film has: an acceptor molecule covalently bonded to the metal oxide surface & linking metal ion bonded to the 5 acceptor molecule & a sensitizer molecule bonded to the linking metal ion. Uses: - This design is to incorporate TTA-UC system into a metal-oxide layer - Metal-oxide layers are used in engineering solar panels - First step to getting TTA-UC systems into solar panels for more efficient solar harvesting Image: - An extensive table with all combinations of TTA-UC pairings - These are the pairings that are patented to be used on their device - Perylene + PdTPBP is present! Patent Information: - Patent submitted by in 2015 - Status ceased - Expired in 2017 - Assigned to Florida State University Research Foundation Inc - Inventors are Kenneth Hanson, Sean Hill, Tristan Dilbeck
Research Question/Problem/ Need	How can a TTA-UC system be incorporated into a metal layer for use in a solar panel?

Important Figures

Acceptor	Sensitizer
Perylene	PtTPBP
2CBPEA	PtTPBP
BD-1	PtTPBP
BD-2	PtTPBP
BDPPA	PtTPBP
BODIPY-deriv	PtTPBP
BPEA	PtTPBP
Perylene	Pt(II)-BODIPY
BPEA	PdTPBP
Rubrene	PdTPBP
Bis-tetracene	PdTPBP
Perylene	PdTPBP
Perylene	PQ_4Pd
Perylene	ZnTPBP
Perylene-BODIPY dyad	PdTBP
Perylene-BODIPY dyad	ZnTPBP
Anthracene	$[Ru(dmb)_3]^{2+}$
DMA	$[Ru(dmb)_3]^{2+}$
DPA	$[Ru(dmb)_3]^{2+}$
PPO	Biacetyl
Rubrene	PdTAP
DPA	PdOEP
DPA	PtOEP
Rubrene	$PdPc(OBu)_8$
Perylene	ZnTPP
C343	ZnTPP
Rubrene	$PdPh_4Ome_8TNP$
BPEN	$PdPh_4Ome_8TNP$
PPO	2MeOTX
Pyrene	$Ir(ppy)_3$
Tert-butylpyrene	$Ir(ppy)_3$
1CBPEA	BODIPY-derivative
BPEA	C70
Perylene	C70
DPA	TIHF
DPA	Pt1
DPA	Pt2
DPA	$[Ru(bpy)_2(Phen)\text{-}pyrene]^{2+}$
DPA	$[Ru(bpy)_2(Phen)ethynyl\text{-}pyrene]^{2+}$
DPA	PtOEP
DPA/DPBF	PtOEP
DPBF	PtOEP
PDI	PyrRuPZn2
PDI	PtTPTNP
PDI	H_2TPBP
Perylene	PPD
DPPA	PtTCPP

Table of all the possible sensitizer-annihilator pairings to use in the patented metal-oxide layer

VOCAB: (w/definition)

Metal-oxide: crucial functional components, serving as charge transport layers (electron/hole transport) in various solar cell
Photodynamic: treatment for cancer involving the injection of a cytotoxic compound, relatively inactive until activated by a laser beam after collecting in the

	tumor Photoactuators: light-activated molecules that change shape, perform mechanical work, or trigger cellular processes in response to light
Cited references to follow up on	N/A
Follow up Questions	1) When will this start being used in commercial solar panels? 2) What is the expense of this? 3) How much does this technology increase solar panel efficiency by?