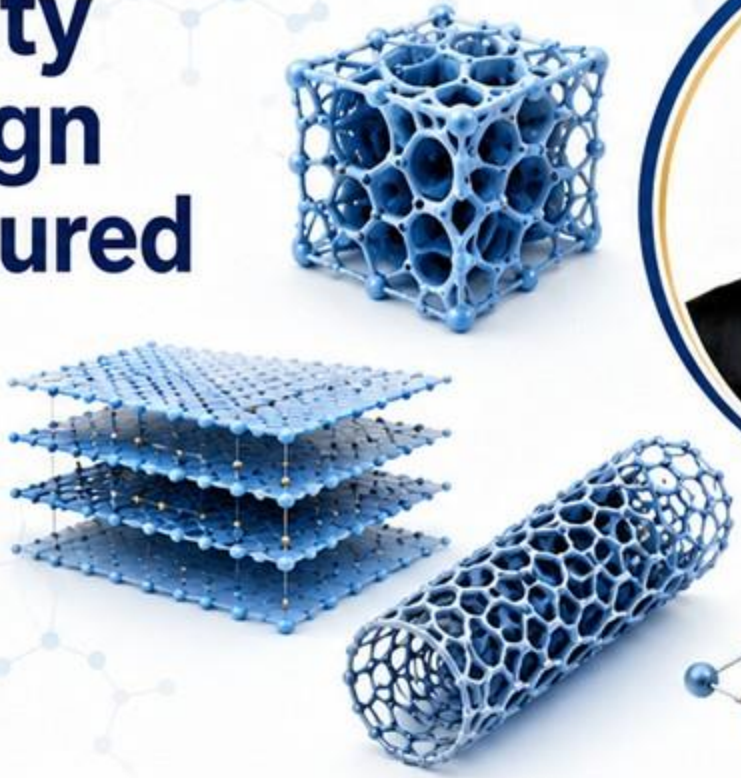
Morphology and Porosity Engineering in the Design of Functional Nanostructured Materials



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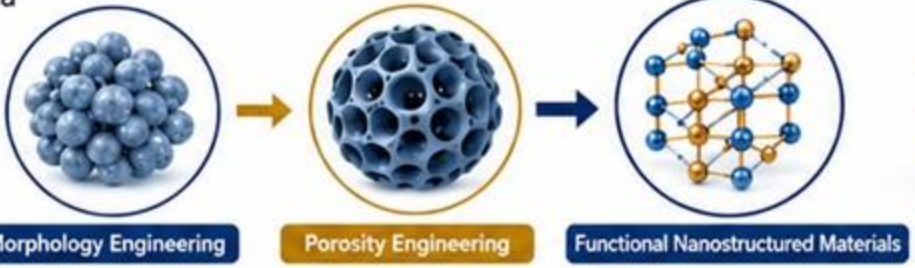
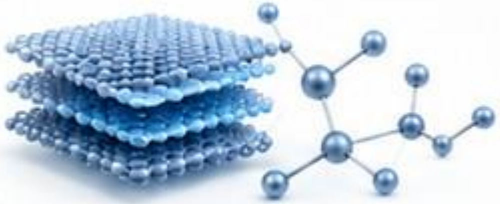




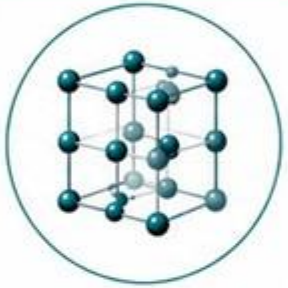
02 FROM COMPOSITION CONTROL TO MULTISCALE STRUCTURE ENGINEERING

In modern materials design, performance depends not only on composition, but also on how structure is controlled across multiple length scales.

1. Early emphasis
Composition control

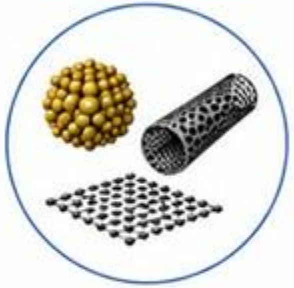
- Discovering materials
- Tuning stoichiometry/ composition
- Improving purity

2. Expanded focus
Crystal structure & defects



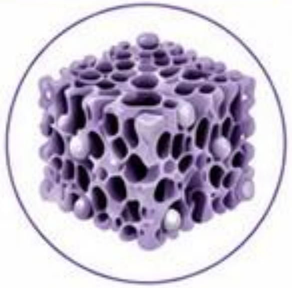
- Phase control
- Doping/defect engineering
- Microstructure tuning

3. Nanoscale design
Size, shape & interfaces



- Nanoparticles, nanorods, nanosheets
- Quantum size effects
- High surface area and interfaces

4. Current frontier
Morphology, porosity & multiscale architecture



- Exposed facets
- Hierarchical porosity
- Transport pathways
- Structure–function synergy

These themes overlap and continue to evolve rather than replacing one another.

A simplified perspective: materials design increasingly integrates composition, crystal structure, defects, interfaces, morphology, and porosity across nano–meso–micro length scales.

SAME COMPOSITION, DIFFERENT STRUCTURE

Structure strongly influences performance.

Same composition (e.g., TiO_2)

Different structures

Photocatalysis	Energy Storage	Photothermal Conversion	Water Treatment	Sensors
Variations in surface area, active sites, and charge transport affect activity.	Differences in capacity, rate capability, and ion transport.	Differences in light absorption and heat localization.	Differences in adsorption capacity and mass transport.	Variations in sensitivity and response due to active sites and transport.

Differences in surface area, active sites, charge transport, light utilization, and mass transport lead to distinct functional performance.

The future of materials design lies in integrating composition with structure engineering— where morphology and porosity are key tools for tailoring functional performance.

03 SAME COMPOSITION, DIFFERENT PERFORMANCE

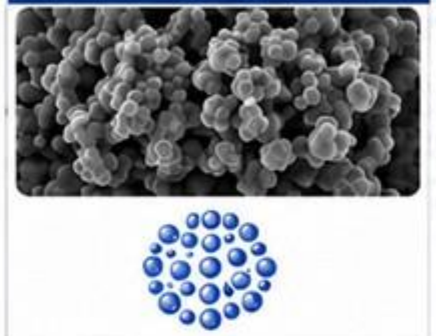
How can the same TiO_2 composition behave differently?

TiO_2 materials with identical composition can exhibit different photocatalytic behavior because morphology and porosity influence surface reactions, light utilization, mass transport, and charge separation.

All examples below are TiO_2 (anatase phase).
Same composition. Same crystal phase. Different morphology, porosity, and exposed facets.

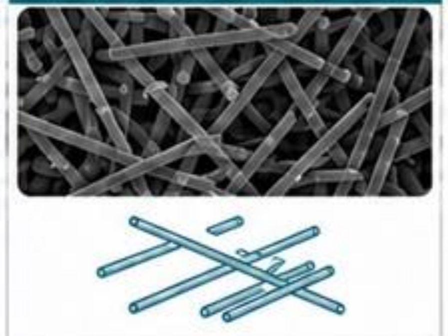
MORPHOLOGY | SCHEMATIC | LITERATURE-BASED TREND

1. TiO_2 Nanoparticles



baseline

2. TiO_2 Nanorods / Nanowires

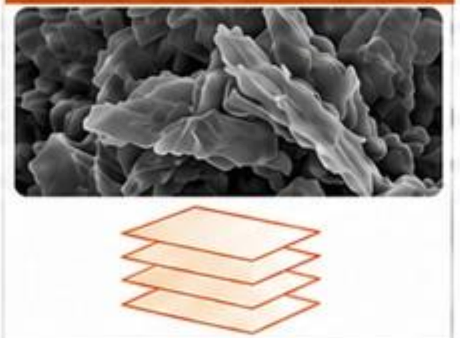


improved charge transport

3. TiO_2 Nanotubes

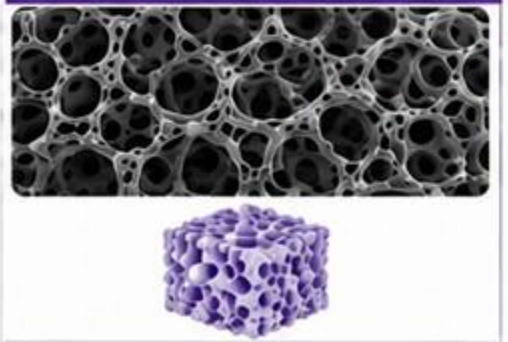
improved transport + accessible surface

4. TiO_2 Nanosheets



highly reactive exposed facets

5. Hierarchical Porous TiO_2



strong mass transport + light harvesting

Potential photocatalytic advantage in many literature reports

Actual performance depends on synthesis, crystallinity, surface area, exposed facets, defects, pollutants, and test conditions.

WHY CAN PERFORMANCE DIFFER?

Surface Area — More accessible surface can provide more exposed active sites.

Active Sites — Surface structure and facet exposure influence reaction sites.

Light Harvesting — Scattering, reflection, and architecture can affect light utilization.

Mass Transport — Open or hierarchical pores can facilitate reactant/product diffusion.

Charge Transport — 1D/2D architectures may assist charge separation and migration.

Photocatalytic Response — Overall activity reflects the combined influence of structure and test conditions.

Composition defines what TiO_2 is; morphology, porosity, and exposed facets strongly influence what TiO_2 can do.

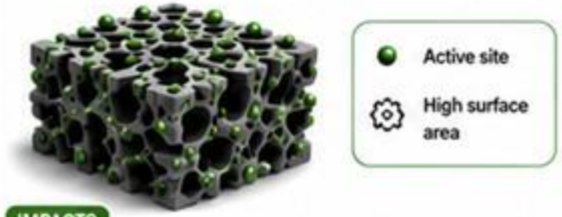
04 WHY MORPHOLOGY AND POROSITY MATTER

Morphology and porosity govern the interaction of matter, energy, and charge with nanostructured materials, ultimately determining their performance.

Structure is the silent engine behind function.
Design the structure, maximize the performance.

1 SURFACE AREA ENGINEERING

Morphology and porosity determine the available surface area and the number of active sites.



IMPACTS

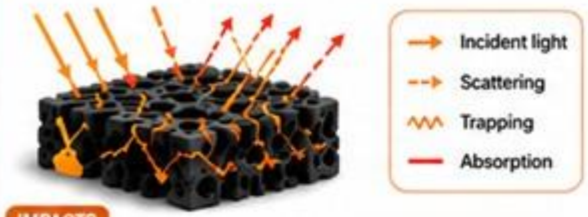
- ↑ Increase adsorption
- ↑ More active sites
- ↑ Higher catalytic activity
- ↑ Improved sensor sensitivity

EXAMPLE MATERIALS

Mesoporous TiO_2 (photocatalysis) | Hierarchical MnO_2 (electrocatalysis) | Nanoporous Carbon (adsorption)

2 LIGHT HARVESTING ENGINEERING

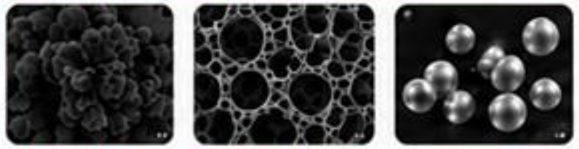
Morphology controls light absorption, scattering, trapping, and utilization.



IMPACTS

- ↑ Enhanced light absorption
- ↑ Improved charge generation (e^-/h^+)
- ↑ Higher photocatalytic efficiency
- ↑ Increased photothermal conversion
- ↑ Better solar energy utilization

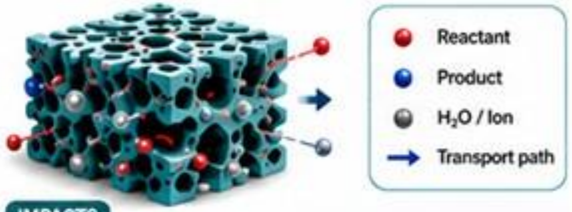
EXAMPLE MATERIALS



Black TiO_2 (photocatalysis) | Hierarchical Porous Carbon (photothermal) | Plasmonic Ag Nanostructures (LSPR, photocatalysis)

3 MASS TRANSPORT ENGINEERING

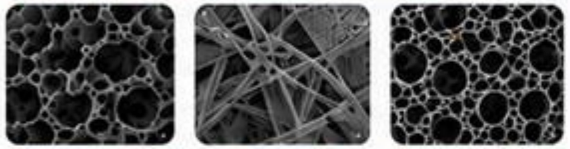
Porosity controls the diffusion of molecules/ions and the transport of reactants/products.



IMPACTS

- ↑ Faster diffusion and transport
- ↑ Better accessibility to active sites
- ↑ Efficient reactant supply and product removal
- ↑ Improved evaporation and fluid transport
- ↑ Enhanced battery/ion kinetics

EXAMPLE MATERIALS



Mesoporous Oxides (electrocatalysis) | Nanoporous Membranes (separation) | Hierarchical Porous Carbon (gas/ion transport)

4 CHARGE TRANSPORT ENGINEERING

Morphology governs charge separation, migration, and recombination.

IMPACTS

- ↑ Efficient charge separation
- ↑ Reduced electron–hole recombination
- ↑ Higher conductivity
- ↑ Improved photocatalytic and electrocatalytic activity
- ↑ Better energy storage performance

EXAMPLE MATERIALS

TiO_2 Nanotubes (photocatalysis) | ZnO Nanorods (electronics/photocatalysis) | $g\text{-}C_3N_4$ Nanosheets (photocatalysis)

MORPHOLOGY & POROSITY → **Large Surface Area** (More active sites) + **Efficient Light Harvesting** (Capture more photons) + **Fast Mass Transport** (Better diffusion & flow) + **Efficient Charge Transport** (Better separation & mobility) = **ENHANCED PERFORMANCE**

Morphology and porosity are not merely structural features—**they are engineering tools** for controlling surface, light, mass, and charge interactions to achieve superior and sustainable performance.

05 MORPHOLOGY ENGINEERING IN NANOSTRUCTURED MATERIALS

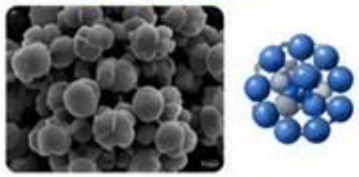
Morphology engineering controls the shape, dimension, exposed facets, and hierarchical architecture of nanostructured materials, thereby governing their functional properties.

KEY MESSAGE

By rationally designing morphology, we can optimize **surface area**, regulate **transport**, enhance **light utilization**, and improve **charge separation** to achieve **superior performance** across diverse applications.

1 DIMENSIONALITY CONTROL

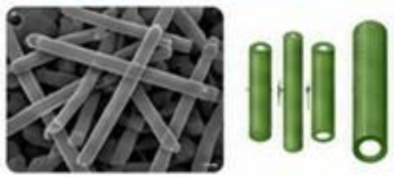
0D (Nanoparticles)



Examples: Ag nanoparticles, TiO_2 nanoparticles

- High specific surface area
- Many surface active sites

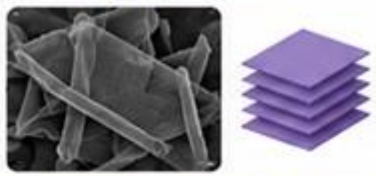
1D (Nanorods / Nanowires / Nanotubes)



Examples: ZnO nanorods, TiO_2 nanotubes

- Direct pathways for charge transport
- Reduced recombination of charge carriers

2D (Nanosheets)



Examples: g-C_3N_4 nanosheets, MoS_2 nanosheets

- Abundant exposed active sites
- Short diffusion length for fast transport

3D (Hierarchical Structures)

Examples: TiO_2 nanoflowers, $NiCo_2O_4$ hollow spheres

- Combines advantages of 0D–2D
- High surface area and efficient transport

2 SHAPE ENGINEERING

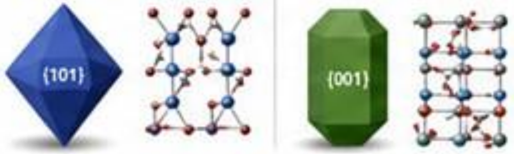
Different shapes expose different surface facets and reaction environments.

3 FACET ENGINEERING

Example: TiO_2 (Anatase)

Dominant {101} Facet

Dominant {001} Facet



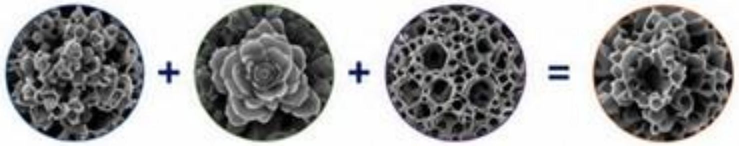
Crystal Facet → Surface Energy → Active Sites → Catalytic Activity

Although the composition is identical, different exposed facets exhibit different surface energy and catalytic activity.

4 HIERARCHICAL MORPHOLOGY

Integrating multiple length scales to build hierarchical architectures.

Nano-scale + Micro-scale + Macro-scale = Hierarchical Structure



Advantages:

- High surface area
- Efficient mass transport
- Enhanced light trapping
- Improved charge separation
- Superior performance

5 IMPACT OF MORPHOLOGY ENGINEERING

Surface Area	More active sites and stronger adsorption
Light Harvesting	Better absorption, scattering, and light trapping
Mass Transport	Shorter diffusion paths and easier reactant access
Charge Transport	Faster migration and reduced recombination

Enhanced Functional Performance (Photocatalysis, Electrocatalysis, Energy Storage, Sensors, etc.)

Morphology Engineering → Shape Control (0D, 1D, 2D, 3D) + Facet Control (Exposed Facets) + Hierarchy Control (Multi-scale Structures) + Architecture Control (Hollow, Core–Shell, etc.) → **Tailored Functional Properties & High Performance**

TAKE-HOME MESSAGE

Morphology engineering is not merely changing the shape of a material; it is a strategy to tailor **surface chemistry, transport pathways**, and **energy conversion processes.**

06 POROSITY ENGINEERING IN NANOSTRUCTURED MATERIALS

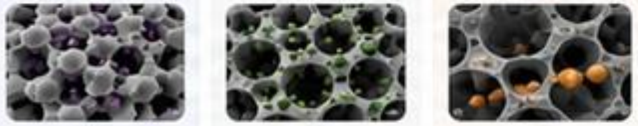
Tailoring pore size, pore connectivity, and hierarchical pore architecture for enhanced transport and interfacial processes.

KEY MESSAGE

Porosity engineering determines how molecules, ions, fluids, photons, and heat move through a material, ultimately dictating its performance in energy, environmental, and catalytic applications.

1 PORE SIZE ENGINEERING

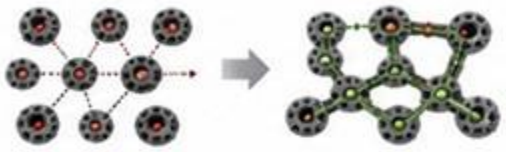
IUPAC classification of pores by size



Micropores < 2 nm	Mesopores 2 – 50 nm	Macropores > 50 nm
• Strong adsorption • Very high surface area	• Fast diffusion • Accessible active sites	• Efficient fluid transport • Low flow resistance
Examples: Activated carbon, Zeolites, MOFs	Examples: Mesoporous TiO_2, SBA-15, MCM-41	Examples: Porous foams, Aerogels, 3D scaffolds

2 PORE CONNECTIVITY ENGINEERING

Connectivity of pores creates continuous transport pathways.



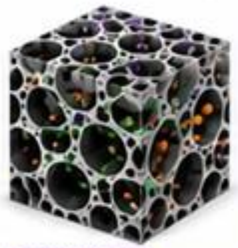
IMPACTS

- Faster mass transport
- Better reactant accessibility
- Efficient water transport
- Enhanced ion diffusion
- Improved overall performance

3 HIERARCHICAL POROSITY

Combining micro-, meso-, and macropores to build multi-scale pore architectures.

Micropores (< 2 nm) Adsorption
+
Mesopores (2 – 50 nm) Diffusion
+
Macropores (> 50 nm) Fluid transport
=



ADVANTAGES

- ✓ Very high surface area
- ✓ Efficient transport at all scales
- ✓ Enhanced light trapping
- ✓ High activity and durability

4 IMPACT OF POROSITY ENGINEERING

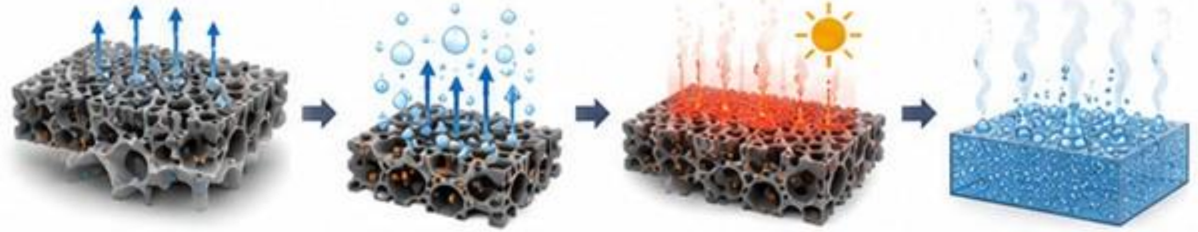
Porosity engineering influences multiple key processes that determine material performance.

Adsorption (More active sites)	Enhanced pollutant capture and catalytic activity
Mass Transport (Molecules, ions, fluids)	Faster diffusion and better reactant/product transport
Heat Management (Heat dissipation or localization)	Improved thermal control and photothermal performance
Light Trapping (Multiple reflection, scattering)	Stronger light absorption and higher photoconversion efficiency
Ion Diffusion (Electrolytes)	Enhanced ion transport and charge transfer kinetics

5 APPLICATION EXAMPLES AND ROLE OF POROSITY

Application	Role of Porosity	Key Benefits	Example Materials
Photocatalysis	Facilitates reactant diffusion and product release	Higher activity, fewer recombination losses, better light utilization	Mesoporous TiO_2, $g\text{-}C_3N_4$, ZnO
Electrocatalysis	Improves electrolyte access and gas bubble release	Higher current density, lower overpotential, better durability	Porous $NiCo_2O_4$, CoP, Fe-N-C
Batteries / Supercapacitors	Enables electrolyte penetration and ion transport	High rate capability, high capacity, long cycle life	Hierarchical carbon, TiO_2, MoS_2
Solar Water Evaporation (SWE)	Provides efficient water transport and heat localization	High evaporciont rate, stable operation, low energy loss	Porous carbon, MXene, Metal oxides
Adsorption	Increases accessible surface and pore volume	High adsorption capacity, fast adsorption kinetics	Activated carbon, MOFs, Zeolites
Membrane / Separation	Controls selective transport through designed pores	High selectivity, high flux, anti-fouling properties	Porous polymers, Ceramic membranes

6 POROSITY AND WATER TRANSPORT FOR SOLAR EVAPORATION



TAKE-HOME MESSAGE

Porosity engineering transforms passive materials into highly efficient platforms for adsorption, transport, energy conversion, and interfacial reactions.

Pore Size · Connectivity · Hierarchy · Transport · Performance

07 SYNERGISTIC INTEGRATION OF MORPHOLOGY AND POROSITY ENGINEERING

The synergy between morphology and porosity maximizes the advantages of both, unlocking superior performance beyond their individual contributions.

KEY MESSAGE

Optimal performance is achieved when morphology provides efficient functional interfaces, and porosity provides fast transport pathways.

1 WHY SYNERGY IS ESSENTIAL

Morphology provides active interfaces

- High surface area
- Exposed active facets
- Efficient charge transport
- Light management

Porosity provides transport pathways

- Large surface exposure
- Fast mass transport
- Efficient fluid flow
- Heat dissipation

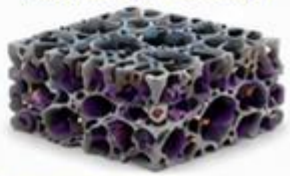
Synergistic integration creates more active sites, better transport, and enhanced energy utilization.

2 FROM NON-SYNERGISTIC TO SYNERGISTIC DESIGN

Non-synergistic design (Only morphology or only porosity)

- Limited active sites
- Slow mass transport
- Inefficient light/charge utilization
- Suboptimal performance

Synergistic design (Morphology + Porosity)



- ✓ Abundant active sites
- ✓ Fast and continuous transport
- ✓ Improved light & charge utilization
- ✓ Superior and durable performance

3 EXAMPLES OF SYNERGISTIC STRUCTURES

Hierarchical Porous Nanosheets

Features
Thin sheets + meso/macropores

Benefits
Large exposed facets, short diffusion path, efficient charge transport

Porous Nanotubes / Nanorods Arrays

Features
1D structure + internal mesopores

Benefits
Direct charge transport, abundant active sites, fast reactant access

Hierarchical Nanoflowers

Features
3D architecture + multi-scale pores

Benefits
High surface area, multiple light scattering, efficient mass transport

Hollow Porous Structures

Features
Hollow interior + porous shell

Benefits
Light trapping, reactant enrichment, eeduced diffusion distance

Porous Core-Shell Structures

Features
Functional core + porous shell

Benefits
Protected active core, efficient transport, enhanced stability

4 SYNERGY ENHANCES KEY PROCESSES

Process	Role of Morphology	Role of Porosity	Synergistic Outcome
Adsorption	Provides more exposed active sites	Increases surface area and adsorption capacity	More active sites and higher adsorption
Mass Transport	Creates short pathways and open channels	Provides continuous and interconnected pores	Faster transport and higher efficiency
Light Harvesting	Enables scattering, trapping, and confinement	Improves light penetration and multiple reflections	Higher light utilization and conversion efficiency
Charge Transport	Facilitates directional charge migration	Allows electrolyte access and ion diffusion	Lower recombination and faster kinetics
Heat Management	Offers heat localization or dissipation channels	Helps heat disslization and water supply	Better thermal regulation and stability
Overall Performance	Enhances intrinsic activity and stability	Improves durability and long-term operation	Superior, stable, and sustainable performance

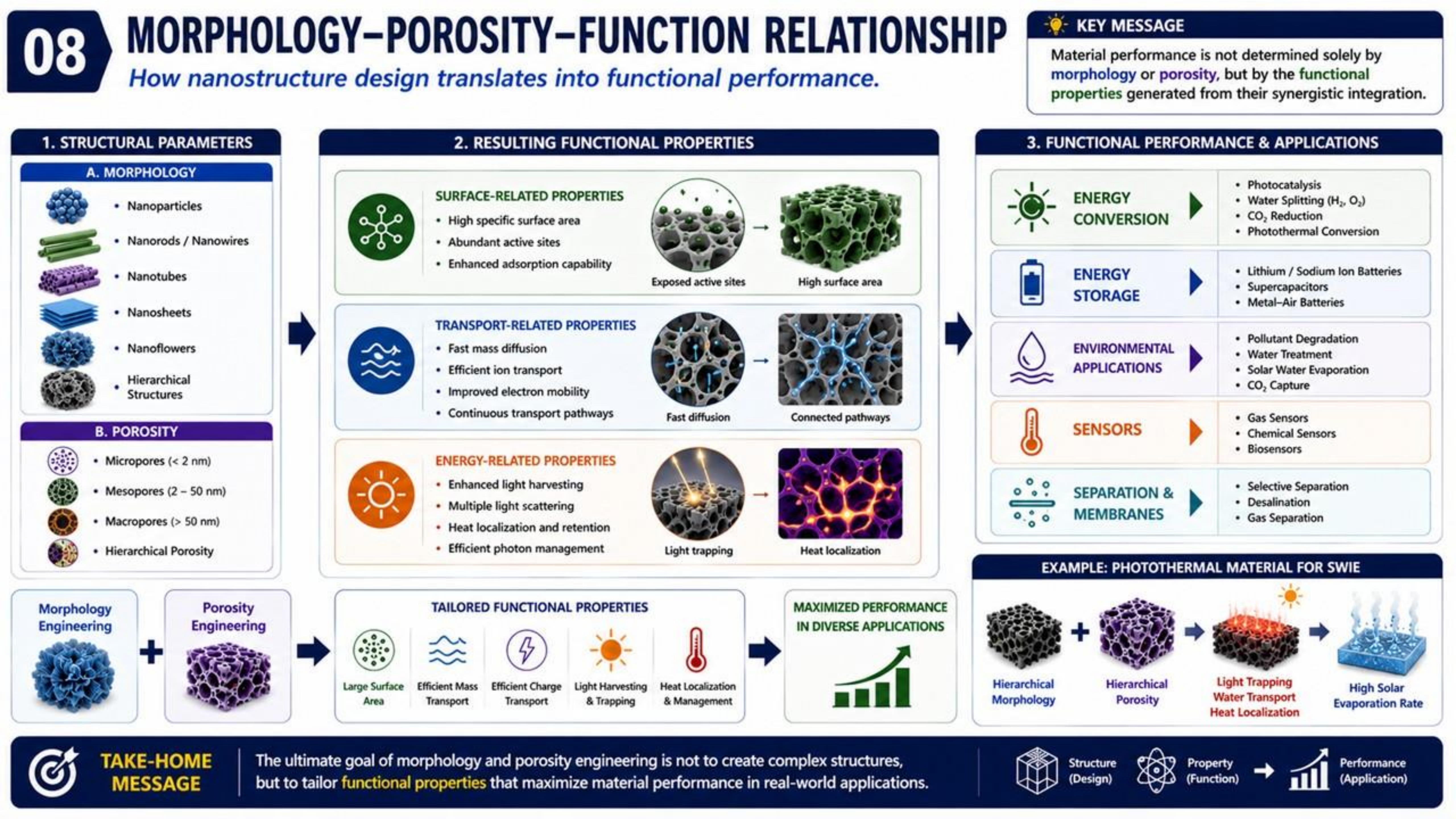
5 DESIGN STRATEGIES

Control synthesis parameters (temperature, precursors, templates) + Use templates or structure-directing agents + Combine top-down and bottom-up approaches + Post-treatment (etching, activation, carbonization, etc.) = Tailored hierarchical structures with optimal synergy

TAKE-HOME MESSAGE

The intelligent integration of morphology and porosity is the key to designing next-generation nanostructured materials with high efficiency, high stability, and multifunctionality.

Morphology | Porosity | Synergy | Performance


08
MORPHOLOGY–POROSITY–FUNCTION RELATIONSHIP
How nanostructure design translates into functional performance.
KEY MESSAGE
Material performance is not determined solely by morphology or porosity, but by the functional properties generated from their synergistic integration.
1. STRUCTURAL PARAMETERS
A. MORPHOLOGY
• Nanoparticles
• Nanorods / Nanowires
• Nanotubes
• Nanosheets
• Nanoflowers
• Hierarchical Structures
B. POROSITY
• Micropores (< 2 nm)
• Mesopores (2 – 50 nm)
• Macropores (> 50 nm)
• Hierarchical Porosity
2. RESULTING FUNCTIONAL PROPERTIES
SURFACE-RELATED PROPERTIES
• High specific surface area
• Abundant active sites
• Enhanced adsorption capability
Exposed active sites
High surface area
TRANSPORT-RELATED PROPERTIES
• Fast mass diffusion
• Efficient ion transport
• Improved electron mobility
• Continuous transport pathways
Fast diffusion
Connected pathways
ENERGY-RELATED PROPERTIES
• Enhanced light harvesting
• Multiple light scattering
• Heat localization and retention
• Efficient photon management
Light trapping
Heat localization
3. FUNCTIONAL PERFORMANCE & APPLICATIONS
ENERGY CONVERSION
• Photocatalysis
• Water Splitting (H_2, O_2)
• CO_2 Reduction
• Photothermal Conversion
ENERGY STORAGE
• Lithium / Sodium Ion Batteries
• Supercapacitors
• Metal–Air Batteries
ENVIRONMENTAL APPLICATIONS
• Pollutant Degradation
• Water Treatment
• Solar Water Evaporation
• CO_2 Capture
SENSORS
• Gas Sensors
• Chemical Sensors
• Biosensors
SEPARATION & MEMBRANES
• Selective Separation
• Desalination
• Gas Separation
Morphology Engineering
Porosity Engineering
TAILORED FUNCTIONAL PROPERTIES
Large Surface Area
Efficient Mass Transport
Efficient Charge Transport
Light Harvesting & Trapping
Heat Localization & Management
MAXIMIZED PERFORMANCE IN DIVERSE APPLICATIONS
EXAMPLE: PHOTOTHERMAL MATERIAL FOR SWIE
Hierarchical Morphology
Hierarchical Porosity
Light Trapping
Water Transport
Heat Localization
High Solar Evaporation Rate
TAKE-HOME MESSAGE
The ultimate goal of morphology and porosity engineering is not to create complex structures, but to tailor functional properties that maximize material performance in real-world applications.
Structure (Design)
Property (Function)
Performance (Application)

09 DESIGNING MORPHOLOGY AND POROSITY FOR TARGETED APPLICATIONS

Different functions require different structural designs.

KEY MESSAGE

There is no universally best morphology or porosity. The optimal structure depends on the targeted function and application.

1 PHOTOCATALYSIS

Dominant Design Requirement

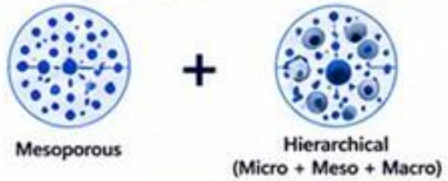
Light absorption + active surface + short carrier diffusion

Most Effective Morphologies

2D Nanosheets | Hierarchical Nanoflowers | Hollow Structures

Preferred Porosity

Mesoporous / Hierarchical Porosity



2 ELECTROCATALYSIS

Dominant Design Requirement

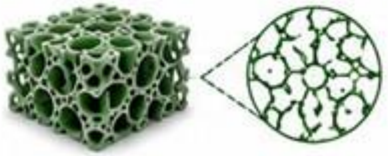
High density active sites + electron transport + electrolyte access

Most Effective Morphologies

Nanorod Arrays | Nanowire Arrays | Hierarchical Architectures

Preferred Porosity

Hierarchical Porosity



- Micropores
- Mesopores
- Macropores

3 ENERGY STORAGE

Dominant Design Requirement

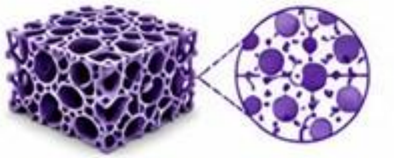
Fast ion diffusion + high loading + electron transport

Most Effective Morphologies

3D Interconnected Networks | Nanotube Networks | Hierarchical Frameworks

Preferred Porosity

Hierarchical Porosity



- Micropores
- Mesopores
- Macropores

4 SOLAR WATER EVAPORATION (SWIE)

Dominant Design Requirement

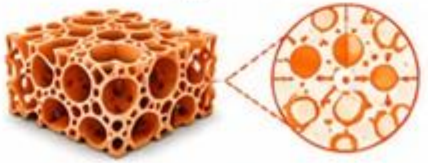
Light trapping + water transport + thermal localization + salt rejection

Most Effective Morphologies

Hierarchical Porous Architectures | Porous Foams | Aerogels / Biomimetic Structures

Preferred Porosity

Macro–Mesoporous Interconnected Networks



- Macropores
- Mesopores
- Micropores

DESIGN LOGIC: START FROM FUNCTION, THEN SELECT STRUCTURE

1. Define Target Application → 2. Identify Key Functional Requirements → 3. Select Optimal Morphology + 4. Choose Suitable Porosity → 5. Achieve Optimized Performance

EXAMPLES OF KEY FUNCTIONAL REQUIREMENTS

Light management	Light absorption, scattering, trapping
Charge transport	Electron conductivity, charge separation
Mass transport	Ion diffusion, reactant/product transport
Thermal management	Heat localization, dissipation control
Interfacial stability	Structural robustness, anti-corrosion

TAKE-HOME MESSAGE

Successful nanostructure design begins with the desired function, then works backward to identify the appropriate morphology and porosity to maximize material performance.

Morphology + Porosity + Synergy = High Performance

10 CASE STUDY 1: KCC-1 (DENDRITIC FIBROUS SILICA)

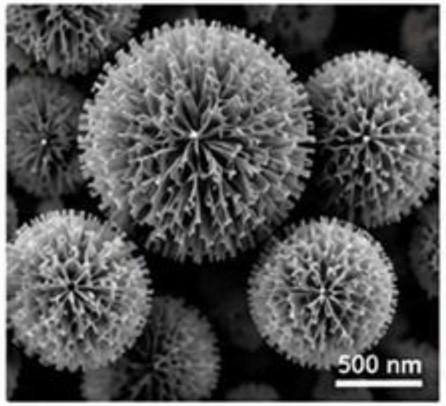
A successful example of simultaneous morphology and porosity engineering.

KEY MESSAGE

KCC-1 shows how unique fibrous morphology combined with an open mesoporous petwoity, creates superior functional properties and outstanding performance.

1 MORPHOLOGY ENGINEERING

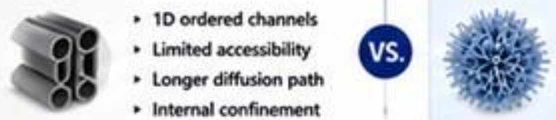
Unique dendritic fibrous architecture



- Spherical particles
- Dendritic / fibrous nanostructure
- Radially oriented fibers
- Hierarchical organization

Radially oriented fibers create highly accessible external and internal surfaces.

Comparison with Conventional Mesoporous Silica



Conventional (e.g., MCM-41)

- 1D ordered channels
- Limited accessibility
- Longer diffusion path
- Internal confinement

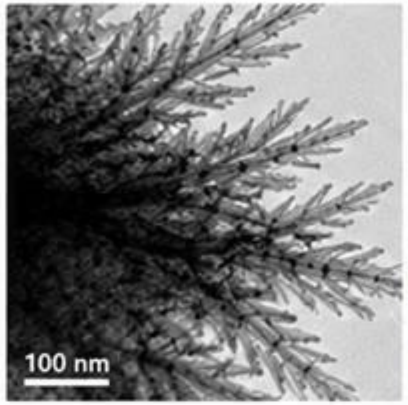
VS.

KCC-1 (Dendritic Fibrous Silica)

- ✓ Radial fibrous pores
- ✓ Highly accessible
- ✓ Short diffusion path
- ✓ Open architecture

2 POROSITY ENGINEERING

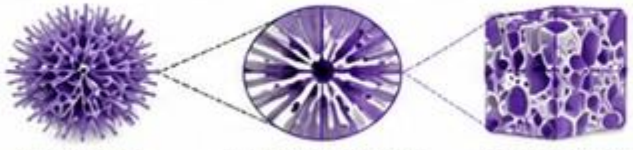
Open mesoporous network with large accessible pores



- Mesoporous structure (2–10 nm)
- Large pore volume
- Open pore entrances
- Interconnected channels
- Thin fibrous walls

Open pore architecture minimizes transport limitations and enables efficient mass transfer.

Pore Structure Illustration



3 RESULTING FUNCTIONAL PROPERTIES

SURFACE-RELATED
- Very high surface area
- Abundant and accessible active sites

TRANSPORT-RELATED
- Rapid molecular diffusion
- Efficient mass transport
- Low diffusion resistance

STABILITY-RELATED
- Excellent thermal stability
- Stable silica framework
- Chemical robustness

Enable high accessibility → Deliver superior performance

WIDELY APPLIED IN

Catalysis (heterogeneous) · Photocatalysis · Adsorption · CO_2 Capture · Drug Delivery · Energy-Related Applications

STRUCTURE → PROPERTY → PERFORMANCE

Fibrous Morphology: Dendritic, radially oriented fibers + **Mesoporous Structure**: Open, interconnected mesopores →

- ✓ High surface accessibility
- ✓ Efficient mass transport
- ✓ Low diffusion resistance
- ✓ Robust and stable framework

→

- Enhanced catalytic activity
- High adsorption capacity
- Improved efficiency
- Superior durability and stability

Outstanding Functional Performance

TAKE-HOME MESSAGE

KCC-1 demonstrates that tailoring morphology (dendritic fibrous architecture) and porosity (open mesoporous network) can dramatically improve accessibility, transport efficiency, and overall material performance without changing chemical composition.

11 CASE STUDY 2: HIERARCHICAL FLOWER-LIKE γ-Al_2O_3

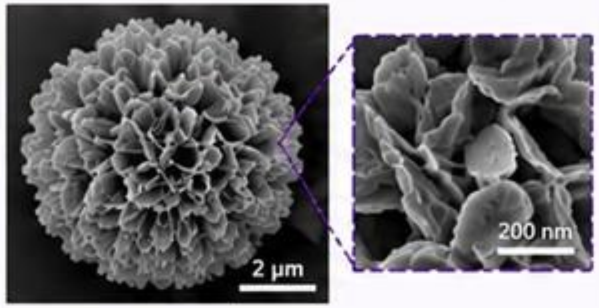
Controlling morphology and porosity through reverse-micelle-mediated synthesis.

KEY MESSAGE

Precise control of synthesis parameters enables the design of hierarchical structures with tailored porosity and superior properties.

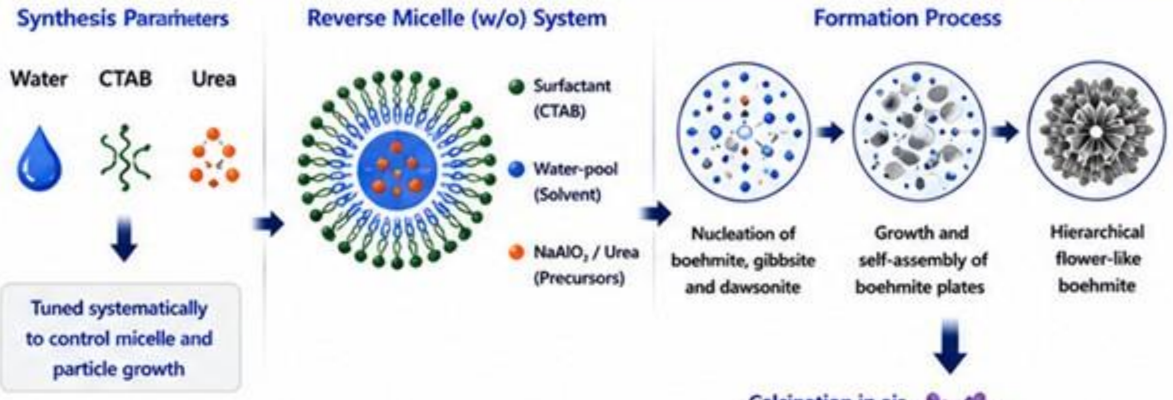
1 MORPHOLOGY ENGINEERING

Hierarchical 3D flower-like particles assembled from nanoscale plates



- Well-defined flower-like morphology
- Constructed from thin nanoscale plates
- Self-assembled architecture
- Morphology retained after calcination (γ-Al_2O_3)

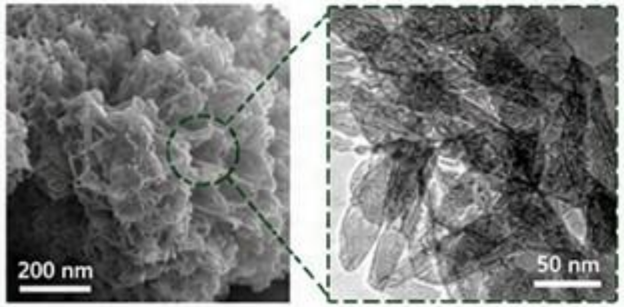
SYNTHESIS STRATEGY AND STRUCTURE FORMATION



- Initial mixture of phases (dawsonite, gibbsite, boehmite) evolves into pure boehmite after 24 h
- Morphology is largely preserved after calcination
- Plate-assembled structure creates abundant open spaces

2 POROSITY ENGINEERING

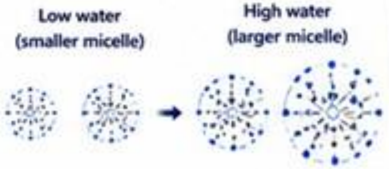
Mesoporous architecture with open pathways



- Type IV isotherm with H3 hysteresis loop
- Dominant mesopores ~2–5 nm
- Interparticle voids and interplate spaces
- Open diffusion pathways for easy transport

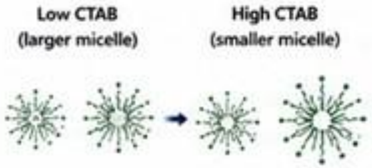
3 TUNING STRUCTURE BY SYNTHESIS PARAMETERS

Water Content



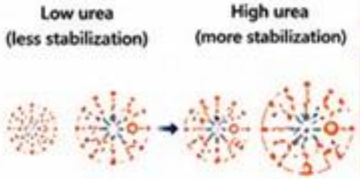
- Smaller particles
- Narrower size distribution
- Smaller crystallite size
- Lower surface area

CTAB Content



- Smaller particles
- Narrower size distribution
- Larger crystallite size
- Higher surface area

Urea Content



- Larger particles
- Wider size distribution
- Larger crystallite size
- Lower surface area

4 RESULTING TEXTURAL PROPERTIES

High Surface Area (BET)	Large Pore Volume	Mesoporous Structure
214 $m^2\ g^{-1}$	0.99 $cm^3\ g^{-1}$	2 – 5 nm
(Best sample: $W75C_{0.25}U_{2.0}$)	(Best sample: $W75C_{0.25}U_{2.0}$)	Dominant pore size

FUNCTIONAL IMPLICATION

- Abundant active sites due to high surface area
- Open mesoporous network for fast mass transport
- High accessibility of reactants and products
- Reduced diffusion limitation and coking resistance

TAKE-HOME MESSAGE

Hierarchical flower-like γ-Al_2O_3 demonstrates how precise control of synthesis parameters can simultaneously tailor morphology, porosity, and textural properties to enhance material functionality, making it a promising support for diverse catalytic applications.

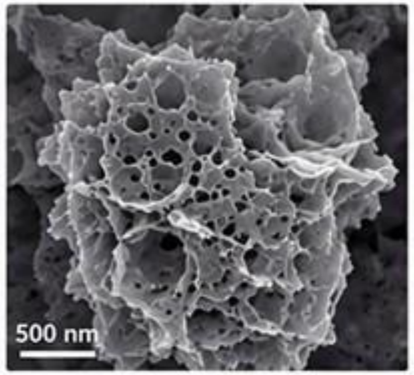
12 CASE STUDY 3: ZnO NANOSTRUCTURES FOR PHOTOCATALYTIC APPLICATIONS

Engineering surface morphology, porosity, and defects for enhanced photocatalytic performance.

KEY MESSAGE

Photocatalytic performance is governed not only by particle shape, but also by surface texture, porosity, and defect density.

1 HOLEY ZnO NANOSHEETS



Structural Features

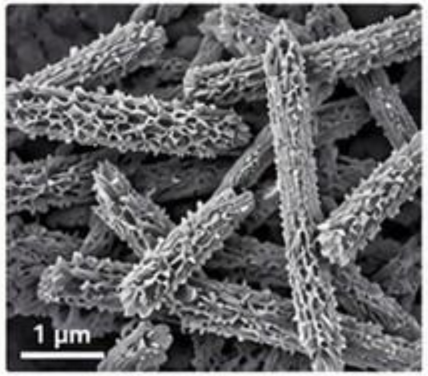
- 2D nanosheet morphology
- Holey architecture
- High surface area
- Open diffusion pathways

Functional Advantages

- ✓ Enhanced light absorption
- ✓ Short charge migration distance
- ✓ Increased active sites
- ✓ Faster reactant transport

Holey nanosheets with small crystallite size, high surface area, and abundant defects show the highest photocatalytic activity.

2 FIBROUS ZnO MICRORODS



Structural Features

- Rod-shaped particles
- Fibrous surface texture
- High aspect ratio
- Roughened surface morphology

Functional Advantages

- ✓ Increased surface-to-volume ratio
- ✓ More accessible reaction sites
- ✓ Improved adsorption
- ✓ Better charge utilization

Fibrous surface morphology increases surface area, defect density, and visible-light response, leading to superior photocatalysis.

3 MORPHOLOGY–POROSITY–FUNCTION RELATIONSHIP

Structural Feature		Functional Effect
Holey architecture (open pores)	→	Fast diffusion of reactants and products
Fibrous texture (rough surface)	→	Increased active sites and better light harvesting
High surface area	→	Enhanced adsorption and more active sites
Surface defects (oxygen vacancies)	→	Improved visible-light response and charge separation
Open porous network	→	Efficient mass transport and reduced diffusion limitation

SAME DESIGN PRINCIPLE AT DIFFERENT pH, RESULTING DIFFERENT MORPHOLOGIES

Holey Nanosheets

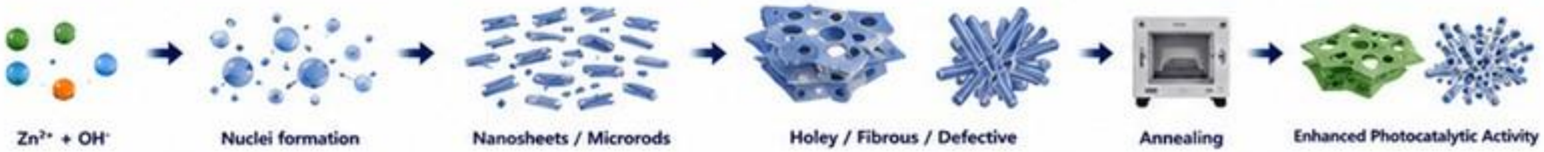
\+

Fibrous Microrods

→ Higher Surface Area + More Active Sites + Improved Light Utilization + Enhanced Charge Separation + Efficient Mass Transport = Higher Photocatalytic Efficiency

SYNTHESIS APPROACH (Hydrothermal / Solvothermal)

Precursors → Nucleation in Solution → Growth & Self-Assembly → Porous & Defective Structures → Calcination → ZnO Nanostructures



KEY OUTCOMES

- **BET Surface Area** up to ~100 $m^2\ g^{-1}$
- **Pore Size** ~2 – 20 nm
- **Defect Density** Increased (oxygen vacancies)

PERFORMANCE BENEFITS

- ✓ Stronger light absorption (UV–Vis)
- ✓ Efficient charge separation & transfer
- ✓ High degradation efficiency of pollutants (MB, RhB, etc.)
- ✓ Stable performance and reusability

TAKE-HOME MESSAGE

By integrating morphology engineering, porosity engineering, and defect engineering, ZnO nanostructures achieve synergistic improvements in light harvesting, charge separation, and mass transport, resulting in superior photocatalytic performance.

Light Harvesting · Charge Separation · Mass Transport · Photocatalytic Performance

CASE STUDY 4 LAMELLAR TiO_2 FOR ENHANCED PHOTOCATALYSIS

How NH_4OH alkaline–hydrothermal treatment creates open-channel morphology for RhB degradation

1 WHY TREATMENT ORDER MATTERS

✓ Effective route: Lamellar morphology is formed

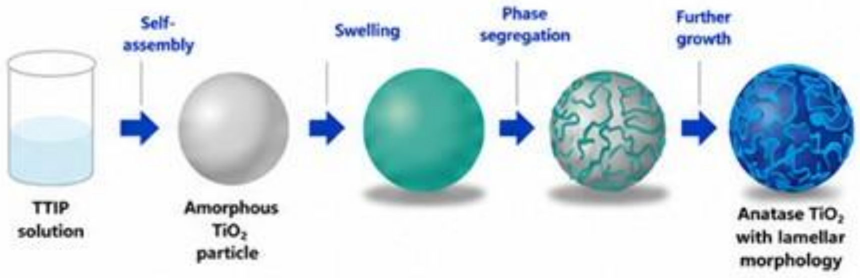
Amorphous TiO_2 (as-synthesized) → NH_4OH alkaline–hydrothermal treatment 120 °C, 12 h → Calcination 500 °C, 1 h → Lamellar anatase TiO_2 (open-channel)

✗ Ineffective route: No significant lamellar transformation

Amorphous TiO_2 (as-synthesized) → Calcination 500 °C, 1 h → NH_4OH alkaline–hydrothermal treatment 120 °C, 12 h → No lamellar structure

Hydrothermal treatment must be applied before crystallization to obtain lamellar morphology.

2 GROWTH MECHANISM OF LAMELLAR TiO_2

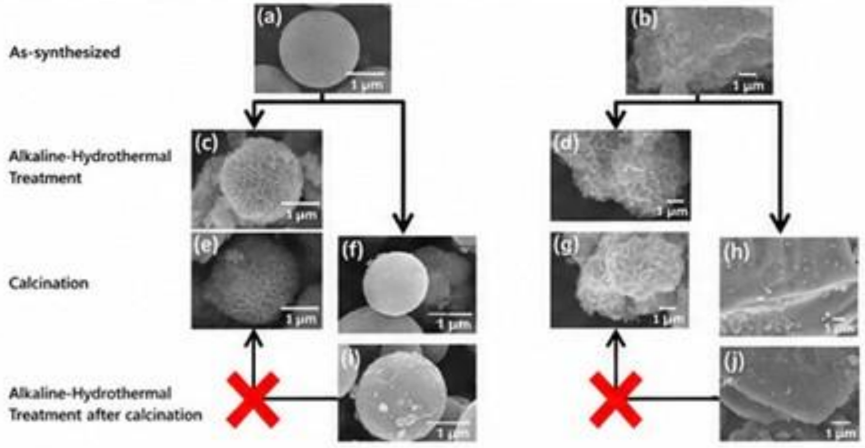


Lamellar structure forms through self-assembly, swelling, phase segregation, and further growth, where titanate layers act as an intermediate phase.

3 STRUCTURE–PROPERTY–PERFORMANCE RELATIONSHIP

- **Lamellar Morphology**
  - Thin sheets on particle surface
  - High degree of exposed surface
- **Open-Channel Pore Structure**
  - Mesoporous, slit-shaped pores
  - Continuous open pathways
- **Higher Surface Accessibility**
  - More surface sites available
  - Better contact with reactants
- **Faster Mass Transport & Diffusion**
  - Reduced diffusion limitation
  - Efficient transport of reactants and products
- **Enhanced Photocatalytic Activity**
  - More effective charge transfer
  - Higher degradation rate and efficiency

4 MORPHOLOGY EVIDENCE (SEM IMAGES)



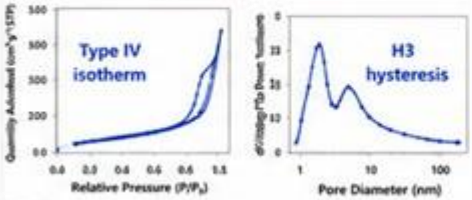
5 KEY EXPERIMENTAL FINDINGS

Surface Area Increase (BET)

S-AS $82\ m^2\ g^{-1}$ → S-HT $337\ m^2\ g^{-1}$ (4.1× increase)

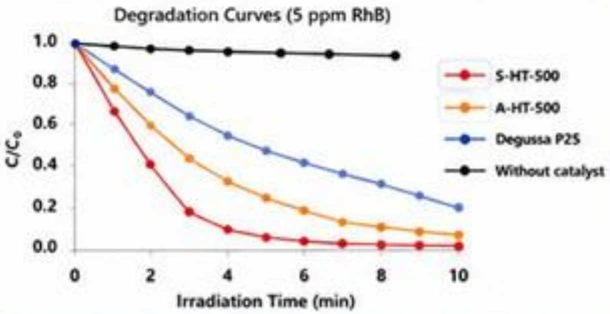
A-AS $211\ m^2\ g^{-1}$ → A-HT $253\ m^2\ g^{-1}$ (1.2× increase)

Porosity (N_2 Adsorption–Desorption)



- ✓ Mesoporous structure
- ✓ Slit-shaped pores
- ✓ Open channels

6 PHOTOCATALYTIC PERFORMANCE (Rhodamine B Degradation)



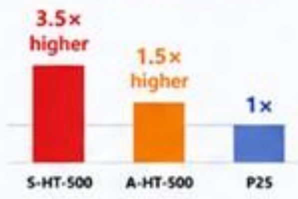
Best Performance S-HT-500

90.93% degradation in 10 min (UV irradiation)

Kinetic Rate Constant, k ($10^{-2}\ min^{-1}$)	
S-HT-500	47.9
A-HT-500	30.9
Degussa P25	13.6

Surface Area–Normalized Rate, k_{sa} ($10^{-3}\ L\ m^{-2}\ min^{-1}$)	
S-HT-500	6.5
A-HT-500	2.6
Degussa P25	1.9

Compared to Degussa P25



(Higher value = better)

TAKE-HOME MESSAGE NH_4OH alkaline–hydrothermal treatment converts uncrystallized TiO_2 into lamellar anatase with open-channel pores, leading to higher surface area, better mass transport, and superior photocatalytic performance.

Steky, F. V., Benu, D. P., Putra, K. L. H., et al.
Phys. Chem. Chem. Phys., 2023.
DOI: 10.1039/d2cp05098f

CASE STUDY 5:

THORNY POLYANILINE NANOSTRUCTURES FOR ENHANCED INTERFACIAL ADSORPTION

Morphology-driven enhancement of adsorption and photovoltaic performance in DSSCs

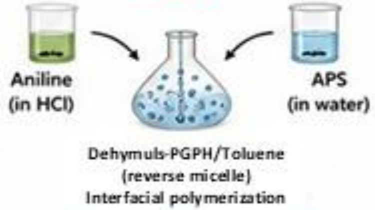
KEY MESSAGE

A well-designed **surface morphology** can dramatically enhance interfacial processes and **device performance**, even when the chemical composition remains unchanged.

SYNTHESIS METHOD

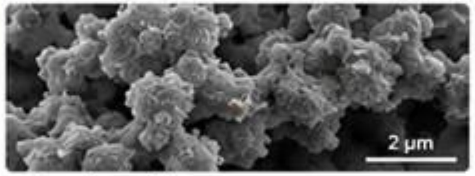
Rapid Mixing Method (Conventional) → PANI ES

Reverse Micelle Polymerization Method → NPES



SURFACE MORPHOLOGY (SEM IMAGES)

PANI ES (Conventional)



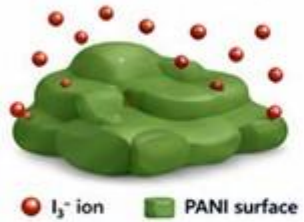
- Irregular particles
- Relatively smooth surface

NPES (Thorny, Durian-like)

- Uniform granules
- Thorny surface with numerous nanospikes

I_3^- ADSORPTION BEHAVIOR (SCHEMATIC)

PANI ES (Conventional)



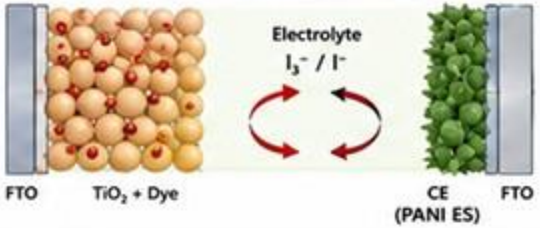
- Fewer accessible adsorption sites
- Lower I_3^- adsorption capacity
- Slower electrolyte regeneration

NPES (Thorny, Durian-like)

- More accessible adsorption sites
- Higher I_3^- adsorption capacity
- Faster electrolyte regeneration

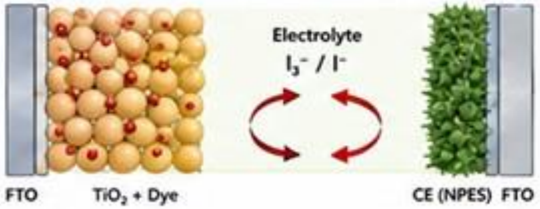
PERFORMANCE IMPACT (DSSC)

Lower DSSC Performance (PANI ES)



Lower Efficiency

Higher DSSC Performance (NPES)

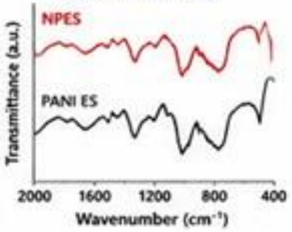


≈30% Higher Efficiency*

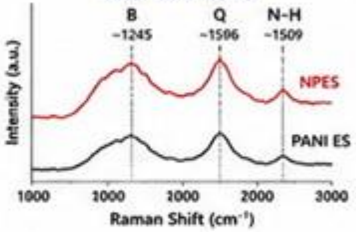
Compared to PANI ES counter electrode under the same DSSC configuration.

STRUCTURAL CHARACTERIZATION

FTIR Spectra (PANI ES vs NPES)



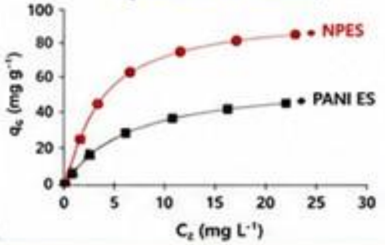
Raman Spectra (PANI ES vs NPES)



- ✓ Similar vibrational features
- ✓ Similar chemical structure
- ✓ Differences arise from morphology, not composition

ADSORPTION HIGHLIGHTS

Adsorption Isotherm (I_3^- on PANI ES vs NPES)



- NPES shows **higher** maximum adsorption capacity
- Adsorption is spontaneous and **endothermic** for both materials
- Follows dual-site **Langmuir–Freundlich** isotherm (DSLF model)

OVERALL CONCLUSION

- Thorny durian-like morphology provides abundant accessible sites for I_3^- adsorption.
- Enhanced adsorption leads to faster electrolyte regeneration and better charge transfer.
- Result: ~30% improvement in DSSC power conversion efficiency compared to conventional PANI ES.

TAKE-HOME MESSAGE

Morphology engineering—especially the creation of thorny, high-surface structures—plays a crucial role in maximizing interfacial adsorption and device performance without altering chemical composition.

15 CASE STUDY 6:

CORRELATING MORPHOLOGY WITH N_2 PHYSISORPTION BEHAVIOR IN Al-INCORPORATED *bcl* SILICA

KEY MESSAGE

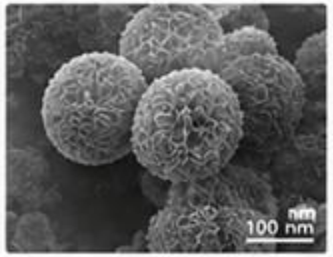
Morphology is not only observed by SEM; it can also be **inferred from adsorption–desorption behavior** of N_2.

SYNTHESIS PARAMETERS

- Reflux time (15–25 h)
- Temperature (100–130 °C)
- Surfactant type (CTAB, BKC, PGPH)
- Al precursor concentration (0.5–5 mol)
- NaOH concentration

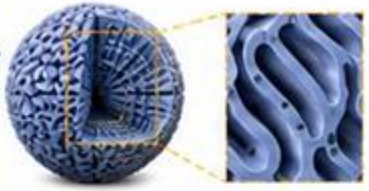
MORPHOLOGY DEVELOPMENT

Al-incorporated bcl silica



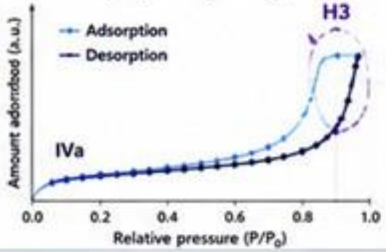
PORE ARCHITECTURE

Interconnected lamellar structure with mesoporous-scale pores



N_2 PHYSISORPTION BEHAVIOR

Type IVa isotherm with H3 hysteresis (loop at high P/P_0)



FUNCTIONAL PROPERTIES

- High surface area
- High pore volume
- Efficient mass transport
- Enhanced performance in catalytic applications

OPTIMAL SYNTHESIS CONDITION

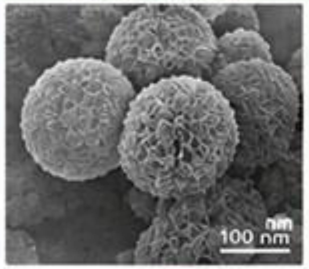
- Temperature : 130 °C
- Reflux time : 20 h
- Surfactant : CTAB
- Al precursor : 1 mol sodium aluminate

RESULTING MATERIAL

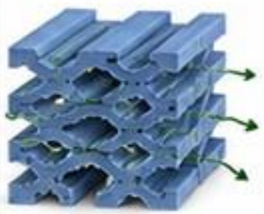
- Spherical bcl-like morphology surrounded by lamellae
- Surface area ≈ 513 $m^2\,g^{-1}$
- Pore volume ≈ 1.00 $cm^3\,g^{-1}$
- Mesopore size ≈ 3.89 nm

CORRELATION BETWEEN MORPHOLOGY AND N_2 PHYSISORPTION BEHAVIOR

IDEAL bcl MORPHOLOGY (Well-Developed)

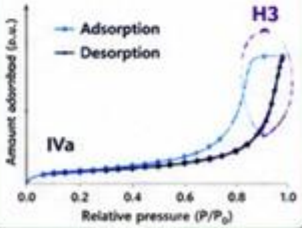


Connected Lamellae (Open V-groove pores)



N_2 Adsorption Behavior

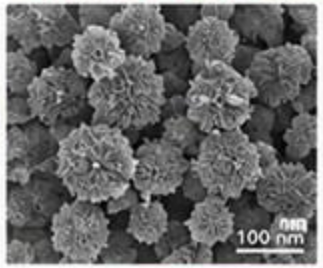
Type IVa + H3 hysteresis



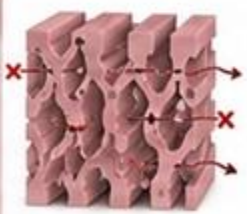
✔ Interconnected pores → Efficient adsorption/desorption → High surface area & pore volume

VS.

FAILED bcl MORPHOLOGY (Overdeveloped / Imperfect)

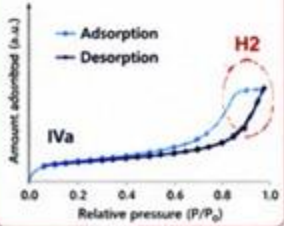


Disconnected Lamellae (Pore blocking)



N_2 Adsorption Behavior

Type IVa + H2 hysteresis



✘ Pore blockage / disconnection → H_2 hysteresis → Lower surface area & hindered mass transport

SIGNIFICANCE

- ✓ Demonstrates the link between synthesis parameters, morphology, and N_2 adsorption behavior
- ✓ Provides a reference for the development of zeolites with bcl morphology
- ✓ Enables prediction of morphology from physisorption signatures

KEY FINDINGS

- Al precursor concentration strongly influences bcl formation.
- NaOH concentration has no significant effect on morphology.
- CTAB at 130 °C for 20 h with 1 mol Al precursor gives the best bcl morphology.
- Excess Al (> 3 mol) prevents bcl morphology; hysteresis shifts to H_2 due to pore blocking.

PROPOSED MECHANISM

1. Reverse micelle formation
2. Silica–aluminate condensation
3. Lamellar growth and assembly
4. bcl structure formation
5. Calcination

Controlled growth → Well-organized lamellae → bcl morphology

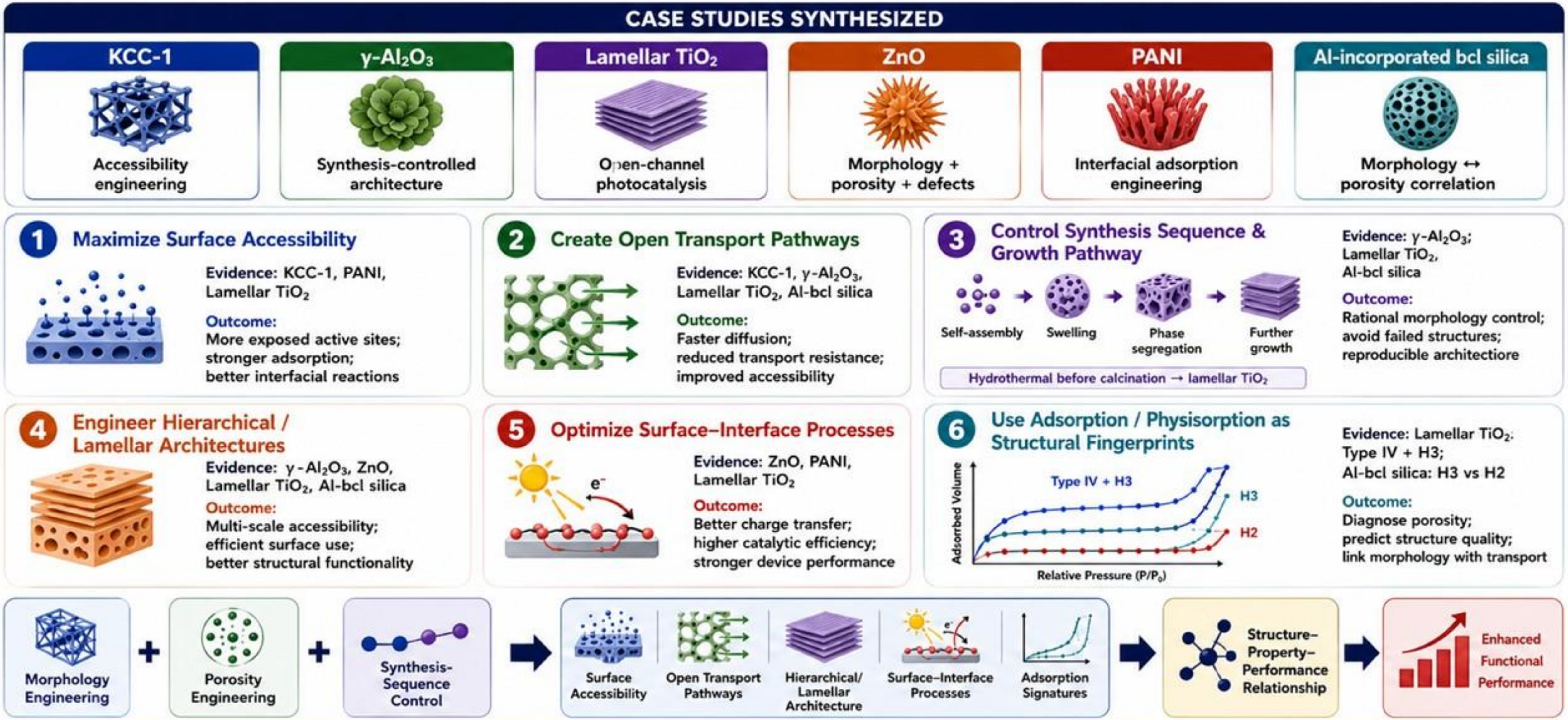
TAKE-HOME MESSAGE

Morphology leaves a **measurable signature** in adsorption behavior.
N_2 physisorption isotherms can be used as a **fingerprint** to infer pore architecture and predict the quality of bcl-morphology materials.

H. E. Wogo et al., *Langmuir* **2025**, 41, 5794–5807
DOI: 10.1021/acs.langmuir.4c03286

16 UNIVERSAL DESIGN PRINCIPLES DERIVED FROM CASE STUDIES

Common lessons from KCC-1, γ-Al_2O_3, Lamellar TiO_2, ZnO, PANI, and Al-incorporated bcl silica



TAKE-HOME MESSAGE: Successful nanostructured materials are not defined by composition alone, but by how **morphology, porosity, and synthesis pathways** are engineered to control **accessibility, transport, interfaces**, and measurable **structure–property relationships**.

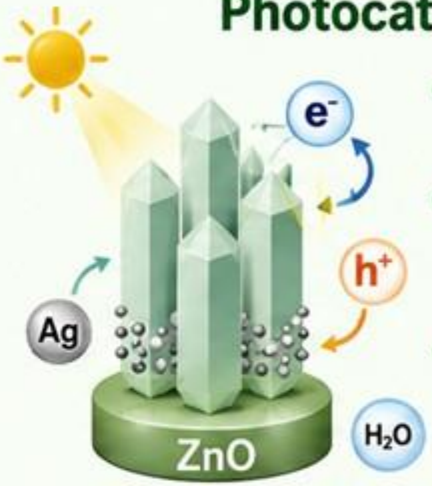
17 Translating Design Principles into Our Current Research Portfolio

Morphology–Porosity–Interface Engineering for Water and Environmental Applications

From Universal Design Principles to Active Research Programs

Cluster 1

Green ZnO-Based Photocatalysts

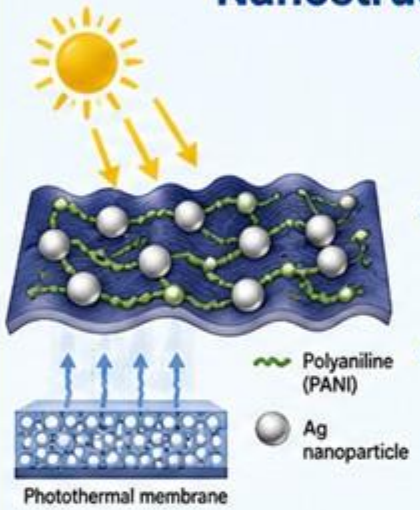


- Green synthesis of ZnO and ZnO–Ag
- **Focus:** morphology control, Ag decoration, photocatalysis
- **Application:** water treatment

Funding
LPPM Universitas Timor

Cluster 2

PANI-Based Photothermal Nanostructures

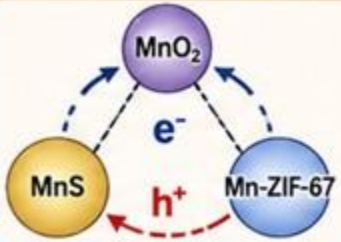


- Nanostructured polyaniline decorated with Ag nanoparticles
- **Focus:** light harvesting, heat localization, interfacial evaporation
- **Application:** clean water production from seawater

Funding
BRIN–LPDP | RIIM Kompetisi

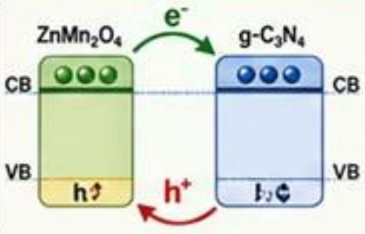
Cluster 3

Local Mn-Based Heterojunction Photocatalysts



3A MnS/MnO_2/Mn-ZIF-67

- Based on local manganese rock from Timor Island
- **Focus:** band alignment, charge-transfer mechanism, morphology study



3B $ZnMn_2O_4/g\text{-}C_3N_4$

- Based on local manganese rock from Timor Island
- **Focus:** interface engineering for pesticide-contaminated water remediation

Funding
Ministry of Higher Education, Science, and Technology | PFR & PDP

Morphology Engineering → **Porosity Engineering** → **Interface Engineering** → **Targeted Functional Applications**

Our current research portfolio translates morphology–porosity–interface engineering principles into funded research programs on photocatalysis, photothermal conversion, and local resource-based environmental technologies.

CLOSING MESSAGE

Engineering Structure, Enabling Function

The future of functional nanostructured materials lies in the rational engineering of *morphology*, *porosity*, and *interfaces* to control accessibility, transport, and energy conversion.

DESIGN the Structure — *Control morphology and porosity*
→ **CONTROL** the Pathways — *Enhance accessibility and transport*
→ **OPTIMIZE** the Interface — *Improve charge transfer and interfacial processes*
→ **MAXIMIZE** the Function — *Achieve superior performance*

1. WHAT WE HAVE LEARNED

Material performance is not determined by composition alone.
The same composition can show different performance with different structures.

Morphology controls surface exposure, active sites, and interfacial interactions.
Nanostructure design maximizes surface accessibility and functionality.

Porosity controls accessibility, diffusion, mass transport, and adsorption behavior.
Open and hierarchical porosity ensures efficient transport and reaction.

2. UNIVERSAL DESIGN LOGIC

3. FUTURE DIRECTION

Function-first design
Start from the target application, then design morphology, porosity, and interfaces.

Local resource-based materials
Convert local minerals and biomass into advanced functional materials with added value.

Green and scalable synthesis
Develop simple, low-cost, and environmentally friendly synthesis routes.

Mechanism-guided engineering
Use characterization, band alignment, physisorption, and kinetics to guide rational material design.

Nanostructured materials should not only be synthesized; they should be architected.

Thank you for your attention!

Together, let's build advanced functional materials for a better and sustainable future.

Discussion and collaboration are welcome.