

SWPNIOE 2026

Applied Physics & Sustainable Energy Technologies Session

From Bio-Waste to Sustainable Energy Materials

Carbon-Polymer Nanocomposites for Durable, Cost-Effective Applications

Dr. Monalisa Halder

Assistant Teacher (Physics), Dept. of School Education, Govt. of West Bengal
Research Collaborator, Department of Physics, National Institute of Technology Durgapur, India

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Outline

- ① Motivation & Context
- ② Precursor Architecture
- ③ Synthesis Route Overview
- ④ Carbonization & Pyrolysis
- ⑤ KOH Activation Thermodynamics
- ⑥ Mass-Ratio Optimization
- ⑦ Morphological Characterization
- ⑧ XRD Analysis
- ⑨ UV—Vis Spectroscopy
- ⑩ Optical Bandgap (Tauc Analysis)
- ⑪ Electrochemical Validation: CV
- ⑫ GCD & Impedance Spectroscopy
- ⑬ Charge-Transport (CBH) Mechanism
- ⑭ Nanocomposites: PVA Host
- ⑮ Summary & Scalability
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Research Objectives & Scope



Synthesize

KOH-activated microporous carbon from tea waste — a scalable chemical-activation route



Formulate

Flexible AC-PVA nanocomposite films across a 0 / 2 / 4 wt% loading series (R1 / R2 / R3)



Evaluate

Structural, optical, electrochemical, and electrical-transport prospects for energy storage & microwave absorption

This talk centers on the tea-waste / AC-PVA system, where full experimental data is available; the rice-husk and PVDF extension is presented later as ongoing work.

The Energy Transition Challenge

- Fossil fuels are a leading source of global warming pollution — and even the waste products are hazardous to public health and the environment.
- Conventional nanocarbons (pristine CNTs, synthetic graphene) perform exceptionally — but at high production cost, with toxic solvents and energy-intensive manufacturing.
- ‘Bio-waste-to-Energy’ is increasingly recognized as an important renewable pathway — biomass valorization offers abundance, carbon richness, and genuine circular-economy feasibility.

0

cost of the feedstock —
it's waste

KOH

low-cost chemical
activation route

Circular

economy pathway:
waste → material →
device

Flexible

films for energy storage
& microwave-absorbing
applications

Regional Context: Tea Waste in India

- India is the second-largest producer of tea (Assam and Darjeeling tea) in the world, after China.
- As the world's largest consumer of tea, India uses nearly 30% of global tea output — generating a large amount of tea waste daily.
- Tea waste is usually disposed of by burning or landfill deposition, causing environmental harm.
- **Conversion to porous/activated carbon is a far more environment-friendly, higher-value route.**



Why Tea Waste?

Abundant, low/zero-cost, and otherwise an environmental liability

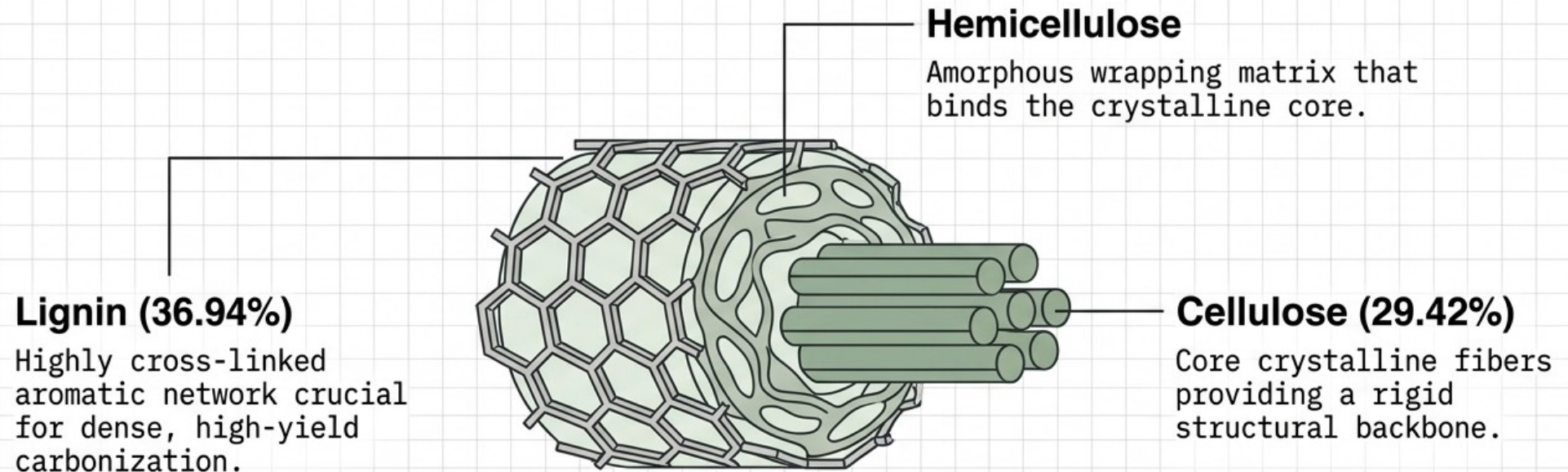


Also Widely Used

Dates' stones, coconut shells, wood, rice husk, banana peel are other reported AC precursors

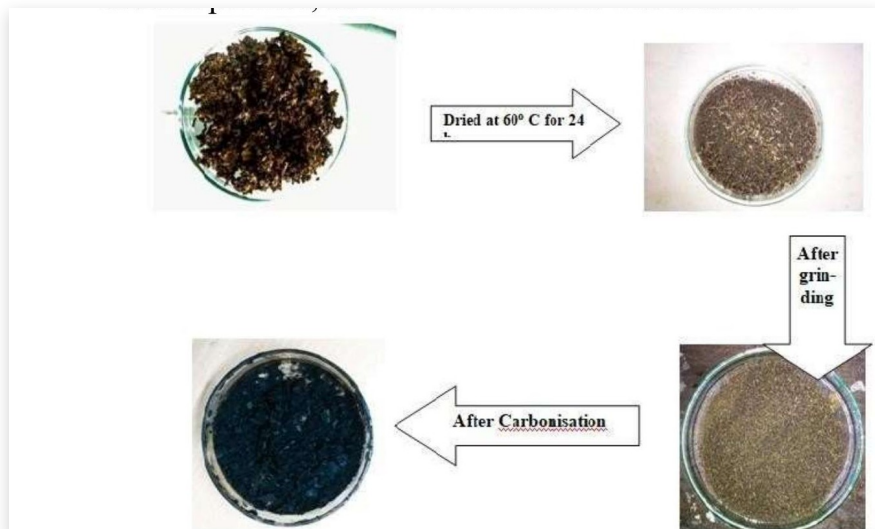
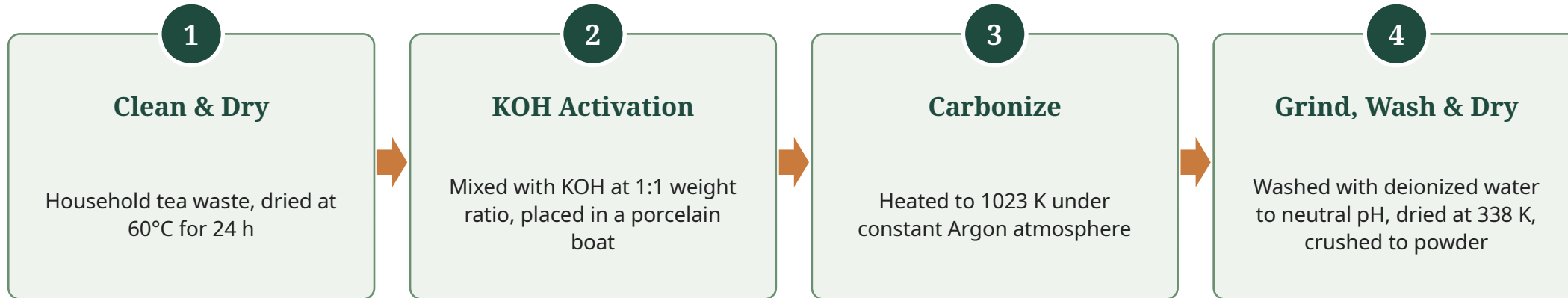
"...as the world's largest consumer of tea, India uses nearly 30% of global output."

The Precursor Architecture: Unlocking Lignocellulose



Core Insight: High native concentrations of cellulose and lignin directly correlate to a more robust, highly porous activated carbon yield after controlled thermal decomposition.

Synthesis of Bio-Derived Activated Carbon



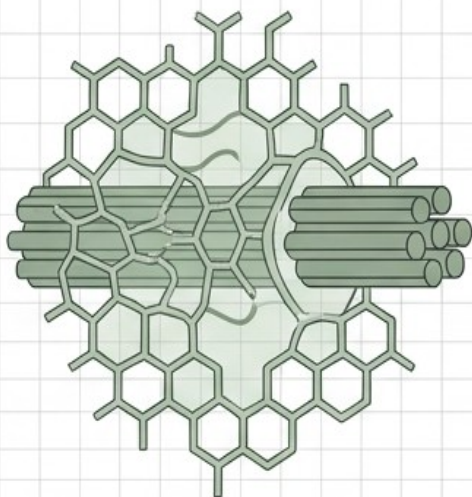
- By crushing into smooth powder, the final activated carbon (AC) is obtained — ready for nanofiller loading into the PVA matrix.

Digital-image flowchart: tea waste → dried → ground → carbonized.

Thermal Pyrolysis: Inert Atmosphere Carbonization

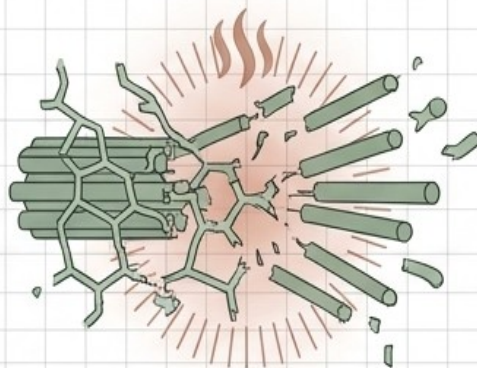
Step 1: Preparation

Pre-treated tea waste is loaded into a porcelain boat.



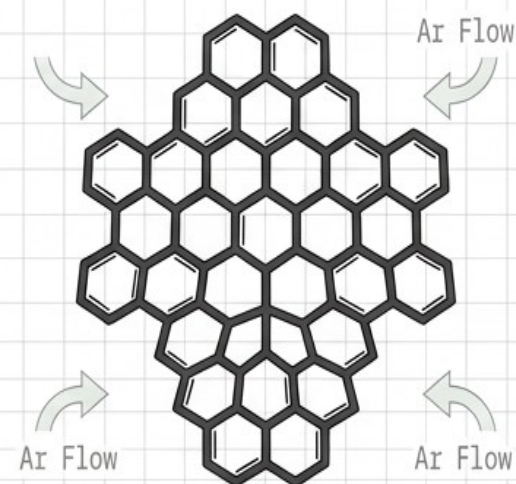
Step 2: The Thermal Cycle

Heated to a precise temperature of 1023 K (800°C) with controlled ramping and cooling.



Step 3: Inert Atmosphere

Constant, high-purity Argon (Ar) gas flow surrounds the precursor.



Atmosphere Rationale

High-purity Argon physically prevents any combustion or oxidation of the carbon networks at extreme temperatures.

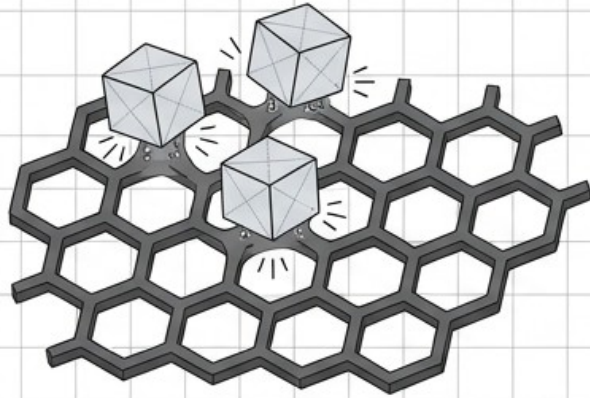
Physical Result

Complete thermal elimination of non-carbon organic elements, leaving a volatile-free black bio-char primed for chemical activation.

The Thermodynamics of KOH Activation

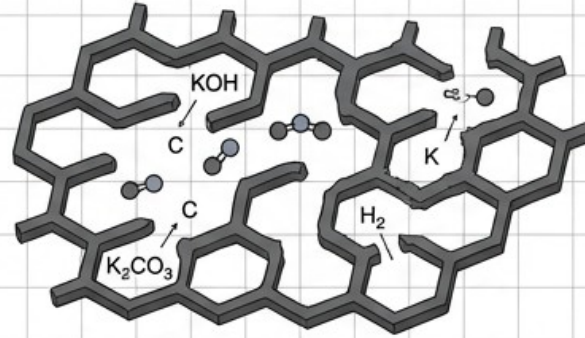
Mechanism: Chemical activation of bio-char via potassium hydroxide (KOH) mixing at a precise 1:1 initial weight ratio.

1. Solid-Solid Contact



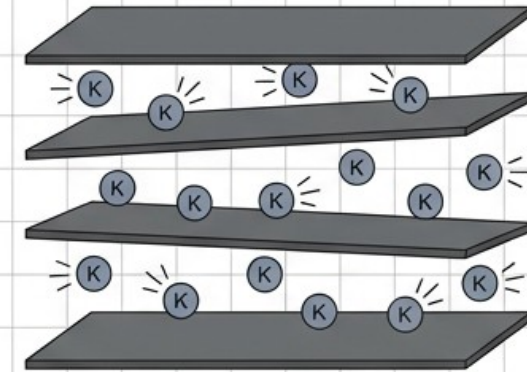
Solid-scale KOH particles contact and fuse into the carbon matrix under initial heating.

2. Solid-Liquid Etching ($T > 700^{\circ}\text{C}$)



Decomposition of K₂CO₃ to K₂O and CO₂ aggressively etches the carbon network.

3. Vapor Intercalation



Metallic potassium vapor physically wedges (intercalates) between carbon layers, exfoliating them to create extreme, ultra-high microporosity and surface area.

Composite Processing — Solution Casting

- Host polymer: PVA — easily processable, cheap, eco-friendly (PVDF is the next-stage matrix for piezoelectric work).
- AC dispersed at 2 wt% and 4 wt%; solutions poured into glass Petri dishes and dried in natural environment for 6 days.
- **Samples: R_1 = pure PVA, R_2 = 2 wt% AC-PVA, R_3 = 4 wt% AC-PVA.**

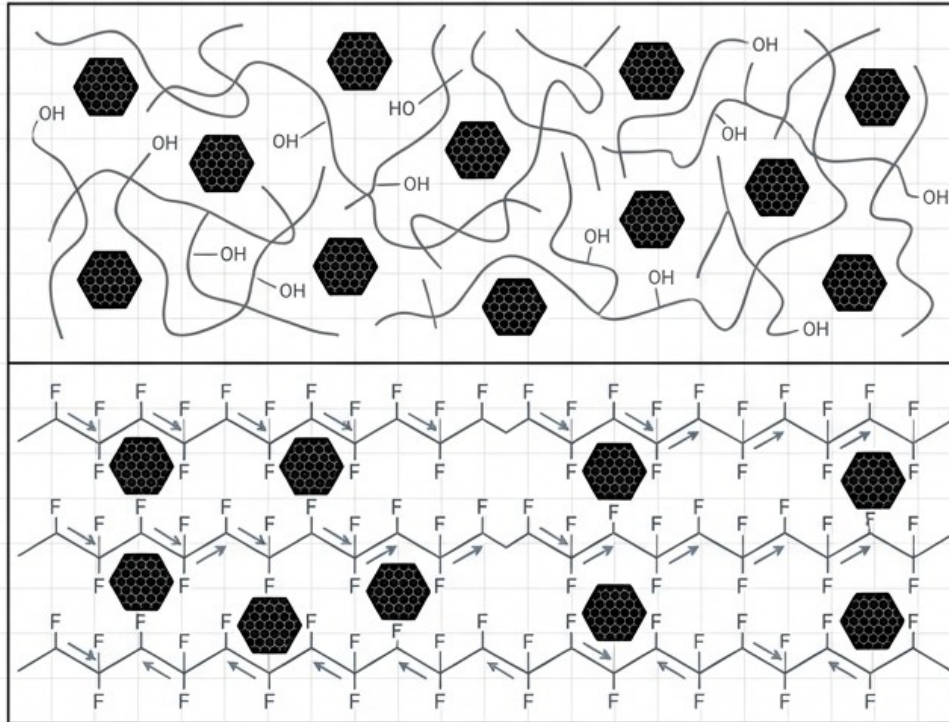


PVA solution under continuous stirring at 430 rpm.



The Composite Matrix: Tuning Polymer Hosts

Unifying Rationale: Dispersing high-surface-area activated carbon (AC) fillers into host polymers via solution casting at 430 rpm bridges atomic electrical properties with macroscopic device flexibility.



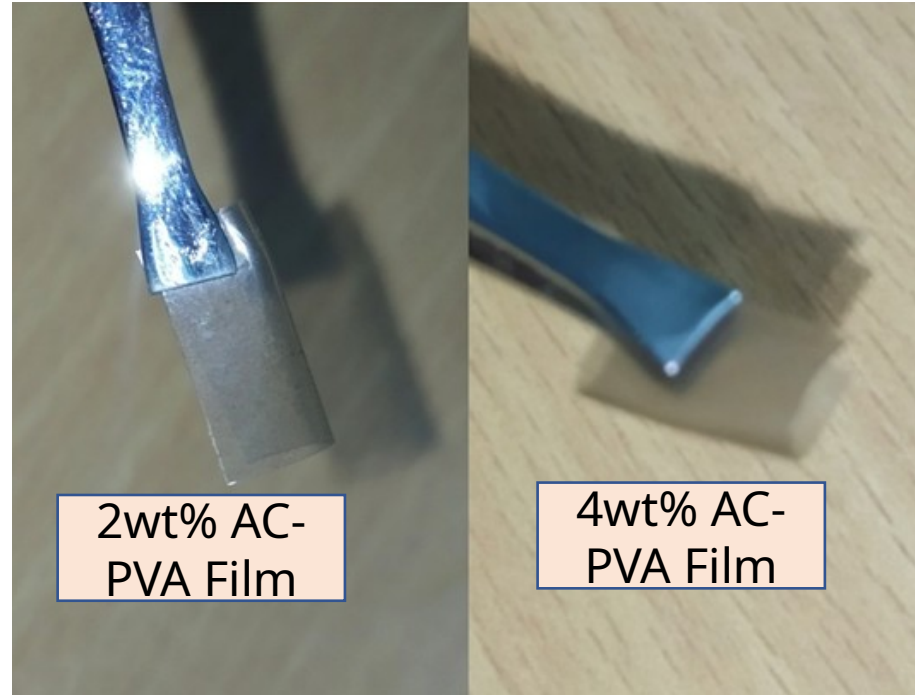
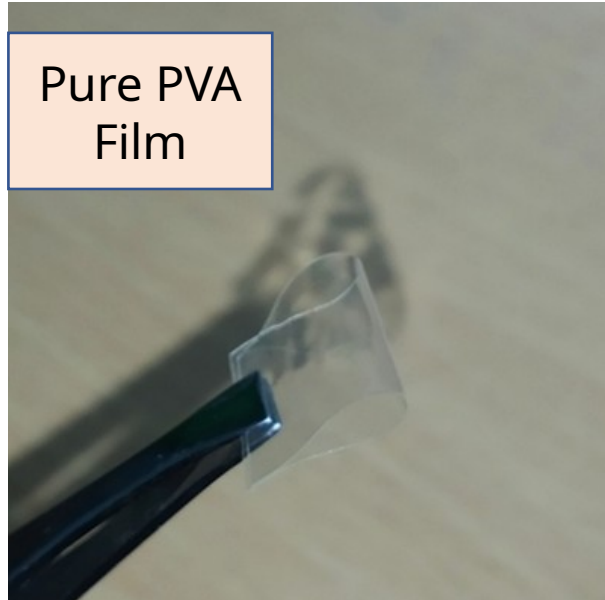
PVA (Polyvinyl Alcohol) Matrix

- Highly processable, abundant hydroxyl (-OH) groups, cost-effective, and eco-friendly.
- Serves as an ideal baseline for flexible, high-permittivity dielectric films in electrostatic energy storage.

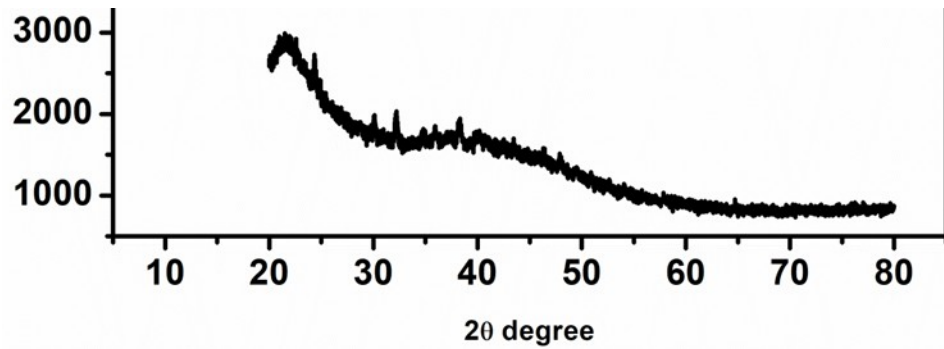
PVDF (Polyvinylidene Fluoride) Matrix

- Semicrystalline, polar beta-phase with fluorine (F) backbones, yielding intense dipole moments.
- Promotes strong interfacial polarization, unlocking stress-responsive Piezoelectric and Triboelectric (PENG/TENG) energy-scavenging devices.

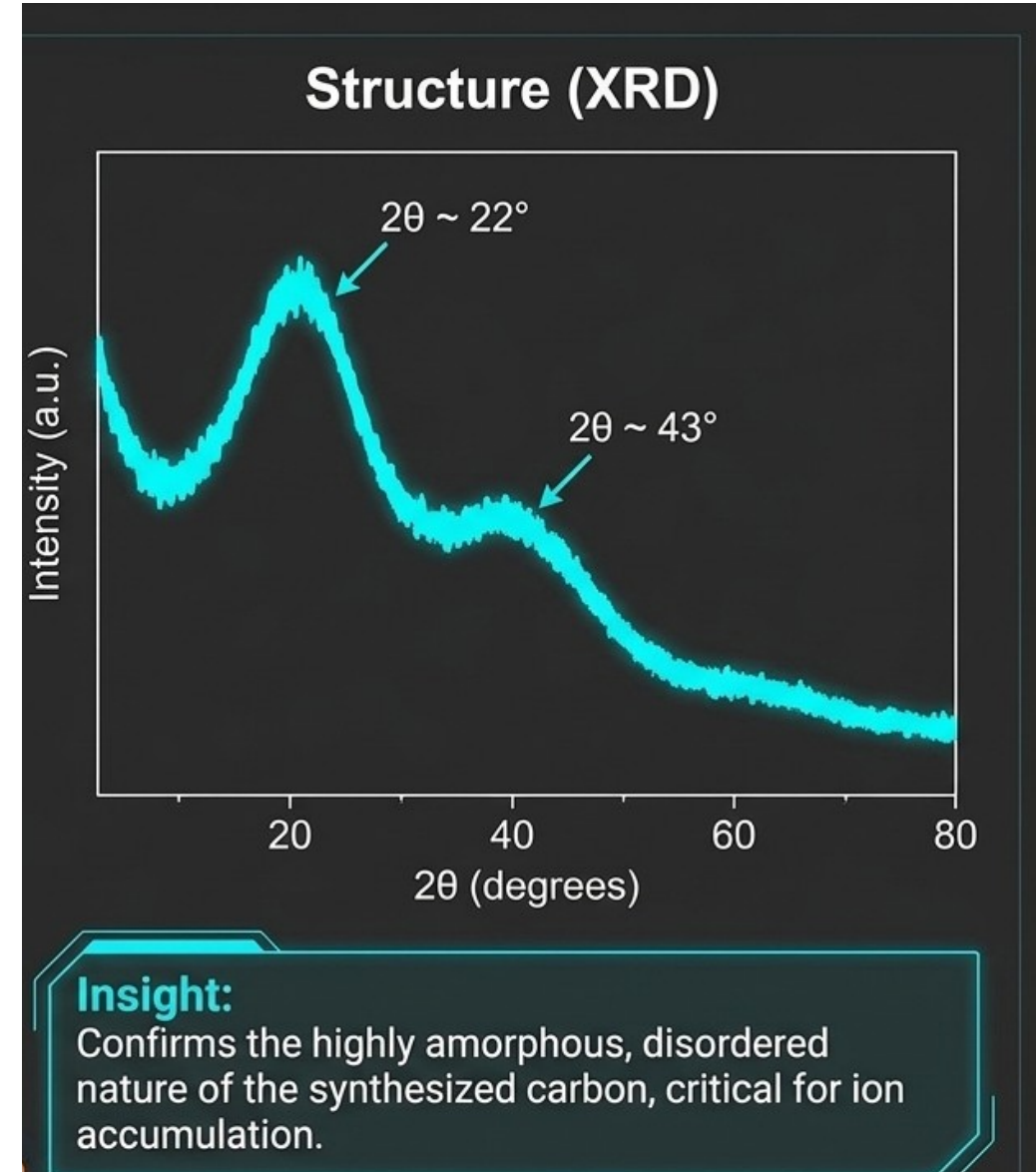
Flexible Films



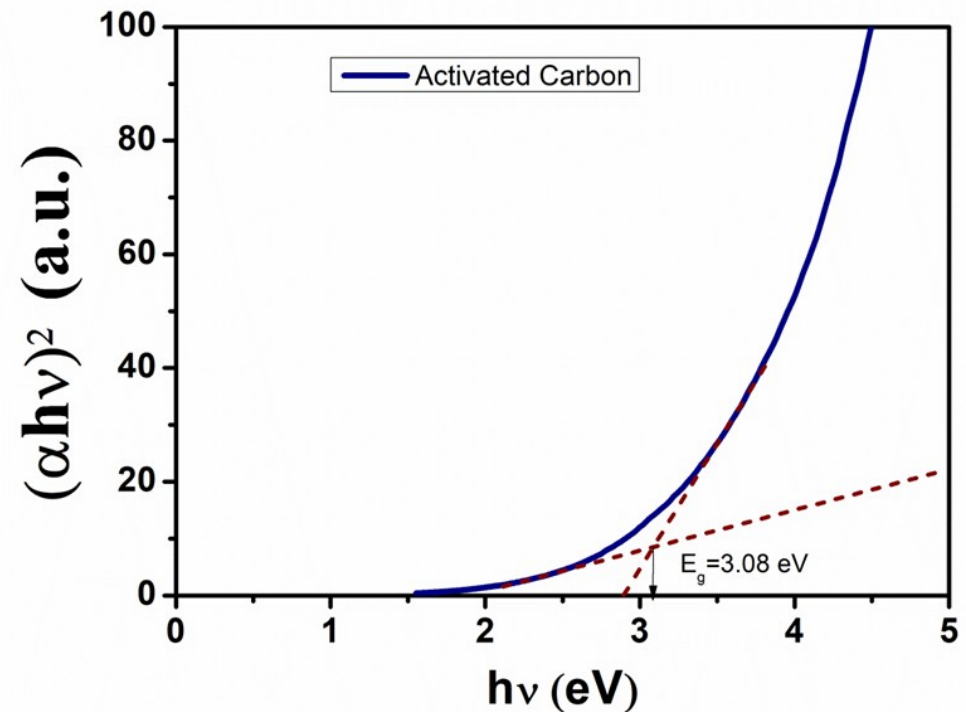
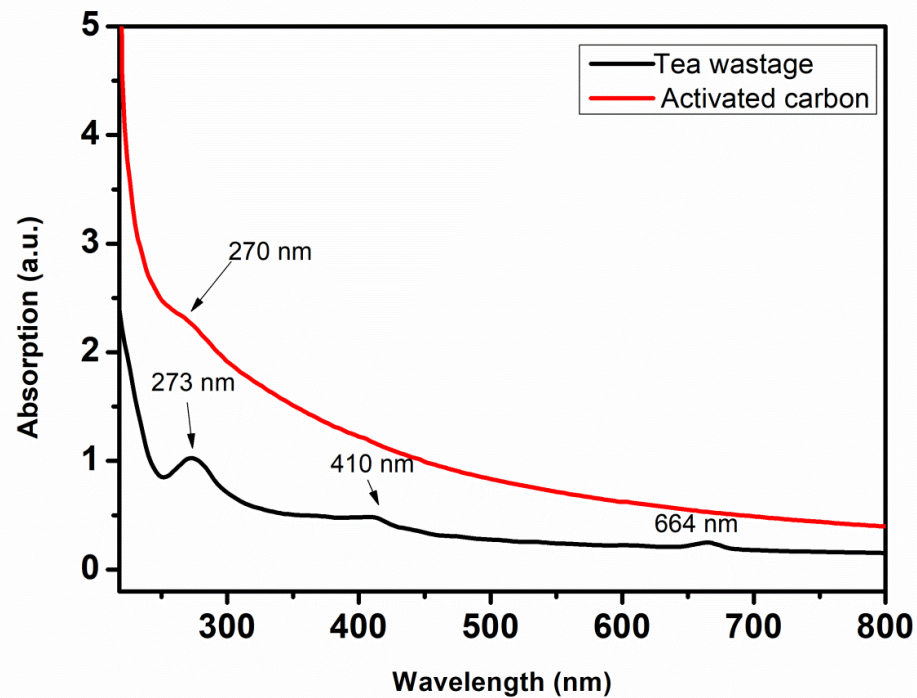
XRD Analysis



Room temperature XRD of tea wastage and synthesised activated carbon

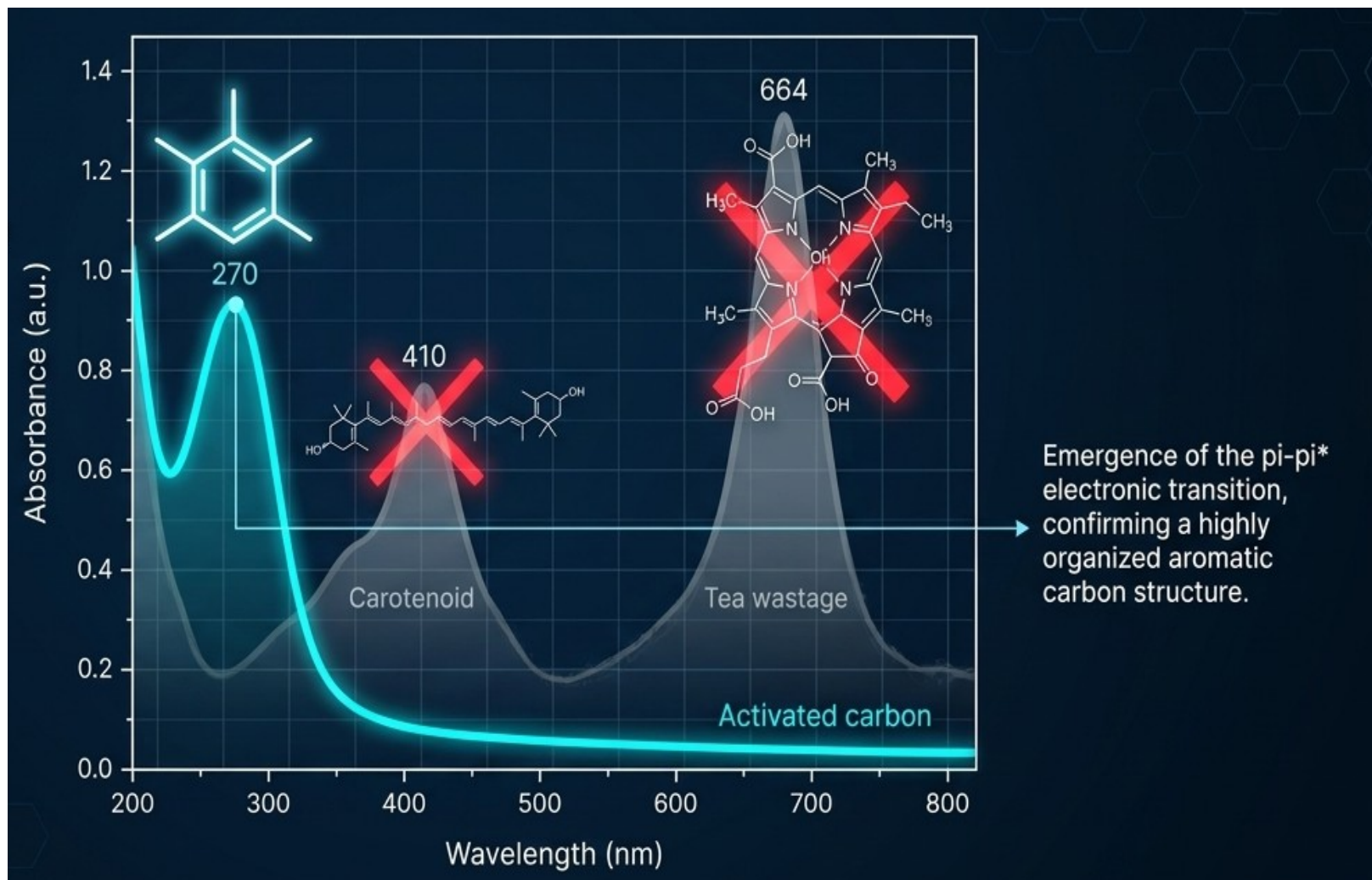


Optical Absorption & Bandgap

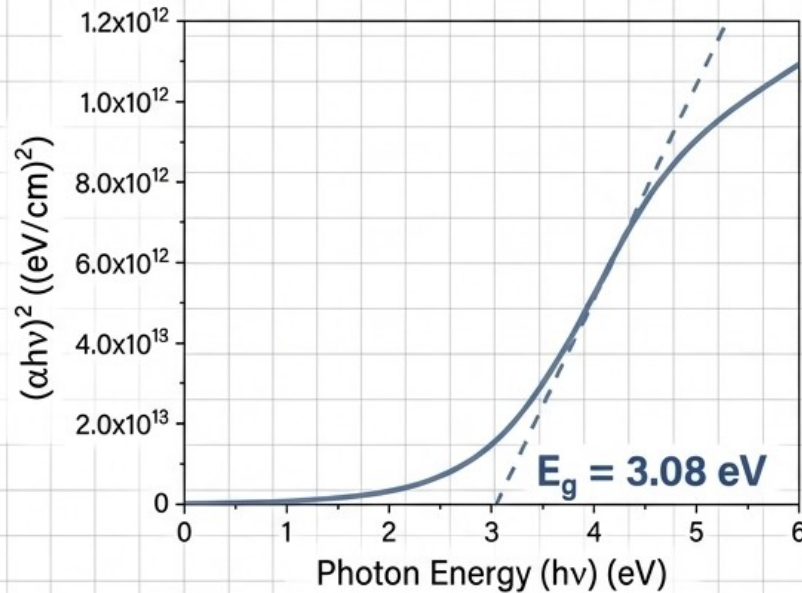


(a) UV-Vis: raw tea waste vs. activated carbon. (b) Tauc plot (direct transition) of activated carbon.

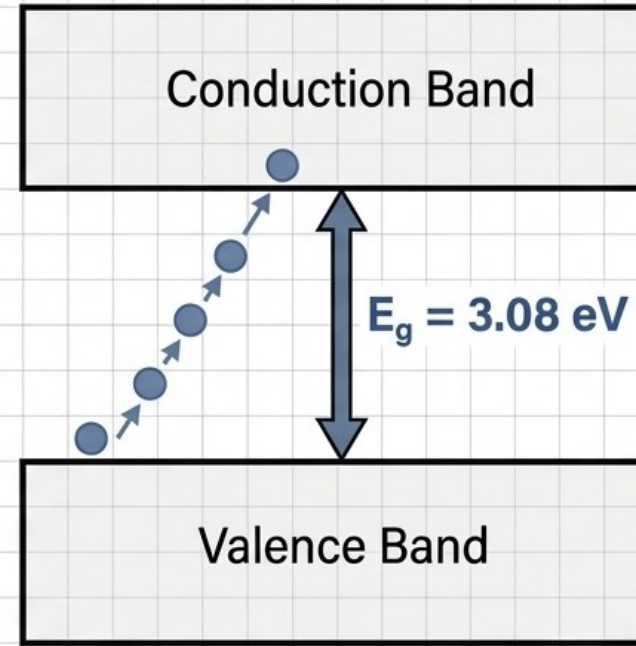
$E_g = 3.08$ eV — semiconducting, photoactive behaviour



Quantum Emergence: Optical Bandgap Analysis



Analytical Method: Extrapolation of the direct optical bandgap using the Tauc relation.

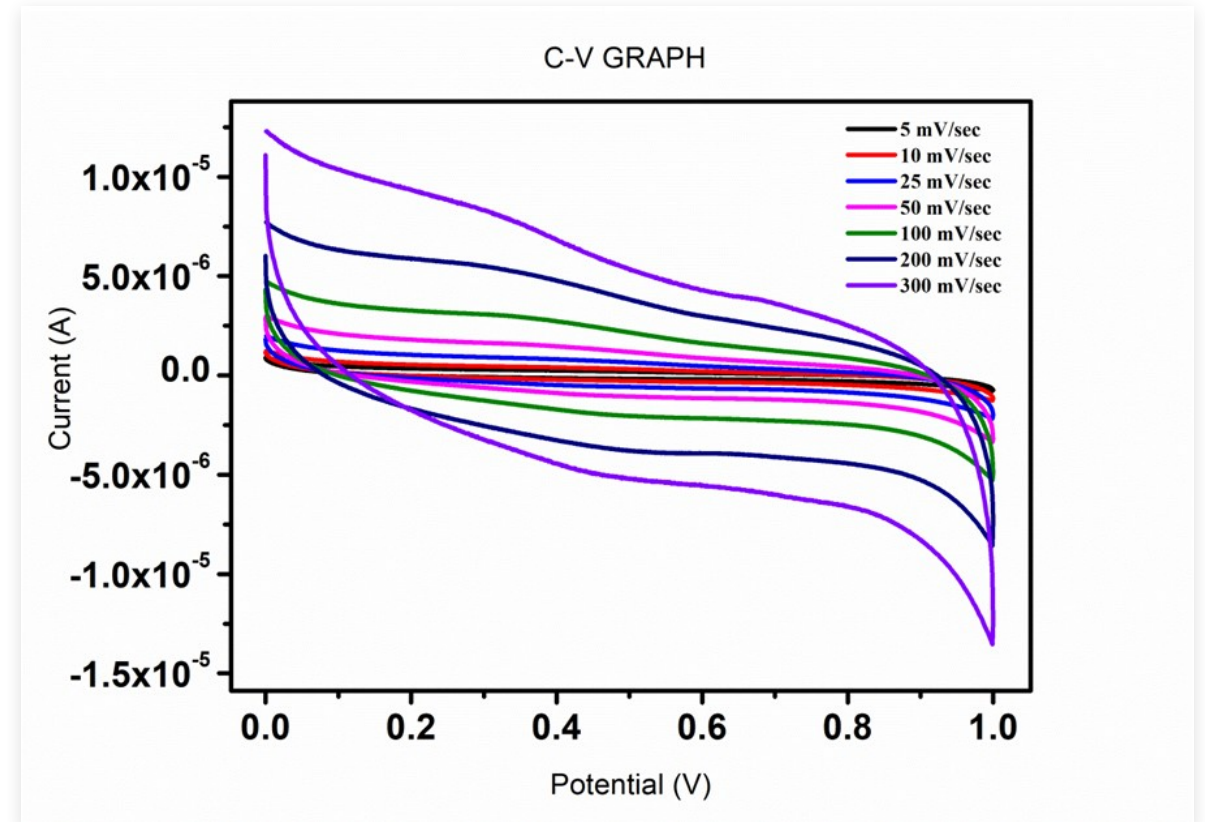


Scientific Conclusion: A bandgap of $< 4.0 \text{ eV}$ ($E_g = 3.08 \text{ eV}$) confirms that the bio-derived activated carbon behaves as a wide-bandgap semiconductor. This unlocks photoactive potential under UV light, qualifying the material for active optoelectronic and photocatalytic applications.

Gemini Notebook

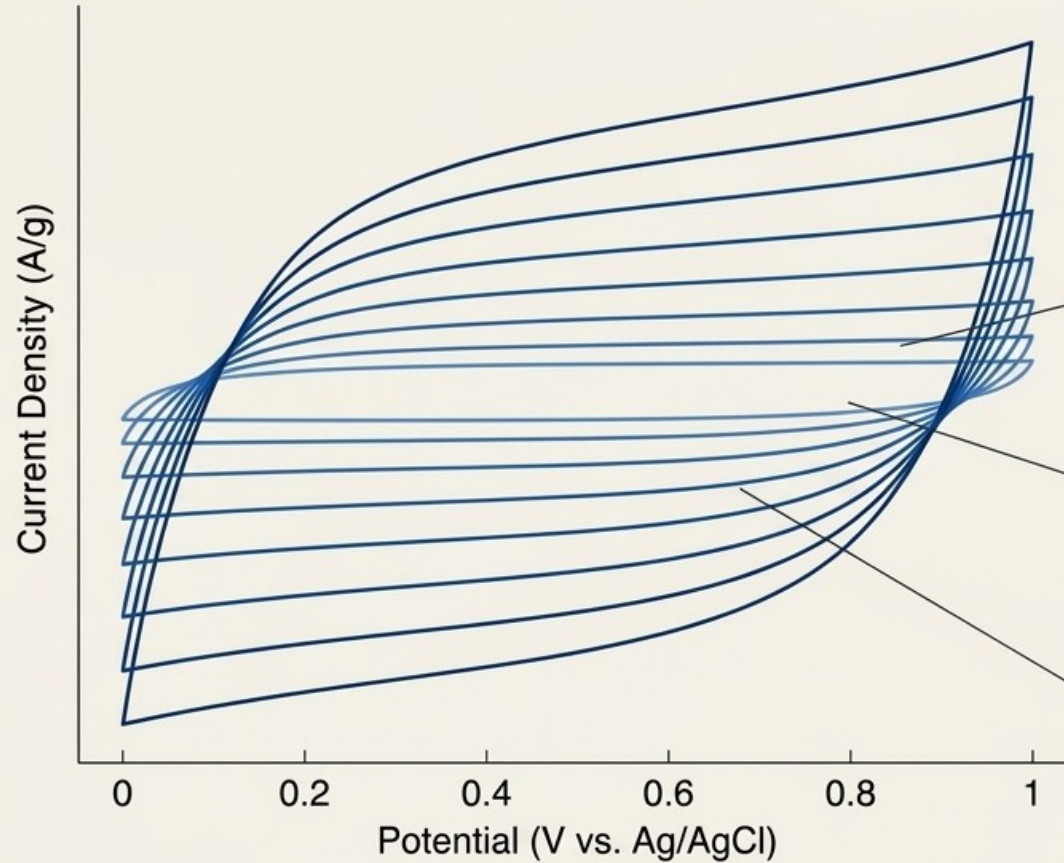
Cyclic Voltammetry & Charge Dynamics

- Rectangular, quasi-ideal EDLC response maintained up to 100 mV/s — good capacitor-like, electric-double-layer characteristics.
- Curve deforms above 200 mV/s; current density rises with scan rate.
- **No redox peaks — the supercapacitive property is free from Faradaic reactions.**



CV curves of activated carbon, 5–300 mV/s, 0–1 V (room temperature).

Electrochemical Performance: Cyclic Voltammetry



Test Conditions:

Room temperature, potential range of 0 to 1 V.

Insight 1: EDLC Behavior

Curves maintain a rectangular, quasi-ideal response up to 100 mV/s, representing strong Electric Double Layer Capacitance.

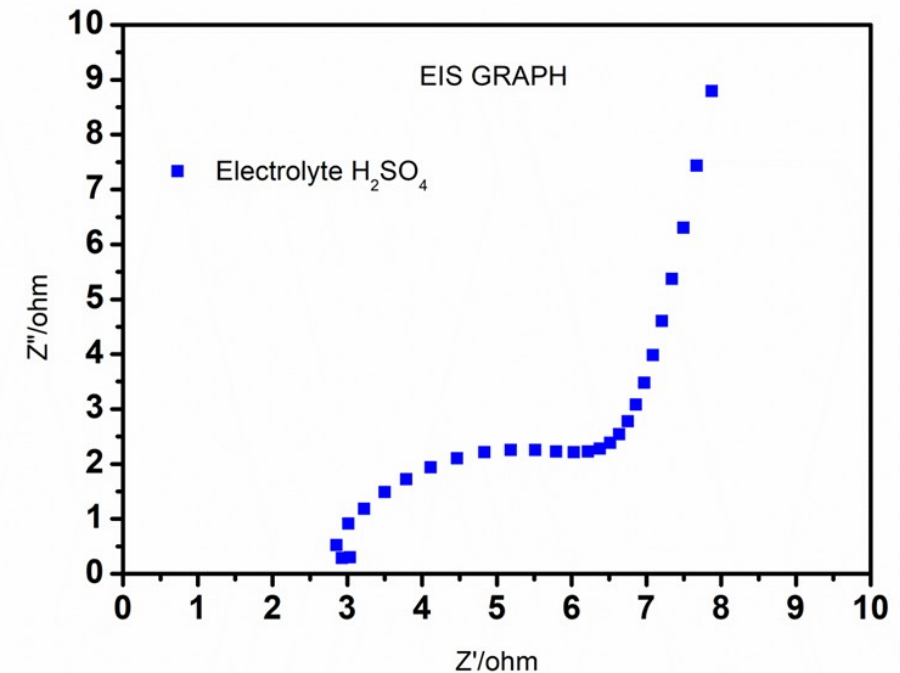
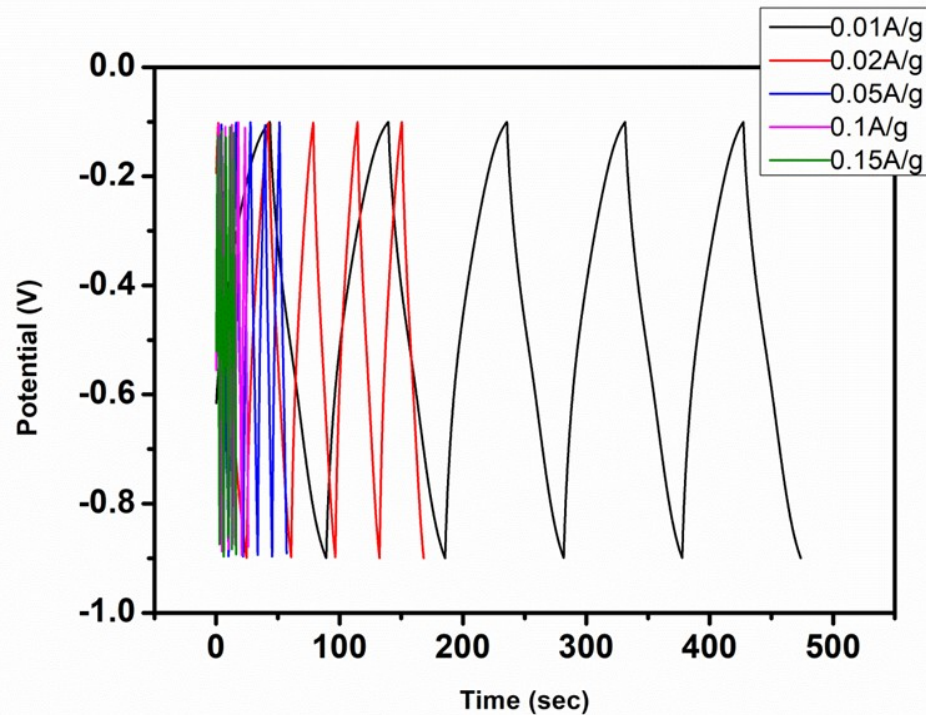
Insight 2: Rate Capability

Current density scales predictably with increased scan rate, though slight curve deformation occurs above 200 mV/s.

Insight 3: Redox-Free

The total absence of distinct peaks in the CV curve confirms the supercapacitive property is entirely free from Faradaic (redox) reactions.

Charge–Discharge Behaviour & Impedance



(a) GCD curves, 0.01–0.15 A/g. (b) Nyquist plot (EIS), 100 Hz–106 Hz, 1 M H_2SO_4 electrolyte.

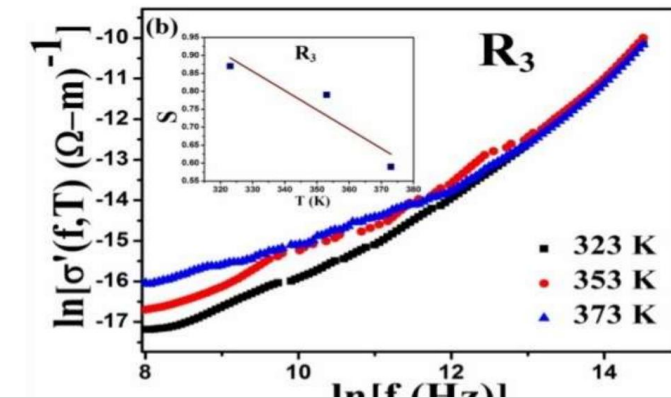
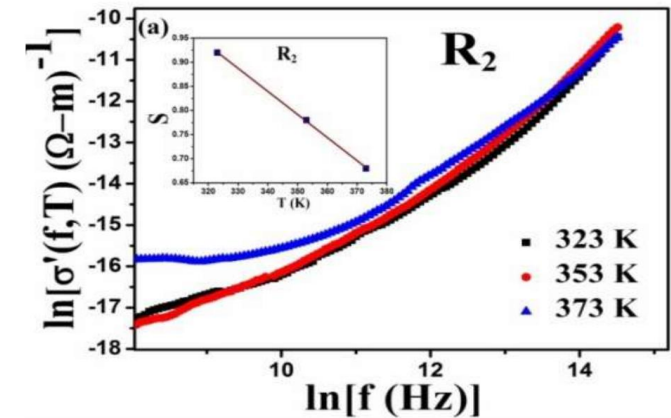
- Symmetric, triangular GCD curves at all current densities — typical of carbon-based supercapacitors; discharge time drops as current density rises.
- Nyquist plot: small high-frequency semicircle indicates the resistive (charge-transfer/contact) nature of the supercapacitive system

AC Conductivity & Conduction Mechanism

- Frequency variation of total conductivity investigated over 20 Hz–2 MHz, above room temperature, for R2 and R3.
- At low frequency, conductivity is frequency-independent — DC contribution dominates; frequency dependence grows at higher frequency.
- Jonscher's power law: $\sigma_{\text{total}}(f) = \sigma_{\text{dc}} + A \cdot f^S$. S decreases as temperature increases — the signature of Correlated Barrier Hopping (CBH): mobile charges hop over a potential barrier between two defect sites.

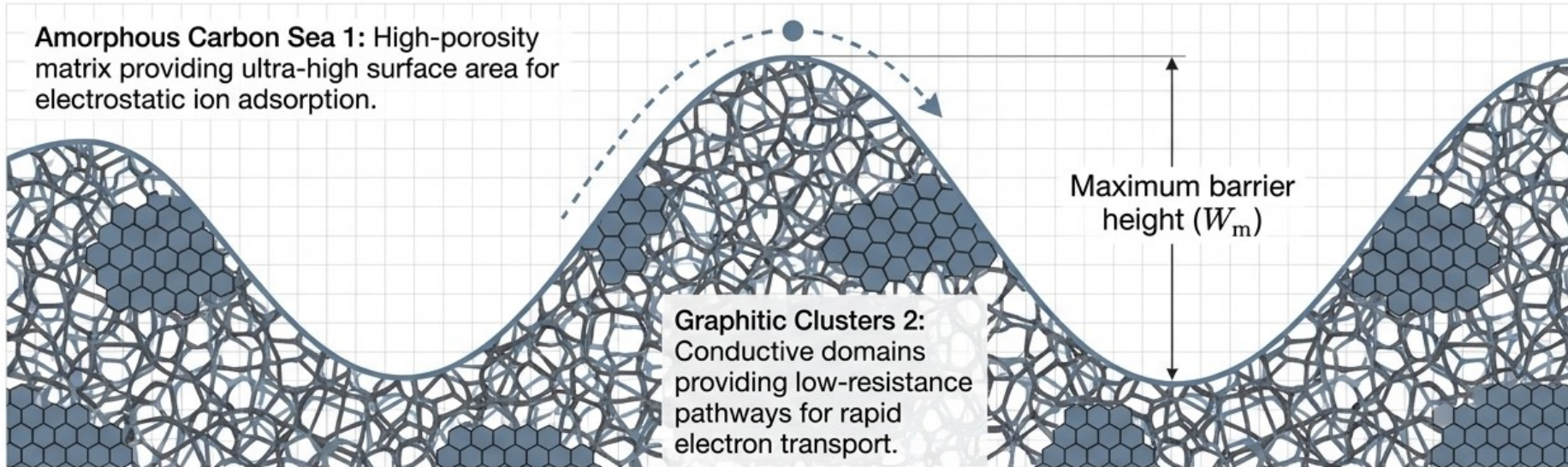
Sample	Max. Barrier Height (Wm)	Activation Energy (EA)
R2 (2 wt% AC)	35 meV	0.88 eV
R3 (4 wt% AC)	31 meV	0.28 eV

Maximum barrier height is lowest in the 2 wt% AC-loaded film (Table 1).



$\ln[\sigma'(f,T)]$ vs. $\ln f$ for (a) R2 and (b) R3 at 323/353/373 K; insets: frequency exponent S vs. T .

The Structural Physics of Charge Transport



Conduction Mechanism: AC conductivity variation analyzed via Jonscher's Power Law: total conductivity $\sigma(f) = \sigma_{dc} + A * f^S$. Exponent S decreases with rising temperature, confirming a Correlated Barrier Hopping (CBH) model.

Film R2 (2 wt% AC filler in PVA matrix)	Film R3 (4 wt% AC filler in PVA matrix)
Maximum barrier height $W_m = 35$ meV Activation Energy $E_A = 0.88$ eV	Maximum barrier height $W_m = 31$ meV Activation Energy $E_A = 0.28$ eV
Insight: Lowest barrier height optimizes charge transport for rapid kinetic response.	

Key Quantitative Findings

Property	Result	Technique
Optical bandgap	$E_g = 3.08 \text{ eV}$ (semiconducting)	UV-Vis + Tauc plot
EDLC behaviour	Rectangular CV up to 100 mV/s, redox-free	Cyclic Voltammetry
Charge-discharge	Symmetric, reversible triangular curves	GCD, 0.01–0.15 A/g
Impedance	Small charge-transfer resistance	EIS Nyquist, 100 Hz–106 Hz
Conduction mechanism	Correlated Barrier Hopping (S decreases with T)	AC conductivity, 20 Hz–2 MHz
Barrier height	$W_m = 35 \text{ meV (R2)} / 31 \text{ meV (R3)}$	Jonscher power-law fit

Together: KOH-activated tea-waste carbon behaves as a typical carbon-based supercapacitor with CBH-governed charge transport in the PVA matrix.

The New Paradigm: Circular Materials Design

Parameter	Traditional Synthetics (CNTs, Graphene)	Bio-Waste Derived Carbon
Feedstock Cost	Extremely high, resource-intensive	Near-zero (abundant household tea waste)
Processing Method	High-temperature CVD, hazardous gases	Scalable thermochemical activation, cheap KOH
Environmental Impact	High carbon footprint, toxic solvents	Carbon-negative, waste- to-energy circular loop
Device Performance	Excellent electrical & mechanical baseline	Comparable high-capacity EDLC (162.6 F/g)

Summary: Engineering tea-waste carbon establishes a robust, sustainable, and mathematically precise pathway from zero-value agro-residues to advanced quantum-capacitive energy-storage and harvesting devices.

Extending the Platform: Rice Husk & PVDF

Conceptual / in-progress direction — shown here as design rationale, not yet backed by measured data.



Second Feedstock

Rice husk as a parallel, high-abundance precursor alongside tea waste — broadening the sustainable carbon source base.



PVDF Matrix

Moving from PVA to piezoelectric PVDF (and PVDF/PDMS hybrids) to unlock stress-responsive, self-powered device behaviour.



Piezo / Triboelectric Harvesting

Hierarchical porosity and conductive filler networks are expected to promote dipole orientation for PENG/TENG-type energy harvesting.

Conclusions

- Tea wastage collected from household successfully converted into activated carbon (AC) via KOH activation.
- Physical characterization (UV-Vis, Tauc) confirms semiconducting, photoactive behaviour with $E_g = 3.08$ eV.
- Electrochemical properties (CV, GCD, EIS) match a typical carbon-based supercapacitor, as expected.
- Electrical transport follows the Correlated Barrier Hopping model, with the lowest barrier height in the 4 wt% AC-PVA film.
- **Depending on these results, the AC and AC-PVA film are promising candidates for flexible, environmentally friendly energy-storage devices and microwave absorbents.**

Future Scope & Acknowledgements

Future Scope

- Complete the rice-husk / PVDF piezoelectric extension with full experimental characterization.
- Structural and morphological characterization (e.g. XRD, SEM) of the AC-PVA films.
- Direct measurement of microwave-absorption performance of the flexible films.

Acknowledgements

- Prof. Ajit Kumar Meikap and the research group, Department of Physics, NIT Durgapur
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Acknowledgments

Funding

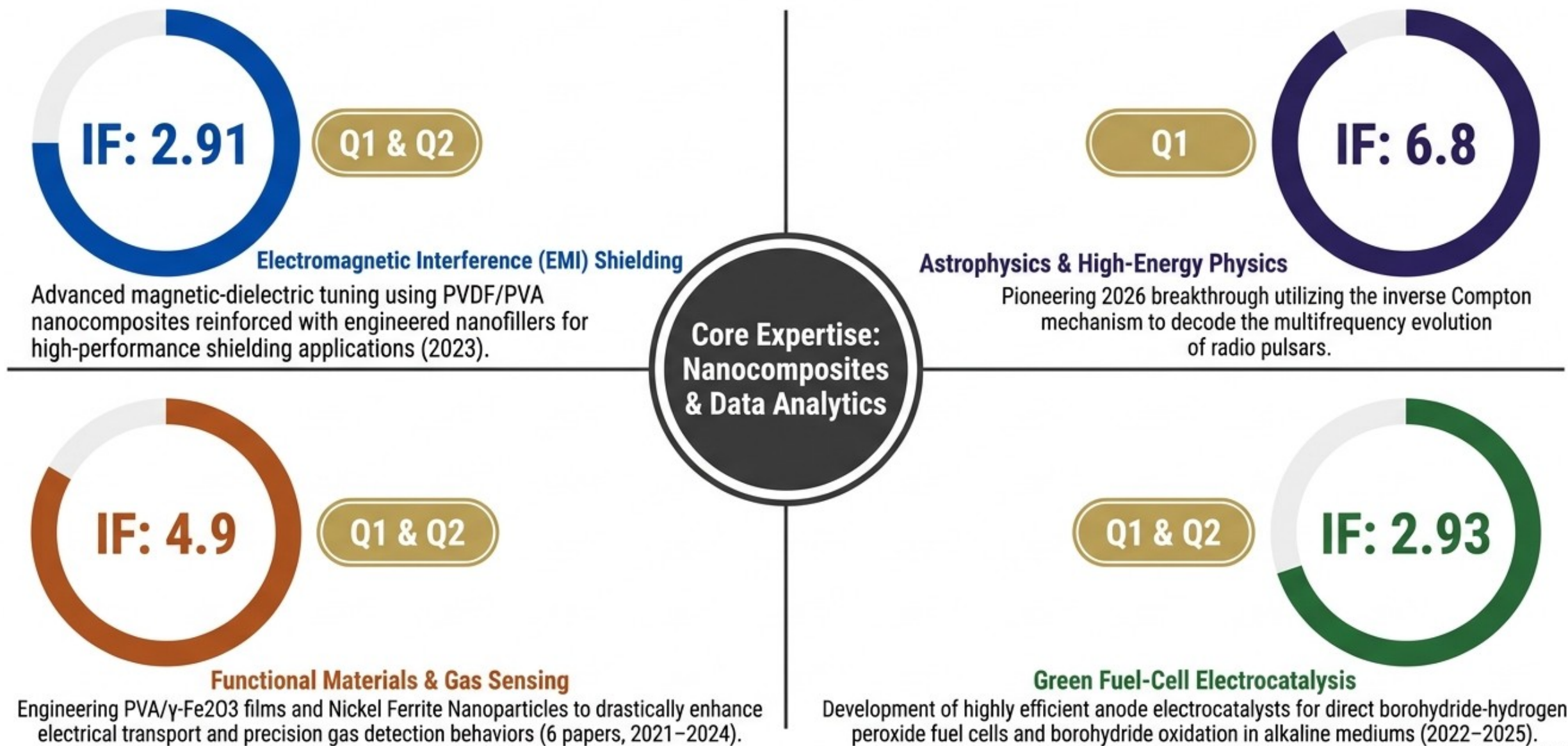
DST—SERB, Government of India (Grant No. EMR/2016/001409); DST—INSPIRE Fellowship, Government of India.

Key References

- ① Halder, M., Halder, S., Mukherjee, A., & Meikap, A. K. (2021). KOH-activated microporous carbon from tea waste for flexible PVA-based dielectric films. *Applied Journal of Advanced Carbon*. DOI: 10.1584/ajac.21003
- ② Sagar, B. *et al.* (2025). Biomass Waste-Derived Hierarchically Porous Carbon-Reinforced ZnS/PDMS-Based Flexible Hybrid Piezo-Triboelectric Nanogenerator. *Advanced Materials Technologies*, 10(22), e00924.

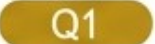
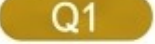
Dr. Monalisa Halder: Multidisciplinary Research Impact (2021–2026)

11 High-Impact Q1/Q2 SCI/SCIE Publications Driven by Advanced Nanomaterial Innovation



Q1 & Q2 Research Highlights: Translating Materials into Applications

Selected SCI/SCIE Indexed Breakthroughs (2021–2026)

SCIENTIFIC DOMAIN	ENGINEERED MATERIAL / MATERIAL / METHOD	TARGET APPLICATION / BREAKTHROUGH	JOURNAL & IMPACT
 Astrophysics	Inverse Compton Mechanism	Multifrequency evolution of integrated pulse profiles of radio pulsars	J. High Energy Astrophysics (2026) IF: 6.8 
 Green Fuel-Cells	AuyNi100-y Nanoparticles decorated MWCNTs	High-Performance Anode for Direct Borohydride-H2O2 Fuel Cells	ChemNanoMat (2025) IF: 2.6 
 Functional Materials	Polyvinyl alcohol and γ -Fe2O3 nanocomposite	Advanced gas detection behavior and electrical transport modulation	Physica B (2024) IF: 4.9 
 EMI Shielding	NiTbxFe2-xO4 nanofiller in PVDF matrix	Magnetic and dielectric tuning for maximum effectiveness in EMI shielding	Journal of Materials Research (2023) IF: 2.91 
 Functional Materials	Neodymium-doped Nickel Ferrite	Tuning microstructural, optical, and magneto-dielectric properties	Materials Chemistry and Physics (2022) IF: 4.09 

Thank You

Questions & Discussion

Dr. Monalisa Halder

monalisahldr18@gmail.com

Research Collaborator, Department of Physics, NIT Durgapur