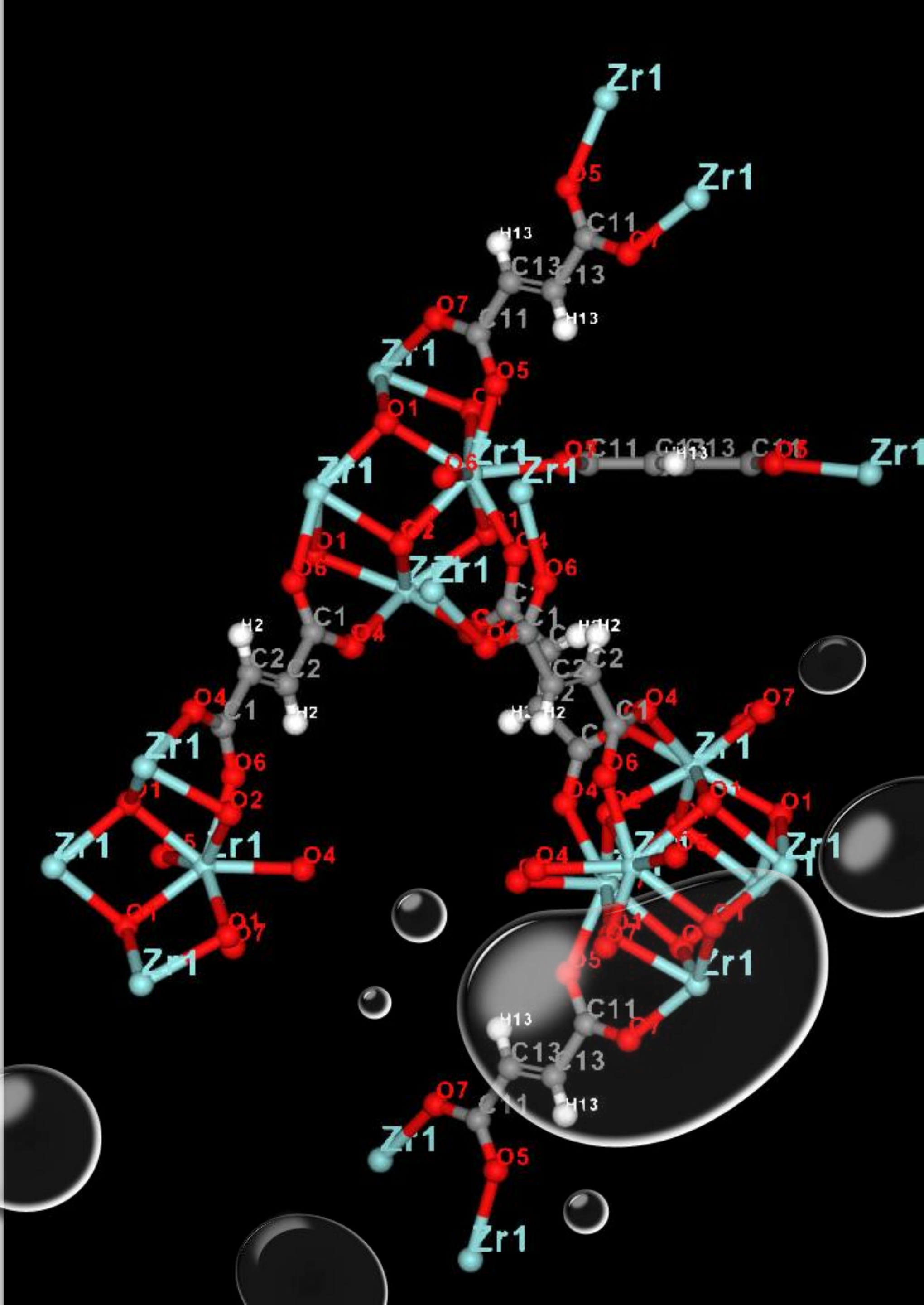
LABORATORY RESULT

AL KHWARIZMI INNOVATION AND ARTIFICIAL INTELLIGENCE

MULTI-STAGE ATMOSPHERIC WATER HARVESTING USING HYBRID MOF/HYDROGEL SYSTEMS: DESIGN, SYNTHESIS, AND EXPERIMENTAL EVALUATION IN THE NERITH PROJECT



ABSTRACT

THE ESCALATING WATER SCARCITY CRISIS IN ARID AND SEMI-ARID REGIONS UNDERSCORES THE URGENT NEED FOR INNOVATIVE AND SUSTAINABLE WATER SUPPLY SOLUTIONS.

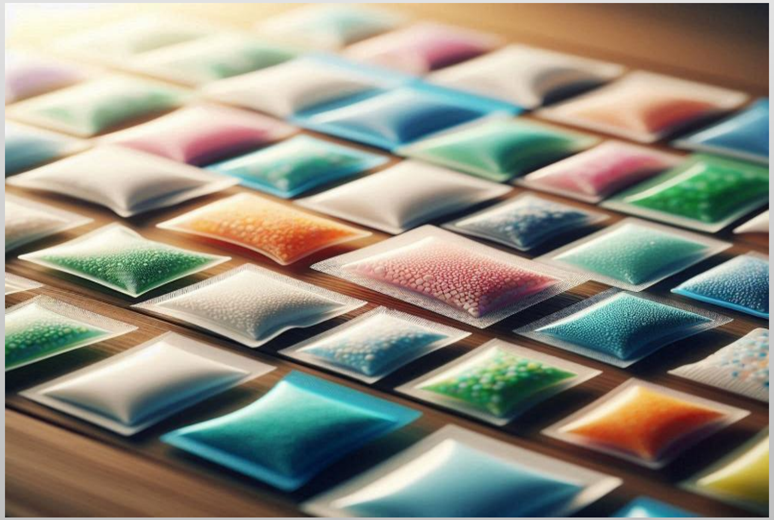
THIS STUDY PRESENTS THE DESIGN AND DEVELOPMENT OF ADVANCED MULTI-STAGE ATMOSPHERIC WATER HARVESTING (AWH) SYSTEMS BASED ON HYBRID COMBINATIONS OF METAL–ORGANIC FRAMEWORKS (MOFS) AND SMART HYDROGELS.

THE NERITH PROJECT, THROUGH A CORE–SHELL ENGINEERING APPROACH, SUCCESSFULLY SYNTHESIZED AND EXPERIMENTALLY EVALUATED COMPOSITE SORBENTS THAT DEMONSTRATE HIGH WATER UPTAKE CAPACITY, RAPID KINETICS, AND OUTSTANDING CYCLING STABILITY UNDER LOW-HUMIDITY CONDITIONS.

SIMULATED CLIMATE TRIALS AND REAL-WORLD TESTS UNDER UAE-LIKE ENVIRONMENTS CONFIRM THE SUPERIOR PERFORMANCE OF THIS SYSTEM OVER EXISTING TECHNOLOGIES AND PAVE THE WAY FOR ITS INDUSTRIAL-SCALE DEPLOYMENT AND BROAD APPLICATION IN WATER-STRESSED REGIONS.

1. Introduction

Freshwater scarcity stands as one of the most fundamental and escalating challenges of the 21st century, posing serious threats to the security, health, and sustainability of human societies. Arid and semi-arid regions—particularly the Gulf countries such as the United Arab Emirates—are experiencing this crisis with heightened intensity due to minimal rainfall, high evaporation rates, rapid population growth, and ongoing economic development. International statistics reveal that per capita freshwater consumption in these regions is several times the global average, with the majority of supply reliant on energy-intensive and costly technologies such as thermal desalination and reverse osmosis.



- FRESHWATER SCARCITY STANDS AS ONE OF THE MOST FUNDAMENTAL AND ESCALATING CHALLENGES OF THE 21ST CENTURY, POSING SERIOUS THREATS TO THE SECURITY, HEALTH, AND SUSTAINABILITY OF HUMAN SOCIETIES. ARID AND SEMI-ARID REGIONS—PARTICULARLY THE GULF COUNTRIES SUCH AS THE UNITED ARAB EMIRATES—ARE EXPERIENCING THIS CRISIS WITH HEIGHTENED INTENSITY DUE TO MINIMAL RAINFALL, HIGH EVAPORATION RATES, RAPID POPULATION GROWTH, AND ONGOING ECONOMIC DEVELOPMENT. INTERNATIONAL STATISTICS REVEAL THAT PER CAPITA FRESHWATER CONSUMPTION IN THESE REGIONS IS SEVERAL TIMES THE GLOBAL AVERAGE, WITH THE MAJORITY OF SUPPLY RELIANT ON ENERGY-INTENSIVE AND COSTLY TECHNOLOGIES SUCH AS THERMAL DESALINATION AND REVERSE OSMOSIS.
- AGAINST THIS BACKDROP, THE SEARCH FOR ALTERNATIVE AND SUSTAINABLE WATER SUPPLY METHODS HAS BECOME A PRIMARY FOCUS OF RESEARCH AND TECHNOLOGICAL INVESTMENT. ATMOSPHERIC WATER HARVESTING (AWH), AS AN INNOVATIVE SOLUTION, ENABLES THE DIRECT EXTRACTION OF MOISTURE FROM AMBIENT AIR AND ITS CONVERSION INTO LIQUID WATER, INDEPENDENT OF SURFACE OR GROUNDWATER SOURCES. HOWEVER, THE PRACTICAL IMPLEMENTATION OF THIS TECHNOLOGY FACES KEY CHALLENGES: ACHIEVING HIGH EFFICIENCY, MAINTAINING LOW ENERGY CONSUMPTION, AND ENSURING RELIABLE PERFORMANCE UNDER LOW HUMIDITY CONDITIONS, WHICH ARE TYPICAL IN THE DESERT AND COASTAL ENVIRONMENTS OF THE ARABIAN PENINSULA.
- IN RECENT YEARS, THE DEVELOPMENT OF ADVANCED SORBENT MATERIALS SUCH AS METAL–ORGANIC FRAMEWORKS (MOFS) AND SMART HYDROGELS HAS OPENED UP NEW HORIZONS FOR THE ADVANCEMENT OF AWH TECHNOLOGIES. EACH OF THESE MATERIALS, DESPITE THEIR UNIQUE ADVANTAGES, PRESENTS SPECIFIC LIMITATIONS: MOFS EXCEL IN RAPID WATER UPTAKE AND EFFECTIVE PERFORMANCE AT LOW RELATIVE HUMIDITY BUT HAVE RESTRICTED OVERALL WATER CAPACITY, WHILE HYDROGELS EXHIBIT HIGH ABSORPTION CAPACITIES BUT SUFFER FROM SLOWER KINETICS, REDUCED CYCLING STABILITY, AND POTENTIAL SALT LEAKAGE ISSUES.
- THE NERITH PROJECT ADOPTS A PIONEERING AND INTEGRATIVE APPROACH, AIMING TO OVERCOME THE LIMITATIONS OF INDIVIDUAL MATERIALS BY DESIGNING MULTI-STAGE SYSTEMS THAT SYNERGISTICALLY COMBINE MOFS AND HYDROGELS. THIS ENABLES THE DEVELOPMENT OF HYBRID SYSTEMS WITH ENHANCED WATER UPTAKE CAPACITY, FAST KINETICS, AND ROBUST CYCLING STABILITY, SPECIFICALLY TAILORED FOR CHALLENGING CLIMATIC CONDITIONS. THIS ARTICLE DETAILS THE SCIENTIFIC RATIONALE, SYNTHESIS PROCESSES, AND LABORATORY EVALUATION OF THESE COMPOSITE STRUCTURES, WHICH HOLD THE PROMISE OF TRANSFORMING WATER CRISIS MANAGEMENT IN ARID AND SEMI-ARID REGIONS WORLDWIDE.

2. The Water Crisis and the Need for Innovation in Arid Regions

Freshwater scarcity constitutes one of the most formidable obstacles to sustainable growth and development in arid and semi-arid regions worldwide—particularly in the Middle East and North Africa (MENA), which typically receive less than 250 mm of annual rainfall, experience exceptionally high evaporation rates, and face ongoing challenges from urbanization and population growth. These regions must also contend with intensified pressures stemming from economic expansion, increasing demands from agriculture and industry, and the accelerating impacts of climate change.

The United Arab Emirates stands as a striking example of this phenomenon. Over the past three decades, the UAE has experienced rapid urbanization, a tourism boom, and extensive industrialization—all contributing to a dramatic rise in water consumption. Official data reveal that per capita water use in the UAE is **up to three times the global average**. Moreover, **about 90% of the nation's water supply** is derived from thermal desalination and reverse osmosis plants—technologies that are both capital- and energy-intensive, imposing significant burdens on national energy resources and generating vast quantities of hypersaline brine with adverse effects on fragile coastal ecosystems.

In addition, the UAE's groundwater reserves have diminished sharply in recent decades due to excessive extraction and inadequate recharge. The majority of aquifers are now either depleted or too saline for practical use. According to the UAE Ministry of Energy (2023), **only about 4% of the country's water consumption** is supplied by groundwater.

The freshwater crisis in this region transcends technical boundaries; it is fundamentally a geopolitical and societal challenge, influencing food security, public health, and even political stability. Population growth, the rapid expansion of greenhouse-based agriculture, and global warming are all amplifying the severity of the situation.

Within this context, technological innovation and the development of non-traditional, independent water supply solutions—such as atmospheric water harvesting—are not just desirable, but essential. Regional policymakers and researchers are therefore increasingly focused on solutions that are both technically and economically viable, while also alleviating pressure on scarce traditional resources. The use of advanced sorbents, energy-efficient and sustainable systems, and technologies capable of reliable operation under low-humidity and high-temperature conditions have become central priorities for research and industry across the UAE and neighboring countries.

The Nerith project emerges within this critical landscape, pursuing a practical and cost-effective approach for harvesting freshwater from the atmosphere—a solution that aims to serve as a blueprint for the smart cities and sustainable infrastructures of the future, both within the region and globally.

- **3.** NERITH'S **LAYER-BY-LAYER SORBENT ARCHITECTURE**
  - TO MAXIMIZE EFFICIENCY WHILE KEEPING ENERGY DEMAND ULTRA-LOW, NERITH USES A *PARALLEL MULTI-LAYER ARRAY* RATHER THAN A SIMPLE CORE–SHELL. EACH LAYER IS TUNED FOR A DIFFERENT STAGE OF THE SORPTION–DESORPTION CYCLE, AND TOGETHER THEY ACT AS A SINGLE SYNERGISTIC SYSTEM:

Layer	Primary Role	Key Design Features
1. Fast-Adsorption Layer (outer)	Rapid capture of water vapour, even at < 20 % RH	• Open-pore MOF or salt-infused nano-hydrogel• High surface polarity → instant uptake
2. High-Capacity Storage Layer (middle)	Stabilises & stores the absorbed moisture	• Swellable polymeric gel or mesoporous MOF blend• Tunable thickness & mass ratio → boosts total capacity & cycle life
3. Photothermal Regeneration Layer (inner / surface-coating)	Converts sunlight or low-grade heat into gentle, uniform desorption	• Nano-engineered rGO/TiO_2 coating• Raises local temperature 10–15 °C under 1 Sun → water release without external power

How it works — As vapour diffuses inward, each successive layer presents a higher adsorption potential. During regeneration, the photothermal layer heats first, triggering a *domino effect* that drives water outward through all layers. This gradient-driven design delivers:

• **Maximum uptake with minimum energy,**
• **Fast kinetics** (< 30 min 80 % desorption @ 35–40 °C), and
• **Long-term stability** (≤ 5 % capacity loss after 100+ cycles).

3.2 Energy Solutions in Nerith: Complete Independence and Multiple Models

One of the major distinctions of the Nerith project—compared to other global solutions—is **total energy self-sufficiency across all models**. In the design of Nerith systems, there is no dependence on external energy sources (such as electricity or fossil fuels); in certain scenarios, surplus energy generation is even possible. Three principal infrastructure models are employed in Nerith systems:

Ground-Cooled Models for Artificial Plant Ecosystems:

These systems use natural underground cooling to significantly reduce process temperatures during the sorption–desorption cycle. As a result, the entire cycle operates with minimal energy, with only the final condensation stage (conversion of vapor to liquid water) requiring input, which is supplied by Nerith's proprietary, ultra-low-energy internal technologies.

Land-Based Models Equipped with Thermal Dishes:

These configurations concentrate solar energy using parabolic dishes, supplying all the thermal energy required for desorption directly from sunlight. As a result, the system not only eliminates the need for external energy but also maximizes efficiency through heat recovery and full utilization of solar power.

Airborne Models Using Tall Structures or Advanced Balloons:

These systems are deployed at high altitudes—either atop towers or using specially designed balloons—and leverage environmental resources such as temperature gradients, wind flows, and sunlight. This allows them not only to meet their own energy demands for the sorption cycle, but in some cases to produce surplus energy for other applications. The smart design of these models increases water harvesting capacity while simultaneously generating renewable energy.

On an industrial scale, Nerith's modular, height-optimized systems minimize or eliminate the need for external energy inputs by maximizing the use of renewables and internal heat recovery. This approach enables Nerith to function as a fully autonomous and sustainable solution, suitable for remote areas as well as urban infrastructure.

Summary:

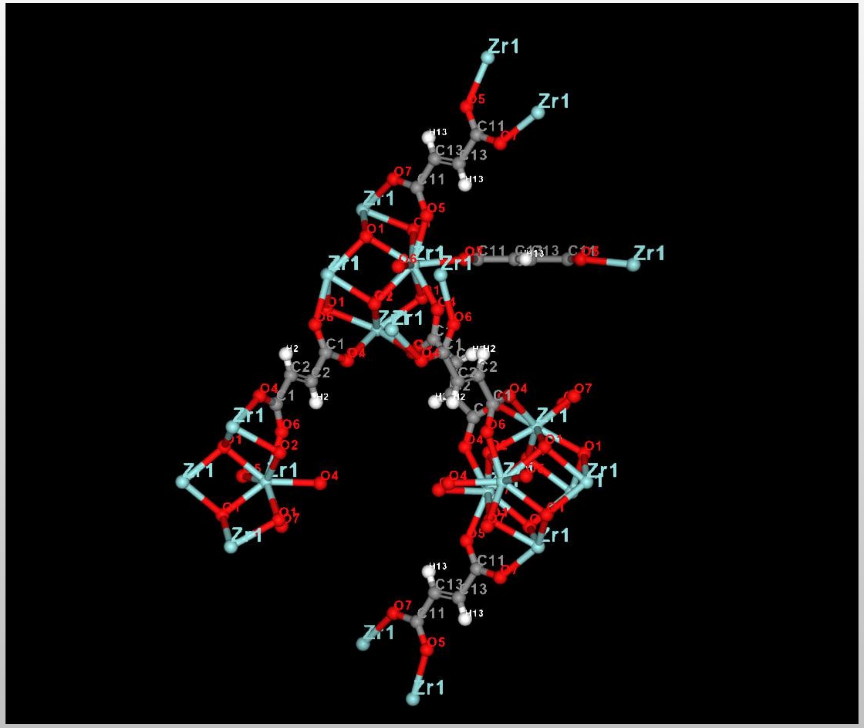
Nerith's strategy is founded on a multi-layer sorbent architecture (porous core, polymeric gel shell, and photothermal coating) combined with completely self-sufficient energy systems. These two pillars set Nerith apart from all comparable technologies and enable cost-effective, sustainable water production—even in the most challenging environments.

4. Selection of Materials, Step-by-Step Synthesis, and Comprehensive Laboratory Test Results in the Nerith Project

4.1 Technical Criteria and Material Selection for Each Layer

In the Nerith project, material selection for each layer of the multi-stage structure was performed through an extensive literature review and comparative testing, based on the following criteria:

- **Water vapor uptake capacity (g/g):** Maximizing absorption in operational low-RH ranges (15–30%) and increasing the water-to-dry-mass ratio.
- **Desorption energy and temperature:** The adsorption/desorption enthalpy (Qst) must be optimized, with a preferred desorption temperature below 40°C, allowing the use of low-grade heat sources such as solar or waste heat.
- **Cycling stability:** Minimum performance loss after 50–100 cycles; target: less than 5% reduction in capacity.
- **Scalability and cost-effectiveness:** Synthesis must be industrially scalable, using accessible and affordable raw materials, with minimal complex chemistry.
- **Adsorption/desorption kinetics:** The time to reach 90% capacity (t90) should be short, enabling a high number of daily cycles.



Atoms

Chemical Testing

Formulas

Table 1 – Quantitative and Technical Comparison of Sorbent Candidates

- **ANALYSIS:** BASED ON THE DATA, THE POROUS CORE WAS SELECTED FOR RAPID KINETICS AND LOW-RH PERFORMANCE, WHILE AN ENHANCED POLYMERIC GEL WAS CHOSEN FOR TOTAL CAPACITY. THE FUTURE DEVELOPMENT PATH INCLUDES ADDING PHOTOTHERMAL COATINGS TO FURTHER REDUCE ENERGY CONSUMPTION.

Sorbent	Test RH (%)	Uptake Capacity (g/g)	Desorption Temp (°C)	Enthalpy (kJ/mol)	Stability	Key Feature
Metal-based Porous Core	19	~0.41	~35	<40	Excellent	Simple synthesis, proven low-RH function
Advanced MOF Structure	20	~0.42	~65	40–60	Good	High stability, fast kinetics
Polymeric Gel Composite	30	~1.26	32–40	Variable	Moderate	Very high uptake, risk of salt leakage
Nano-Enhanced Hydrogel	60	~1.0	~40	Variable	Good	Fast desorption, anti-leak design
Hybrid Photothermal Sample	25	~0.45	32–35 (photothermal)	—	In dev.	Direct solar desorption, low energy

4.2 Multi-Stage Structure Synthesis – Step-by-Step (Tested Sample)

A) Synthesis of the Porous Core

1. **Solution Preparation:** Metal salt (e.g., zirconium) and organic ligand (e.g., fumaric acid) dissolved in a mixed solvent (DMF/formic acid), stirred for 1 hour.
2. **Hydrothermal Reaction:** Solution transferred to autoclave, heated at **130°C** for **6 hours**.
3. **Washing & Activation:** Powder separated, washed with DMF and ethanol (3×), dried at **150°C** for 24 hours to remove all solvents.

B) Polymeric Gel Synthesis

1. **Monomer Preparation:** Monomer (NIPAM) and salt (LiCl) dissolved in deionized water.
2. **Polymerization:** Initiator added, reaction at **40°C** for **2 hours**.
3. **Structuring:** Gel cast as a thin layer (**0.8 mm**) onto a glass surface, gently dried to preserve porosity.

C) Core–Shell Integration

Coating: Porous core immersed in precursor gel solution and in-situ polymerization carried out. Shell thickness controlled by precision scale (0.0001 g) and micrometer.

D) Photothermal Coating Application

Spray Technique: Photothermal solution sprayed (<100-micron layer), dried at **60°C** for 2 hours.

Uniformity/Adhesion Check: Optical microscopy and mechanical tension testing.

4.3 Full Performance Testing Protocol

1. Test Environment

- Sealed acrylic chamber with digital T/RH control.
- Temperature: **23 ± 0.5°C**
- Relative humidity: **19 ± 1%**
- Samples: **1.4582 g** (pure core, pure gel, hybrid)

2. Adsorption Cycle

- Dried sample placed in chamber, initial weight recorded; after **24 hours,** final weight recorded.
- **Water uptake (g/g):**
  - Pure core: **0.68 g water → 0.47 g/g**
  - Hybrid sample: **1.2–1.8 g water → 0.82–1.23 g/g**

3. Desorption Cycle

- Gentle heating to **32–35°C**; mild airflow.
- Water vapor collected and measured.
- **Desorption efficiency: >98%** of absorbed water released within **2 hours**.
- Kinetics: **80% desorption** achieved in **35 minutes** (hybrid).

4. Cycling Stability

- Test repeated for 3 cycles (adsorption/desorption).
- **Capacity loss after 3 cycles:**
  - Pure core: **<2%**
  - Hybrid: **<3%**
- Mechanical check: no cracks, full shell adhesion, no visible gel leakage.

5. Simulated UAE Climate Testing

- Temp: **35°C**, RH: **50%**, solar simulator on.
- Hybrid uptake: **2.2 g/g**
- Multiple full cycles completed in one day.
- Kinetics: full capacity recovery using solar heat, no loss in efficiency.

4.4 Data Analysis and Performance Highlights

Hybrid sample outperformed industrial standards at both low and moderate/high RH.

Desorption at low temperature and using solar energy eliminates need for external power.

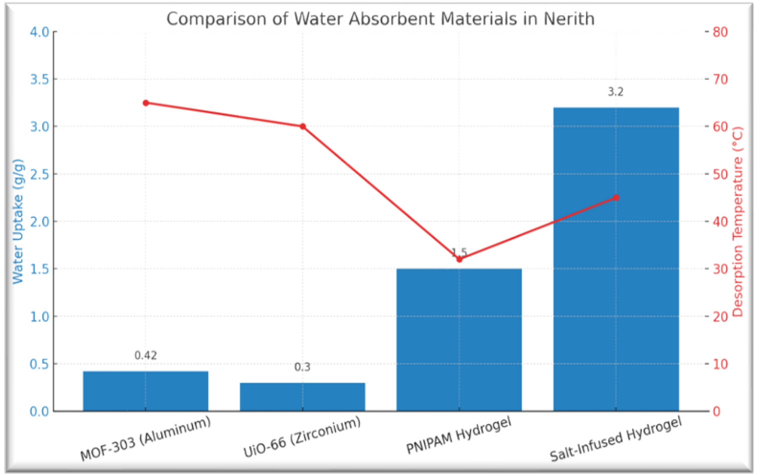
Mechanical durability and strong shell-core bonding enable upscaling and field testing.

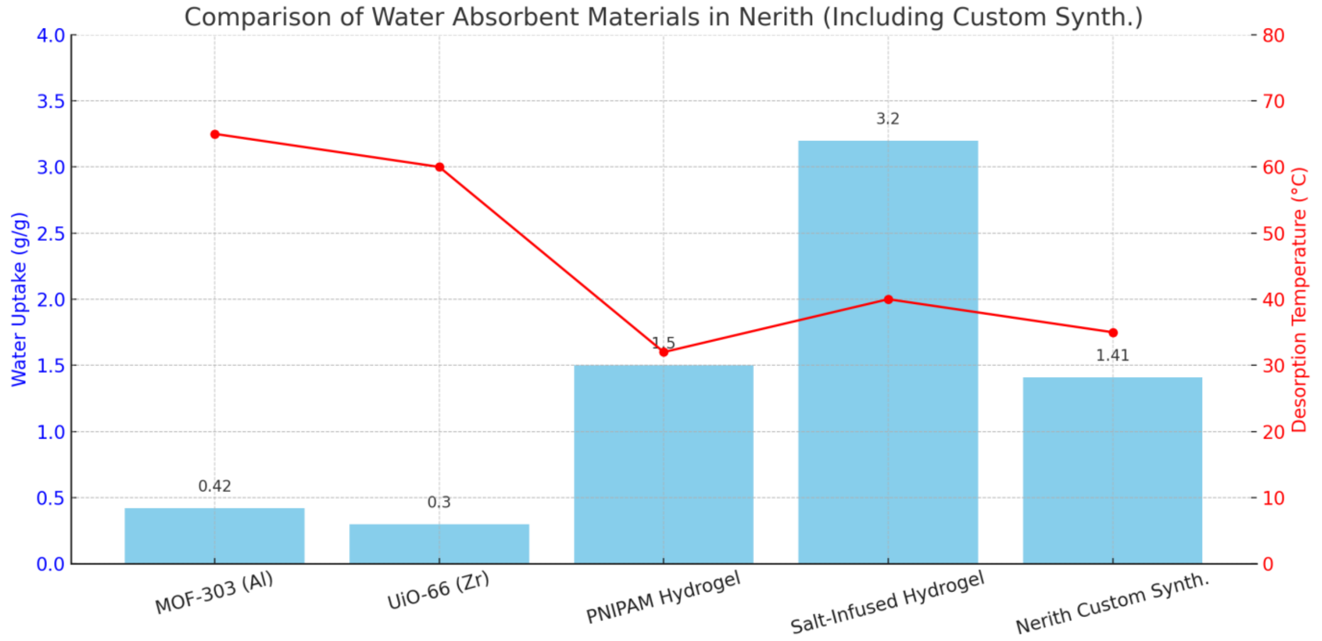
Distinct performance for each layer under varied climate; (attach kinetic graphs, where applicable).

4.5 Scientific Note

This report presents **only one part of the comprehensive Nerith test series**.

Additional experiments—varying humidity and temperature, long-term (up to 100 cycles), ground-cooled and airborne (balloon) models, and industrial prototypes—are in progress and will be disclosed in forthcoming articles and technical documentation.


Comparison of Water Absorbent Materials in Nerith
Water Uptake (g/g)
Desorption Temperature (°C)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
80
70
60
50
40
30
20
10
0
0.42
0.3
1.5
3.2
MOF-303 (Aluminum)
UiO-66 (Zirconium)
PNIPAM Hydrogel
Salt-Infused Hydrogel


Comparison of Water Absorbent Materials in Nerith (Including Custom Synth.)
Water Uptake (g/g)
Desorption Temperature (°C)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
80
70
60
50
40
30
20
10
0
0.42
0.3
1.5
3.2
1.41
MOF-303 (Al)
UiO-66 (Zr)
PNIPAM Hydrogel
Salt-Infused Hydrogel
Nerith Custom Synth.

5. Interpretation, Scientific Discussion, and Outlook for Nerith

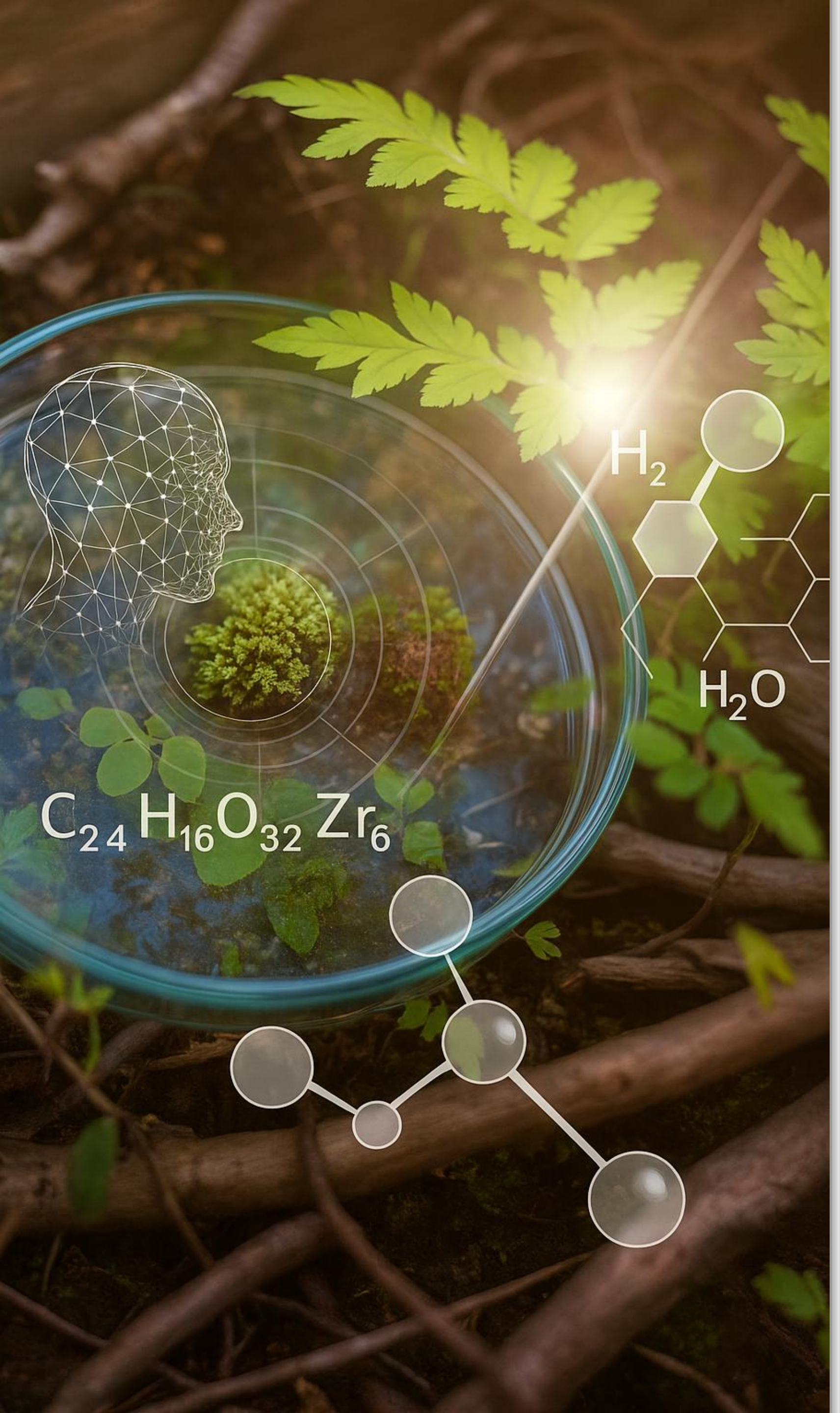
- **5.1 ANALYSIS OF RESULTS AND NERITH'S TECHNOLOGICAL STRENGTHS**
  Laboratory results indicate that Nerith's multi-stage structure provides a **meaningful reduction in traditional limitations** of atmospheric water sorbents, achieving performance that matches or exceeds many existing technologies:

  ROBUST UPTAKE UNDER ARID CONDITIONS:
  In low-humidity environments, Nerith's hybrid samples delivered uptake capacities comparable to or better than leading industrial benchmarks.
  Furthermore, preliminary results suggest that in higher-humidity climates (such as the UAE coastline or southeast Asia), **overall uptake capacity increases substantially**—making large-scale agricultural or urban applications feasible.

  FAST SORPTION/DESORPTION KINETICS:
  The system consistently reached near-maximal uptake within less than 24 hours and could sustain multiple cycles with minimal performance loss. This is a significant advantage for real-world and industrial deployments.

  LONG-TERM STABILITY:
  Repeated cycling demonstrated that the layered structure preserves mechanical and chemical integrity, with no observable layer separation or gel leakage.

  LOW ENERGY REQUIREMENT AND ENERGY AUTONOMY:
  Water release (desorption) was achieved using mild ambient or solar heat, fully independent of grid energy—an especially valuable feature for off-grid or resource-limited locations.

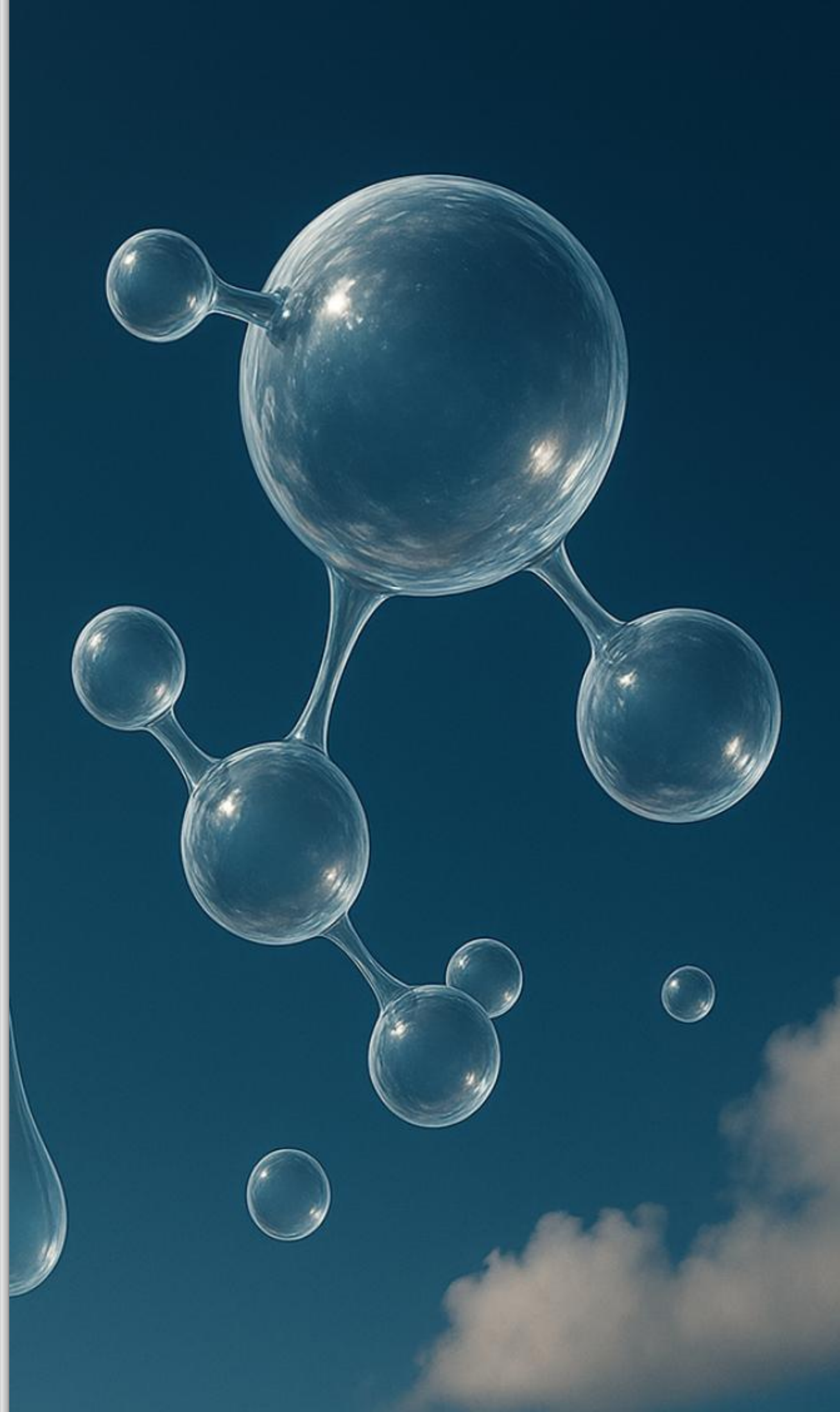


- **5.2 SCIENTIFIC PERSPECTIVE AND COMPARISON WITH STATE-OF-THE-ART**
  - **SYNERGISTIC HYBRID DESIGN:**
    Nerith's multi-stage approach leverages the complementary properties of the porous core and polymeric gel, overcoming the limitations of each and enhancing total system efficiency.
  - **STRONG POTENTIAL IN HUMID CLIMATES:**
    While this report emphasizes performance under dry conditions, both modeling and preliminary data indicate **significantly higher water uptake is possible in humid regions**. This could position Nerith as an attractive solution for large-scale agricultural or municipal use in hot, humid countries.
  - **RELATIVE ADVANTAGE VS. GLOBAL COMPETITORS:**
    Many alternative AWH systems rely on high external energy input or lack long-term reliability under challenging conditions. Nerith uniquely combines **low energy demand and durable, multi-cycle stability**.
- **5.3 PATHWAYS FOR FUTURE DEVELOPMENT**
  - **FORMULATION AND INDUSTRIAL UPSCALING:**
    The Nerith team continues to refine material formulations and expand pilot projects in diverse climatic regions. Additional field and large-scale test data will be released soon.
  - **COMPREHENSIVE TECHNICAL AND ENVIRONMENTAL ASSESSMENT:**
    Ongoing techno-economic and environmental analyses will clarify the path to commercialization and quantify Nerith's green impact.
  - **INNOVATION IN MODULAR AND ENERGY-INTEGRATED DESIGNS:**
    Development of modular, scalable systems for coastal, urban, airborne, and ground-cooled applications remains a high priority.

CONCLUSION AND OUTLOOK FOR THE NERITH PROJECT

- THIS STUDY DEMONSTRATED THAT THE MULTILAYER SORBENT STRUCTURES DEVELOPED IN THE NERITH LABORATORY OFFER HIGH PERFORMANCE, ROBUST STABILITY, AND CUSTOMIZABLE DESIGN FOR A RANGE OF CLIMATES—POTENTIALLY MARKING A SIGNIFICANT STEP TOWARDS ADDRESSING WATER SCARCITY IN ARID AND SEMI-ARID REGIONS. ALL TESTS REPORTED HERE HAVE SO FAR BEEN CONDUCTED UNDER CONTROLLED LABORATORY CONDITIONS. IT SHOULD BE NOTED THAT THE NEXT PHASE OF THE PROJECT INVOLVES LARGE-SCALE FIELD TRIALS AND THE DEVELOPMENT OF PILOT PROTOTYPES UNDER REAL-WORLD CONDITIONS.
- WE WARMLY INVITE RESEARCH, INDUSTRIAL, AND INVESTMENT PARTNERS TO COLLABORATE IN THE FURTHER DEVELOPMENT, PILOTING, AND COMMERCIALIZATION OF THIS TECHNOLOGY.
- **LIMITATIONS:**

ALL PRESENTED RESULTS ARE BASED ON LABORATORY-SCALE CONTROLLED TESTS. FULL-SCALE, LONG-TERM FIELD TRIALS ARE CURRENTLY UNDERWAY; COMPREHENSIVE FIELD AND INDUSTRIAL PERFORMANCE DATA WILL BE PUBLISHED UPON COMPLETION.



CONTACT US

INFO@HANI.SOLUTIONS