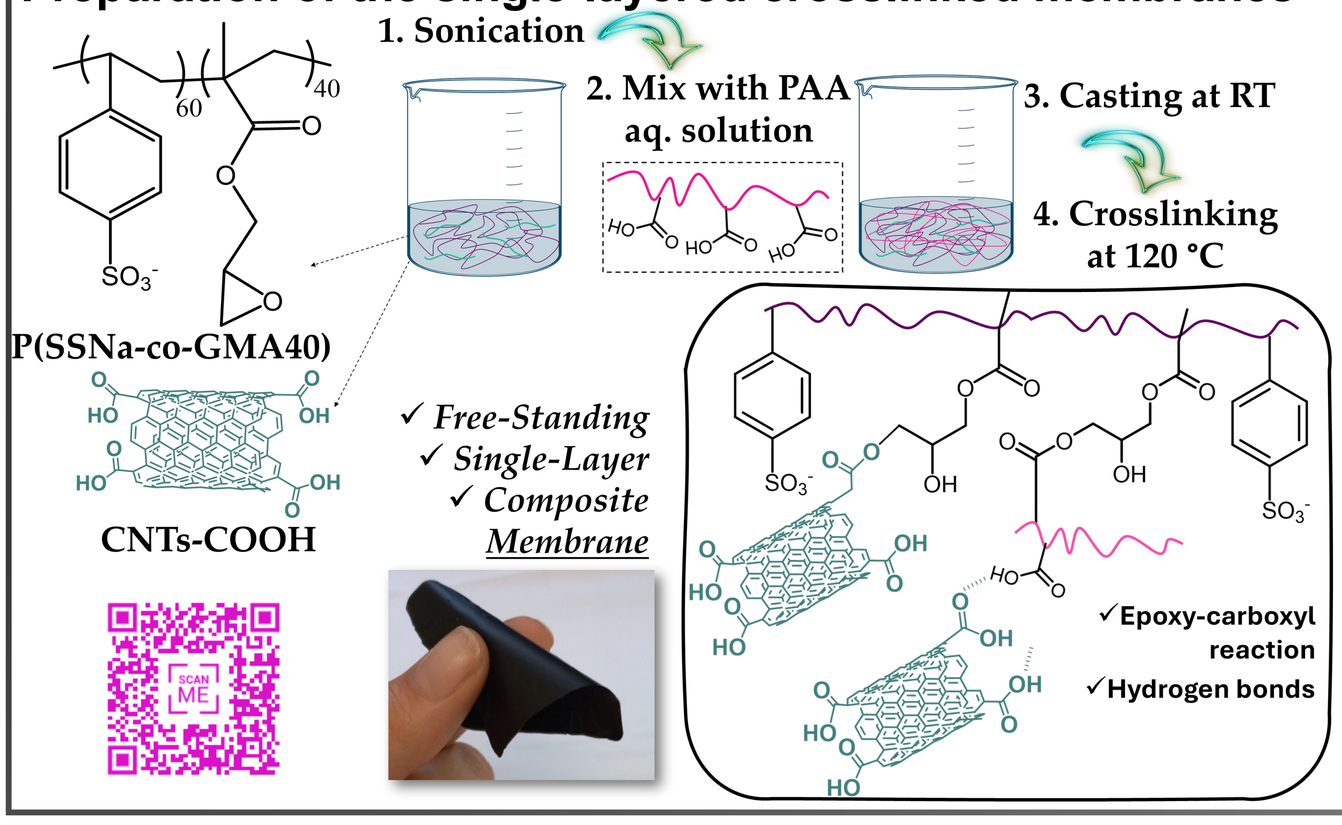
# Single-layer humidity-responsive membranes with advanced applications and moisture-electricity generation ability

**Ioanna Tzoumani[1], Konstantinos C. Andrikopoulos[1], Joannis Kallitsis[1,2]**

[1] Department of Chemistry, University of Patras, GR-26504 Rio-Patras, Greece;
[2] FORTH/ICE-HT, GR-26504 Rio-Patras, Greece

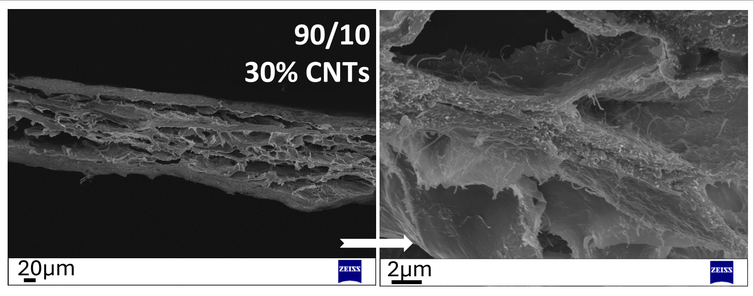
Exploring sustainable energy has been an urgent challenge for human society due to energy shortage. Harvesting electricity from ubiquitous atmospheric moisture has emerged as a promising technology to address the energy shortage challenge. Tremendous amounts of gaseous water molecules are stored in ambient air, serving as an overlooked, huge water and energy source[1]. ***Moisture electricity generators (MEGs)*** hold the potential to be an exciting next-generation platform for energy harvesting, because electricity can be generated directly through spontaneous moisture adsorption by functionalized nanomaterials[2,3]. Centering on the goal of high performance and continuous electricity output, we introduce ***single-layer crosslinked membranes*** employing ***water-soluble functional polymers*** combined with ***various carbon nanostructures***, which show ***high sensitivity to humidity***[4]. The fabrication process is cost-effective, scalable, and environmentally friendly. Properties of these hygroscopic materials, including their microstructure morphology, physicochemical, mechanical, and electrochemical characteristics, as well as their humidity-driven response, have been extensively studied. These self-standing composite membranes, capable of responding to humidity gradients, can likely enhance ***energy harvesting performance*** and unlock additional applications in the fields of ***actuators for non-contact human-machine interfaces and soft robotics***.

## Preparation of the single-layered crosslinked membranes




## Moisture as the key factor for actuation performance

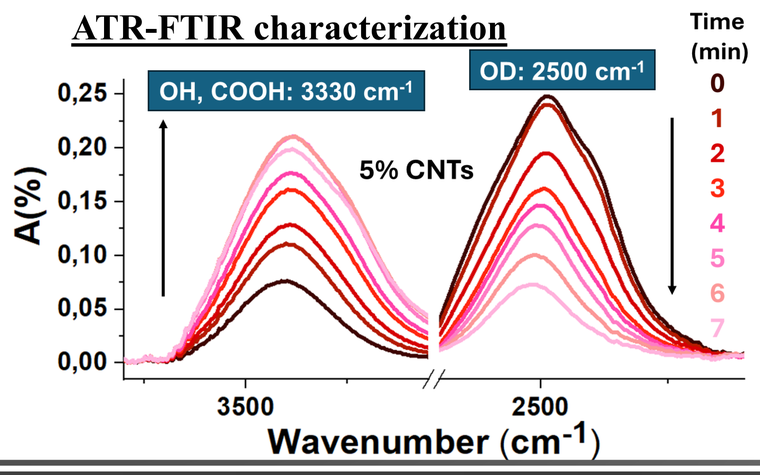
### Structural characterization of the swelled membranes




**Porous structure**

- ✓Moisture transport channels
- ✓Water exchange with surroundings

### ATR-FTIR characterization

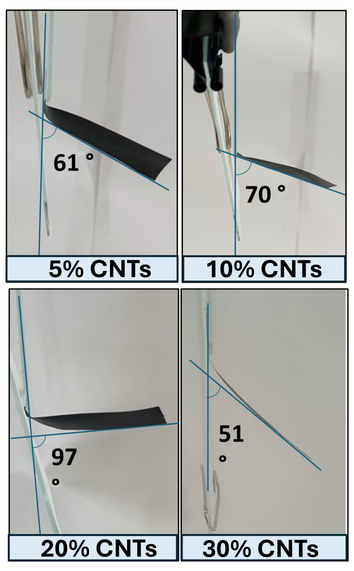



**Efficient and prompt absorption of water from its surroundings**

**Quick and reversible response to changes in environmental humidity**

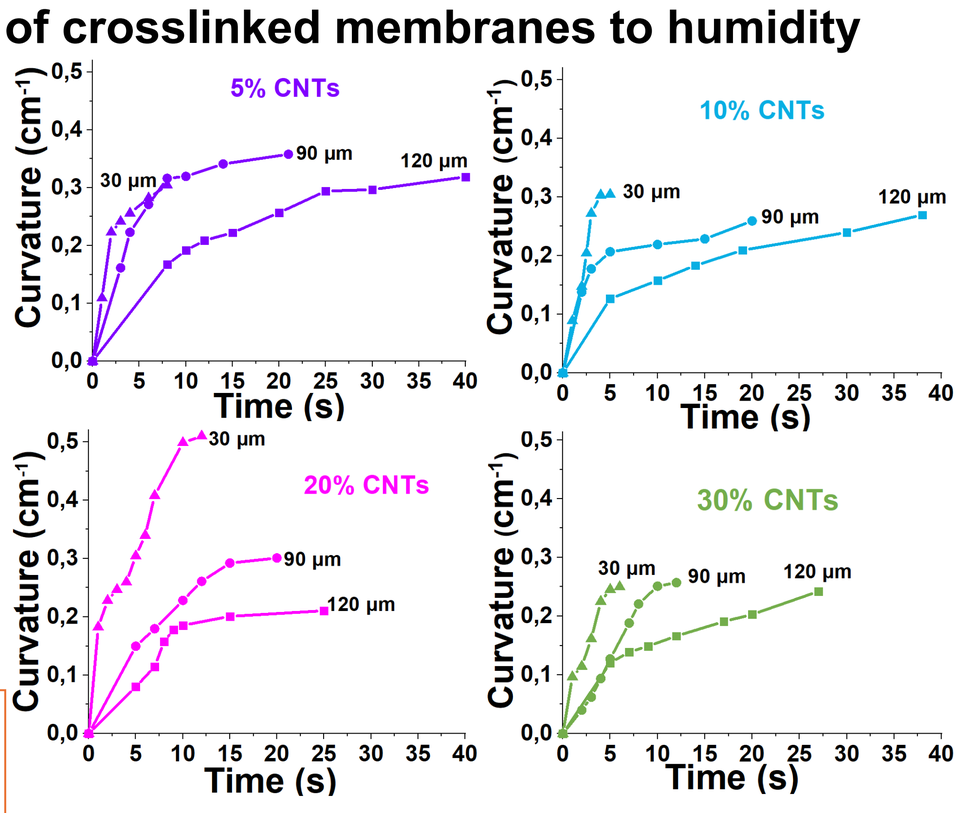
## Responsiveness of crosslinked membranes to humidity

### Bending angles




$$K = \frac{\alpha \times \pi}{180° \times L}$$

α (°): bending angle
L (cm): length of the free section of the curved membrane

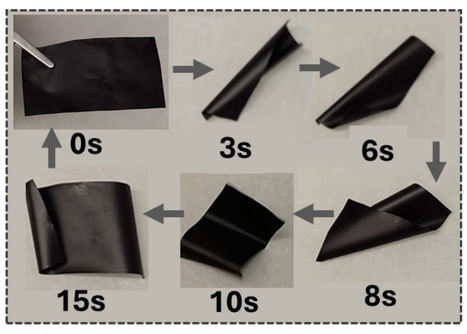


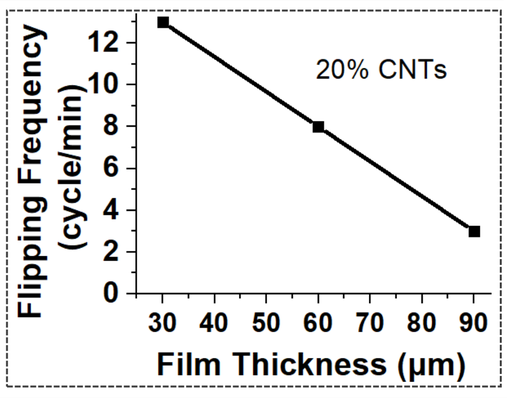

**Lower thickness of the membranes**
→ Higher curvature and speed actuation

### Flipping

- ✓ On moist paper
- ✓ On a bare hand
- ✓ With cargo
- ✓ Different shapes
- ✓ Several thicknesses

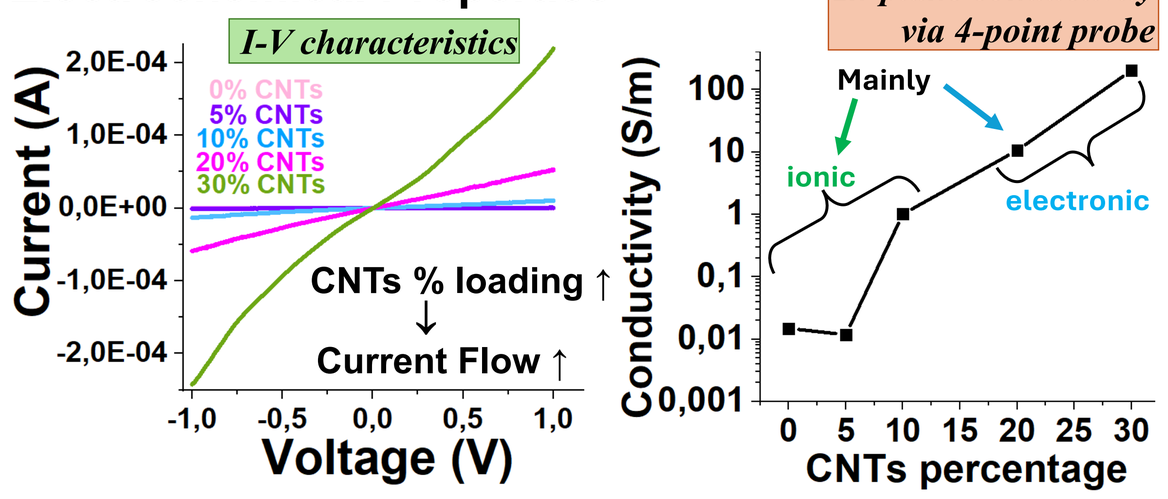
### Full flipping cycle



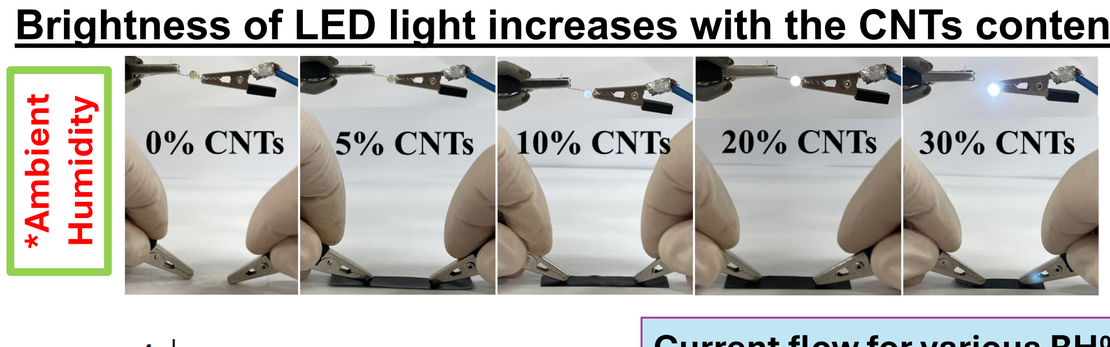




## Electrochemical Properties

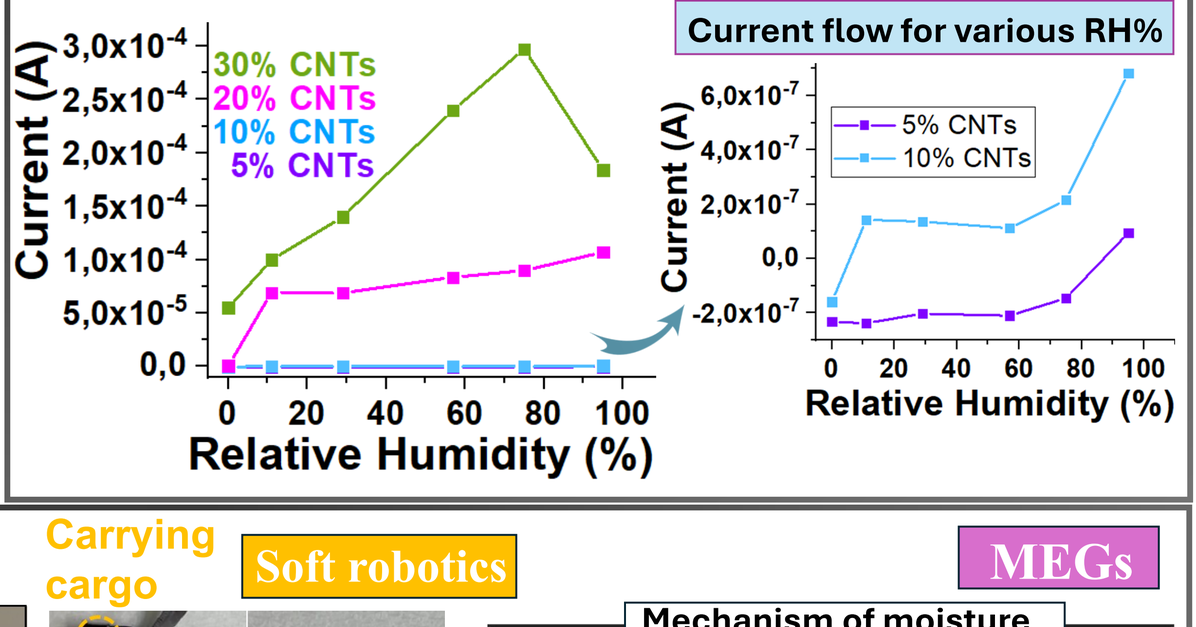
*In-plane conductivity via 4-point probe*



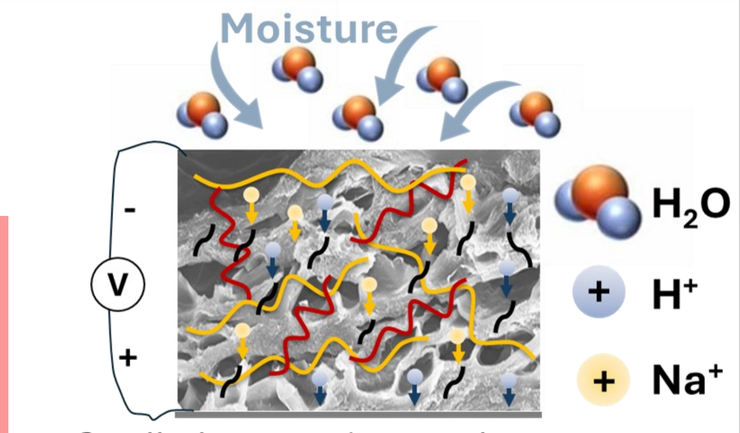

### Brightness of LED light increases with the CNTs content

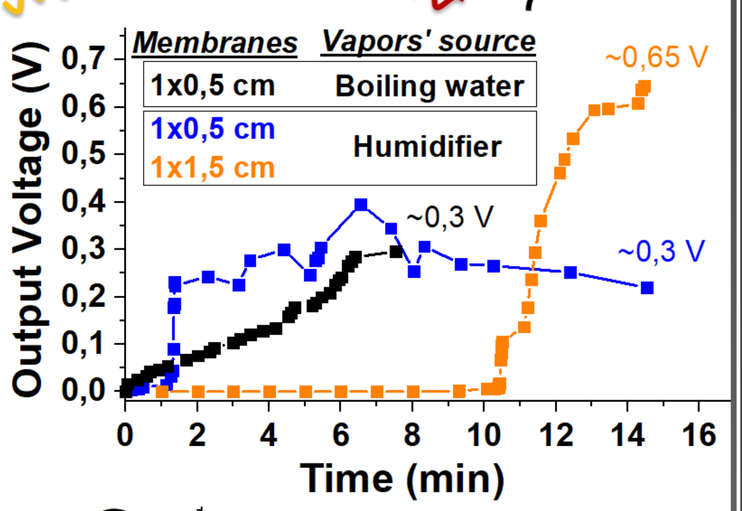


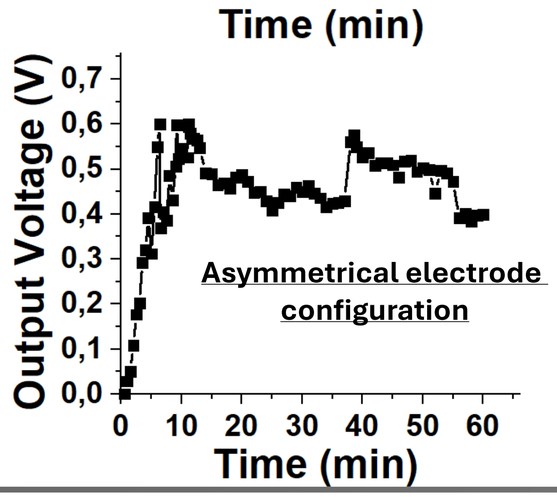

**Current flow for various RH%**




## Use of composite membranes as MEGs

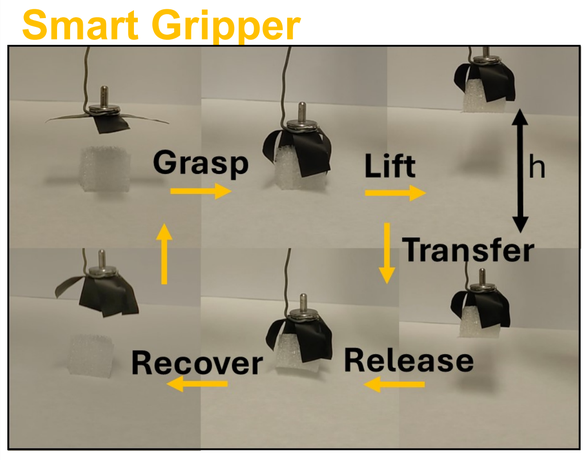


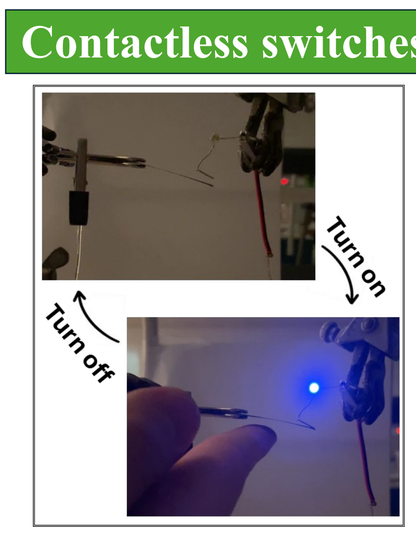

## APPLICATIONS

### Smart Gripper

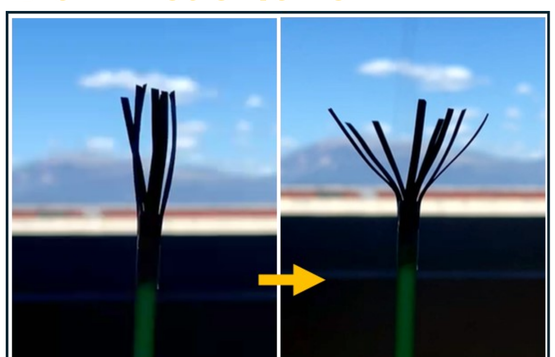



### Carrying cargo — Soft robotics

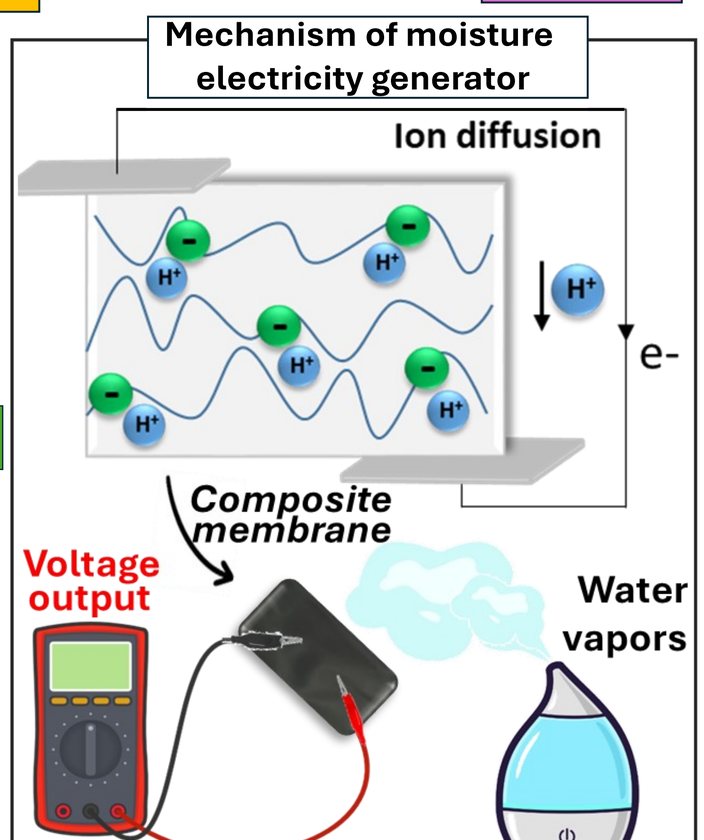
### Contactless switches




### Biomimetic flower




### MEGs




## Conclusions

- We developed humidity-sensitive CNTs-based membranes through a facile and environmentally friendly process.
- Composite membranes:
  - ✓ demonstrate rapid responsiveness to humidity changes.
  - ✓ exhibit mixed conductivity, due to the incorporation of CNTs, and P(SSNa-co-GMA40) that exhibits ionic conductivity.
  - ✓ with 30% CNTs can act as humidity-driven power-generator, providing a maximum voltage of ~600 mV.

## References

[1] Wang, P et al. *Cell Rep. Phys. Sci.* **2023**, *4*(8), 101517.
[2] Zhao, F. et al. *Adv. Mater.* **2015**, *27*(29), 4351-4357.
[3] Xu, T. et al. *Adv. Mater.* **2024**, *36*, 2209661.
[4] Tzoumani, I. et al. *J. Mater. Chem. C* **2024**, *12*, 11594–11602.

## Acknowledgements

This research has been financed by the Greece 2.0-National Re-covery and Resilience Fund: "Development of efficient third generation PV materials and devices to enhance the competitiveness of enterprises to the green energy produc-tion"_3GPV-4INDUSTRY. TAEDR-0537347.