

Next-Generation Biomimetics: Plant-Based Approaches to Nanosensing

Anshika Upadhyay¹, Dr M. Padma Sundari², Dr N.Nagraj³

¹Undergraduate Botany Major student, Department of Botany, St. Joseph's College for Women(A), Gnanapuram, Visakhapatnam

^{2,3}Assistant Professor, Department of Botany, St. Joseph's College for Women(A), Gnanapuram, Visakhapatnam

ABSTRACT

Biomimicking has inspired several designers, architects, and engineers. Mimicking nature's elegant designs, which are produced through a thorough and elaborate process of natural selection, is a familiar concept in human civilization. [1]. Plants dominate the earth, and all biodiversity depends on them [2]. Humans are no exception, as we depend heavily on plants for our livelihood, food, industry, and innovation. Nanotechnology, an emerging field of the 21st century, has also drawn inspiration from plants for the development of new-age nanosensors. Advanced research in nanosensing technology holds a promising future in various fields, including medicine, agriculture, ecology, environmental science, robotics, and photonics. This article addresses cutting-edge nanosensing technology inspired by plants. It also has the potential to lead to a sustainable future. This study explores the following areas. (1) Key concepts of bioinspired nanosensing technology (2) Emerging plant-inspired nanosensing technologies in various fields (3) Concerns and ethical issues.

Keywords: Biomimetics, Nanosensing Engineering, Phytomimetics

INTRODUCTION:

Biomimicry is the practice of learning from and imitating nature for sustainable designs. It is an interdisciplinary approach that involves designers, engineers, chemists, and biologists and helps create a more sustainable, energy-efficient, and environmentally friendly future. Biomimetics was coined by Otto Schmitt in 1957 while designing a physical device to mimic the electronic impulses of nerves. The term biomimicry is derived from ancient Greek 'bios' (*βίος*)- *life*, and 'mīmēsis' (*μίμησις*), - imitation.

The integration of nanotechnology with biomimetics has advanced significantly, with interdisciplinary collaboration playing a crucial role in driving sustainable innovation and underscoring the importance of expertise.

Plant-inspired nanosensing technology is an emerging biomimetic technology that offers promising avenues for sustainable solutions, despite current challenges such as scalability and safety concerns, underscoring the need for continued responsible research. Fig1.

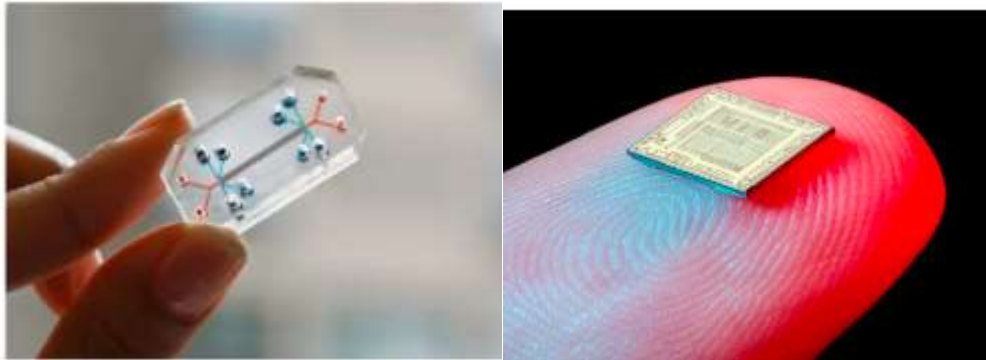
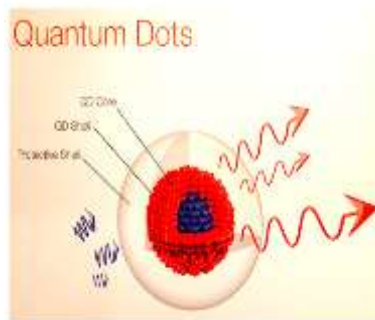


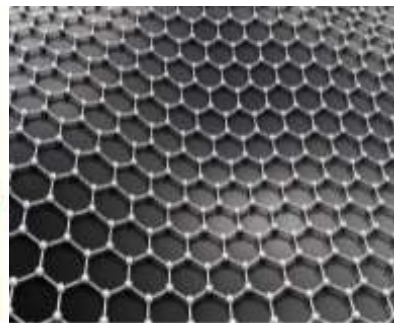
Fig:1 Plant Inspired Nanosensing Technology

Nanomaterials used for developing Inspired Nanosensors

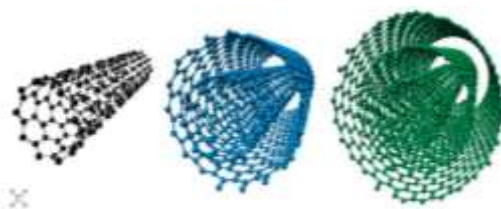
Nanomaterials are materials that have structural features at the nanoscale—typically between 1 and 100 nanometers (nm). Nanomaterials are defined as materials with at least one external dimension in the size range from approximately 1–100 nm, possessing properties that are often unique due to their dimensions, and are manufactured. Several nanomaterials are utilized in the development of plant-inspired nanosensors, including quantum dots, graphene, carbon nanotubes, and nanowires. Fig2.



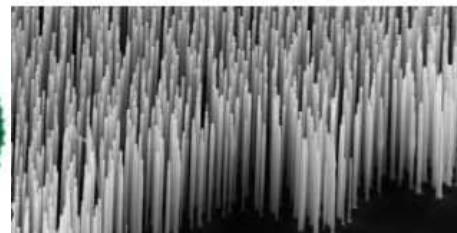
Quantum dots



Graphene



Carbon Nanotubes



Silicon Nanowire

Fig2 :Types of Nanosensors Inspired by Plants

Types of Phytomimetic Nanosensors

1. **Tactile Nanosensors:** These nanosensors replicate the plant's ability to respond to mechanical stimuli, such as pressure and force.
2. **Bioresponsive Nanosensors:** Bioresponsive nanosensors are inspired by plant responses to various biological factors, including those triggered by insects, pathogens, and hormones.

3. **Optical Nanosensors:** These nanosensors can detect light and are developed based on the ability of plant stomata and pigments to respond to light.
4. **Stimuli-Responsive Nanosensors:** They replicate the ability of plants to respond to environmental factors such as heat, temperature, humidity, light, and pH.

Applying phytomimetic nanosensors in various fields offers sustainable solutions; addressing regulatory frameworks and safety standards is vital to foster societal trust and responsible development, encouraging ethical responsibility among researchers and professionals.

Hydrogel-based tactile sensors inspired by the Mimosa pudica (sensitive plant)

Mimosa pudica is a touch-sensitive plant that can detect touch and pressure. It closes its leaves in response to mechanical stress. Similarly, these tactile nanosensors are composed of jelly-like hydrogels that change shape in response to touch or pressure. Fig3.

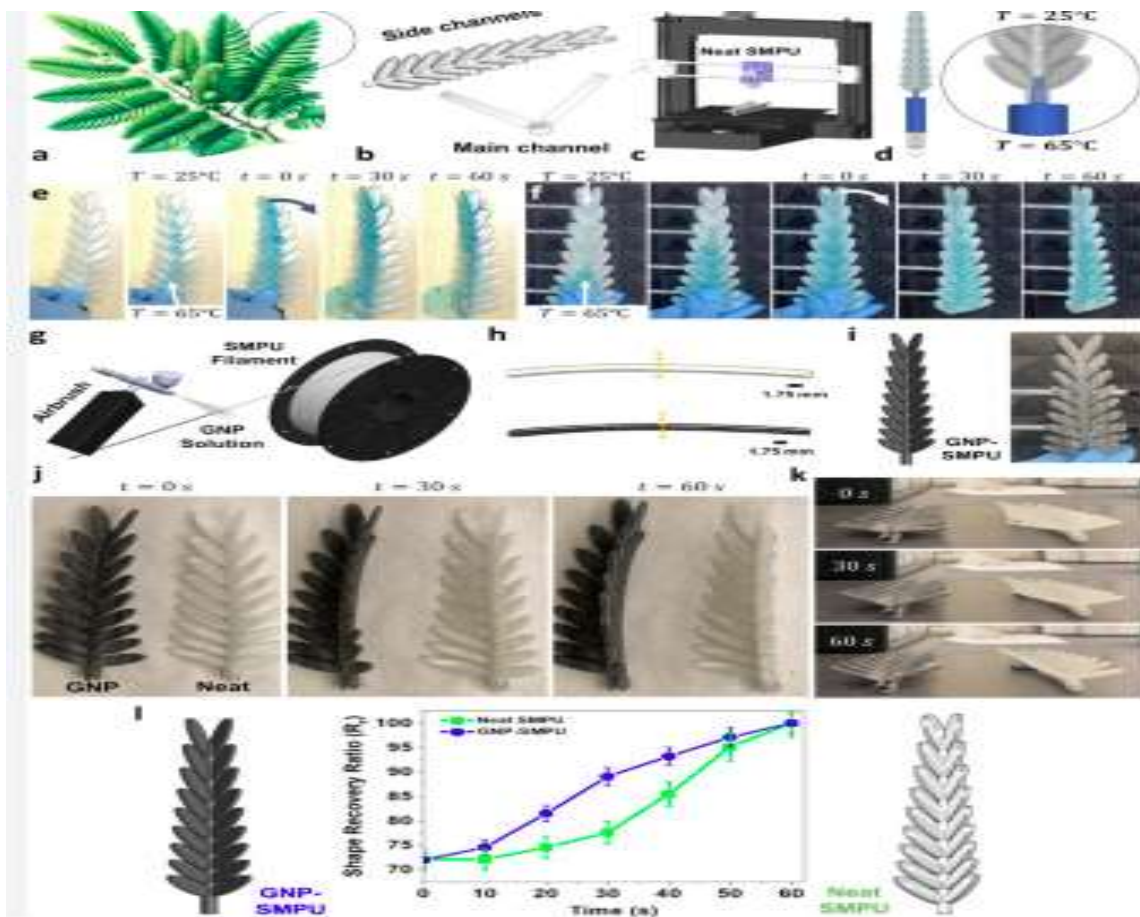


Fig3: Hydrogel-based tactile sensors inspired by the Mimosa pudica

Working: These nanosensors can sense touch or pressure, which causes the constituting hydrogels to change their shape. Other devices interpret this change in shape as a signal.

Applications

The application of hydrogel-based tactile nanosensors is as follows:

1. **Sensitive Robotic Skins** for Enhancing the Touch Sensitivity of Robots. fig4b

2. **Smart Bandages** for monitoring real-time wound healing.Fig4 a.



Fig4: (a) Smart Bandages

(b) Robotic skin

Thermoresponsive Self-Folding Microgrippers

Thermoresponsive self-folding microgrippers are smart, stimuli-responsive nanosensors that autonomously change shape in response to temperature variations. Their bistable states provide stability in both gripping and releasing configurations. These energy-efficient devices are typically fabricated from advanced materials, such as shape-memory alloys and liquid crystal elastomers, which enhance their overall performance and efficiency.

The principles behind thermoresponsive microgrippers draw inspiration from natural mechanisms, such as the Venus flytrap's rapid movement and tulips' temperature-driven petal movements, which inspire innovation in nanotechnology.

The insectivorous plant Venus flytrap (*Dionaea muscipula*) senses mechanical stimuli through sensory hairs. It rapidly closes its lobes via changes in turgor pressure, an example of a bistable, energy-efficient biological mechanism.

Tulips (*Tulipa*) and related species display nastic movements, ie, opening and closing of petals in response to changing temperatures. This thermonasty is due to differential cell growth on the inside and outside of the petals, which helps to shield the reproductive parts from adverse conditions. Microgrippers achieve this thermal response by utilizing materials featuring an integral design that accommodates thermal contraction and expansion.

Applications

1.Agriculture

Thermoresponsive microgrippers enhance precision agriculture through their multifunctional capabilities, including seed handling, soil health monitoring, and intelligent irrigation system control. At various depths, these tools sample soil and provide information on moisture content, nutrient levels, and temperature changes, thereby ensuring optimal planting conditions and facilitating efficient pest management

2. Environmental and Ecological Monitoring

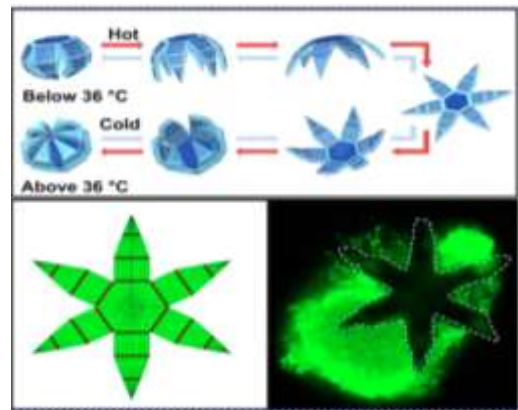
In environmental monitoring, these microgrippers can collect and analyze samples from air, water, and soil to detect pollutants and track changes in ecosystems. Their temperature-responsive mechanisms enable enhanced accuracy in measuring pollution, assessing biodiversity, and tracking climate-related shifts in the behaviors of plants and animals.Fig5.



(a)



(b)



(c)

Fig5: Closure of Venus Flytrap (b) Thermonastic behavior of tulips (c) Biomimetic soft gripping

3. Medicine

Microgrippers enhance medical procedures by delivering precise medication based on body temperature changes, assisting in minimally invasive surgeries by gripping tissues, and improving diagnostic accuracy for sample collection and testing.

4. Energy

In the energy sector, microgrippers help in harvesting energy by converting thermal gradients into electrical energy. It also enhances smart grids through temperature-based monitoring and control of energy flow, thereby improving the thermal management of electronic devices and energy storage systems.

Plant-Inspired Gas Nanosensors

Plant-inspired gas nanosensors mimic natural plant parts to detect gases with high precision. The tiny pores, called stomata, on leaves open and close to regulate gas exchange. Nanosensors utilize this mechanism for sensitive, specific gas monitoring, enabling applications such as air quality monitoring, soil health assessment, and greenhouse gas concentration measurement, such as carbon dioxide (CO₂). The hair-like structures called trichomes help plants sense environmental changes. Inspired sensors are used for industrial gas monitoring and detecting pollutants. The underground parts, such as the roots and rhizomes, interact with soil gases and exchange nutrients. These sensors are designed to evaluate soil conditions and fertility by detecting gases such as methane or hydrogen sulfide. fig6.

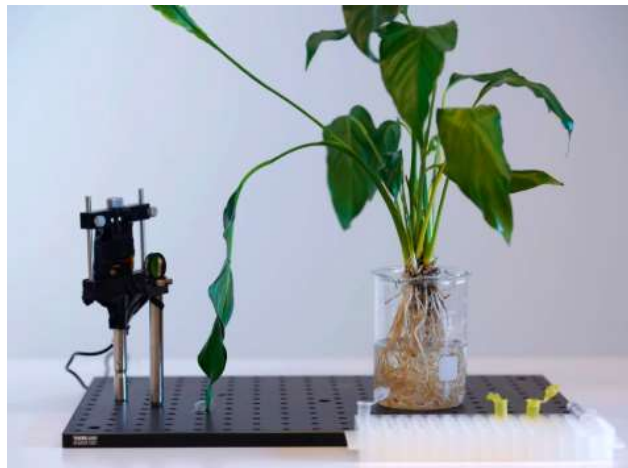


Fig6:Plant Inspired Gas nanosensor

Applications

Agriculture: Monitoring soil health using gas detection (e.g., methane and ammonia) and optimizing greenhouse conditions by measuring CO₂ levels.

Industries: Pollutants are detected by monitoring gases such as carbon monoxide and VOCs, thereby improving safety.

Energy: Enhanced bioenergy production and ensured safety by detecting gas leaks, such as methane.

Ecological Monitoring: Assess air quality, track greenhouse gas emissions, and study their impacts on ecosystems to support climate change research and mitigation efforts.

Microplastic Management: Detect and to analyze microplastics in environmental samples (water and soil) to monitor pollution levels, track sources, and develop remediation strategies.

Concerns and Ethical Issues surrounding Plant-Inspired Nanosensors

Plant-inspired nanosensors raise several ethical concerns and issues that must be carefully considered and addressed. Addressing these issues associated with plant-inspired nanosensors is essential to ensure their responsible development and deployment, striking a balance between innovation, safety, equity, and environmental stewardship. The ethical concerns include the following:

1. Environmental Impact

Nanomaterial Toxicity: Release of nanoparticles into the environment may cause risks to ecosystems. Nanoparticles may accumulate in soil and water, potentially harming plants, animals, and microorganisms.

Biodiversity: Introduction of synthetic nanomaterials into natural systems may disrupt local biodiversity and ecological balance. The long-term effects on biodiversity are yet to be fully understood.

2. Human Health and Safety

There are concerns about the potential toxicity of nanomaterials used in plant-inspired sensors. Inhalation, ingestion, or skin contact with specific nanoparticles may pose health risks to humans.

3. Privacy and Data Security

Data Collection: When agriculture and environmental nanosensors are used, large amounts of data are collected, raising concerns about security and privacy. It can be safeguarded by preventing unauthorized access.

Surveillance Concerns: Nanosensors used for environmental monitoring raise ethical concerns about the need for consent and the protection of individuals' privacy and society's privacy.

4. Regulatory and Governance Issues

Advancements in nanotechnology sometimes surpass the governing structures. Comprehensive regulatory frameworks are required to govern the production, use, and elimination of plant-inspired nanosensors. Establishing ethical guidelines for research and development in this field is essential to ensure that the technology is used responsibly for the benefit of society

5. Research and Development Concerns

Ensuring that the research and development of plant-inspired nanosensors adhere to ethical standards, including the responsible use of funding, transparency, and their potential long-term impacts.

CONCLUSION

Mimicking plants and other biological structures that have evolved over billions of years helps us understand nature's designs by integrating biomimicry with nanotechnology, offering the potential to transform diverse areas of human interest through more efficient, cost-effective, and sustainable solutions. These solutions help us innovate faster, more efficiently, and with fewer resources than traditional methods and research methodologies, which often consume significant time and resources. However, we must prioritize ethical concerns and challenges, including environmental impact, human safety, misuse, data and privacy, and government regulations. With the rapid advancement in the research and development of phytomimetic nanosensing technology, we are hopeful of a brighter, interdisciplinary, and sustainable future.

REFERENCES

1. Plant Structure and Function for Biomimetic Innovation: Dr. M. Padma Sundari, Department of Botany, St. Joseph's College for Women (A), Visakhapatnam. Futuristic Trends in Biotechnology Volume 3 Book 17 (pp.91-96),2024.
2. Biomimicry: Exploring Research, Challenges, Gaps, and Tools by Sunil Sharma and Prabir Sarkar. Research into Design for a Connected World: Proceedings of ICoRD 2019 Volume 1, 2019
3. Advances in Biomimetic Stimuli-Responsive Soft Grippers by Chang Kyu Yoon. Nano Convergence, 2019•Springer
4. Biomimetic Venus Flytrap structures using Smart Composite by Bing Wang, Yi Hou, Shuncong Zhong, Jucheng Zhu, and Cheonlong Guan. <https://www.mdpi.com/1996-1944/16/20/6702>
5. A perspective on plant robotics: from bioinspiration to hybrid systems by Fabian Meder, Bilge Baytekin, Emanuela Del Dottore, Yasmine Meroz, Falk Tauber, Ian Walker, and Barbara Mazzolai. [Bioinspiration & Biomimetics, Volume 18, Number 1](#)
6. Nanotechnology, Nanomedicine; Ethical Aspects by Banu Gockay and Berna Arda, PubMed.
7. From Nature to Technology: Exploring the Potential of Plant-Based Materials and Modified Plants in Biomimetics, Bionics, and Green Innovations by Marcela-Elisabeta Barbinta-Patrascu, Bogdan Bitu, and Irina Negut. *Biomimetics* 2024, 9(7), 390; <https://doi.org/10.3390/biomimetics9070390>
8. Bio-actuated microvalve in microfluidics using sensing and actuating function of *Mimosa pudica* by Yusufu Aishan, Shun-ichi Funano, Asako Sato, Yuri Ito, Nobutoshi Ota, Yaxiaer Yalikun & Yo Tanaka. *Scientific Reports* volume 12, Article number: 7653 (2022)
9. Micro-Mechanosensory Insights from Nature's Mimosa Leaves to Shape Memory Adaptive Robotics by Lihua Lou, Kazue Orikasa Lopez, Arya B. Nair, William Desueza, and Arvind Agarwal. Volume 12, Article number: 7653 (2022)

10. Hoff.man, A. J. (2010). Positive Deviance for a Sustainable World: Linking Sustainability and Positive Organizational Scholarship. http://deepblue.lib.umich.edu/bitstream/2027.42/66462/1/1139_Hoff-man.pdf
11. Enyoh, C., Enyoh, C., Rana, M., Osigwe, S., Ihenetu, S., Wang, Q., & Wang, Q. (2024). Chemicals from Brominated Flame Retardants: Analytical Methods, Occurrence, Transport and Risks. *Applied Sciences*, 14(17), 7892
12. Morales-Martínez, D., Bernal, L., Galindo, J., Aguilar, J., & Acosta-Vargas, P. (2025). **Rethinking Usability in Serious Games: Designing an Instrument That Evaluates What Really Matters in Learning Contexts.** *Applied Sciences*, 15(18), 10084.