



From Laboratory Foundations to Sustainable Materials Solutions: A Scientific Journey

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In the twenty-first century, the defining challenges facing humanity—clean energy, environmental protection, and sustainable development—are inseparable from advances in materials science. From renewable energy integration and high-voltage energy storage to wastewater purification and green hydrogen production, materials form the backbone of technological progress. Yet for developing nations, meaningful participation in this transformation requires more than scientific ideas; it demands laboratories, institutions, and trained minds capable of turning knowledge into enduring solutions.

When I returned to Bangladesh after completing my doctoral training in Materials and Condensed Matter Physics, we faced a fundamental question: How can globally relevant research flourish within limited infrastructure and resources? Rather than perceiving constraints as barriers, we chose to see them as catalysts for resilience and innovation. Since then, my journey has been guided by a simple conviction—that scientific excellence, grounded in integrity and societal purpose, can emerge from anywhere.

This journey began in 2013 with the establishment of the Nanotechnology Research Laboratory at the Bangladesh University of Engineering and Technology (BUET). Over more than a decade, that laboratory has matured into a well-established research ecosystem. In 2025, with financial support from the Bangladesh Energy and Power Research Council, this foundation was further expanded through the establishment of the Energy Materials and Supercapacitor Research Laboratory. Together, these two laboratories now form complementary pillars of sustainable materials research for energy and environmental applications.

Building the First Foundation: The Nanotechnology Research Laboratory

The Nanotechnology Research Laboratory (NRL) was founded in 2013 with a seed grant of BDT 1.36 lakh from the University Grants Commission of Bangladesh. The funding was modest, but the vision was expansive. With determination and careful planning, a small unused room was transformed into a functioning research space.

Over time, competitive national and international grants enabled the mobilization of nearly BDT 4 crore to develop laboratory infrastructure. Within just 425 square feet, NRL evolved into a fully equipped nanomaterials facility, housing high-temperature furnaces, UV–visible and fluorescence spectrometers, a xenon solar simulator, electrochemical workstations, and advanced characterization tools (Figure 1).

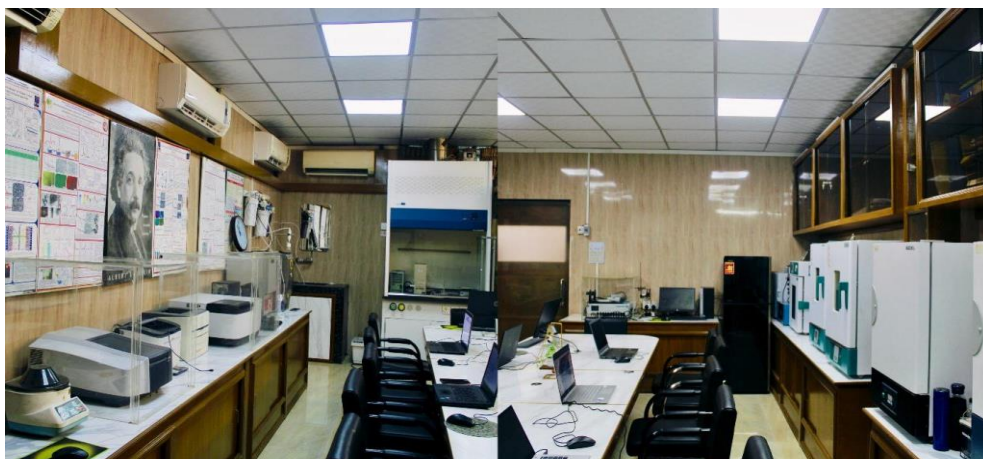


Figure 1. Nanotechnology Research Laboratory (NRL), established in 2013–2014

Yet a laboratory is defined not only by its instruments, but by the minds it shapes. NRL became a space where young researchers cultivated experimental rigor, critical inquiry, and scientific integrity. Over the past decade, more than 65 peer-reviewed publications have emerged from the laboratory, and over 35 postgraduate students have completed their PhD, M.Phil., and MSc degrees under my supervision. Many now serve in academia, research institutions, and industry at home and abroad. In a developing-country context, nurturing capable scientists may be the most enduring and sustainable contribution of all.

Expanding the Mission: The Energy Materials and Supercapacitor Research Laboratory

While the Nanotechnology Research Laboratory had matured into a robust and productive research center, emerging global energy challenges called for a dedicated and forward-looking initiative. In 2025, with financial support from the Bangladesh Energy and Power Research Council, we established the Energy Materials and Supercapacitor Research Laboratory (EMSRL) at BUET.

EMSRL was created to design low-cost, environmentally responsible materials for safe and efficient energy storage. Our focus centered on aqueous supercapacitors—water-based systems that offer inherent safety and environmental advantages over conventional organic-electrolyte technologies. For countries where affordability, safety, and scalability are essential, such systems carry particular significance.

The establishment of EMSRL marked a natural progression in our work. Having built strong foundational capacity through NRL, we were now able to align our scientific efforts even more directly with national energy priorities and global sustainability goals. Insights gained from earlier studies in environmental photocatalysis began to crystallize into broader scientific principles that would guide this next phase.

From Materials Discovery to Interface Engineering

In our early years, research at NRL concentrated on synthesizing nanostructured perovskite and ferrite oxides composed of earth-abundant elements. By tailoring crystal structures, regulating oxygen vacancies, and refining morphology, we enhanced charge separation and minimized recombination losses. These advances enabled efficient solar-driven degradation of industrial dyes and pharmaceutical pollutants, demonstrating that carefully engineered oxides could offer practical and affordable environmental solutions [1,2] (Figure 2).

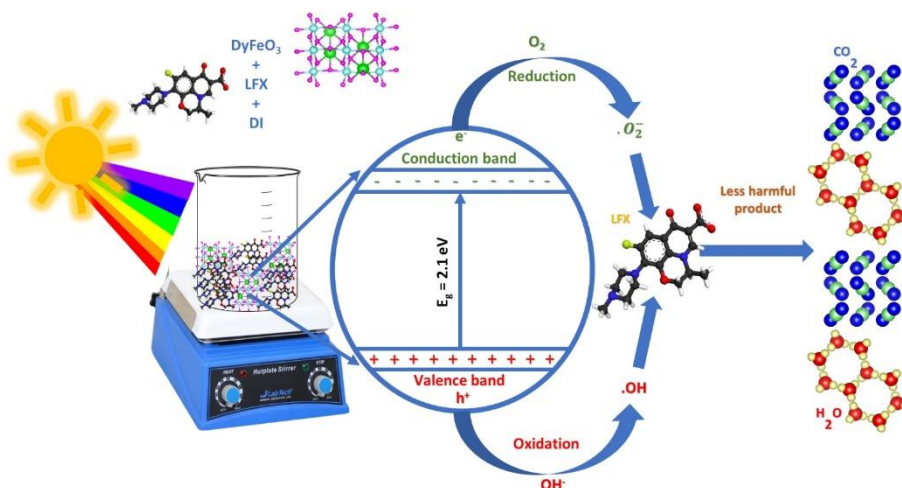


Figure 2. Schematic illustration of the levofloxacin (LFX) degradation mechanism in the presence of dysprosium orthoferrite (DyFeO₃) photocatalyst. Upon sunlight absorption, DyFeO₃ nanoparticles generate electron-hole pairs that produce reactive oxygen species, facilitating the breakdown of organic pollutants into simpler products such as H₂O and CO₂.

As we pursued improved performance across environmental remediation and energy storage applications, a deeper understanding emerged. Efficiency was not determined solely by intrinsic material properties; it was profoundly influenced by processes occurring at interfaces—where charges transfer, defects accumulate, and electronic structures reorganize.

This recognition transformed our research philosophy. We moved from synthesizing isolated nanomaterials to deliberately engineering heterointerfaces, understanding that controlled electronic coupling and defect modulation could unlock greater stability and functionality [3-6].

Interfacial Engineering and Built-In Electric Fields

This conceptual shift found a defining expression in our development of moisture-stable Cesium Tin Bromide-Molybdenum Disulfide ($\text{CsSnBr}_3\text{-MoS}_2$) heterostructures for aqueous energy applications. Rather than blending materials post-synthesis, we adopted a synthesis-driven approach in which perovskite nucleation and heterointerface formation were engineered simultaneously through a carefully controlled liquid-phase hot-injection process.

Sulfur-vacancy-rich MoS_2 nanosheets introduced during nanocrystal growth conformally wrapped the perovskite particles, creating purposeful 2D–3D encapsulation. The resulting type-II band alignment generated a built-in electric field across the interface, promoting directional charge separation and suppressing recombination.

Vacancy-induced donor states modulated band alignment and reduced charge-transfer barriers, while the hydrophobic MoS_2 layer limited moisture ingress and electrostatically stabilized the Sn^{2+} state. The interface thus became both protective and functional—an active participant in performance rather than a passive boundary.

Through integrated structural, spectroscopic, and electrochemical analyses, we established a clear structure–defect–interface–performance relationship. Stability and efficiency were not incidental; they were engineered through deliberate interfacial design.

High-Voltage Aqueous Energy Storage and Beyond

These interfacial innovations translated directly into device-level performance. In aqueous–organic hybrid electrolytes, the engineered heterostructures achieved a 2.8 V operating window, high energy density, and sustained cycling stability—remarkable for lead-free perovskite systems in water-based environments (Figure 3). The durability observed was not accidental; it was the deliberate outcome of interfacial electrostatic engineering [7].

The same philosophy was subsequently extended to aqueous electrocatalysis. Under alkaline water-splitting conditions, including seawater environments, the heterostructures demonstrated prolonged operation without structural degradation or undesirable side reactions.

Together, these advances underscored a broader principle: materials traditionally considered fragile can be stabilized through intrinsic electronic design. By controlling interfaces during growth itself, sustainability can emerge from fundamental physical insight rather than external protection alone.

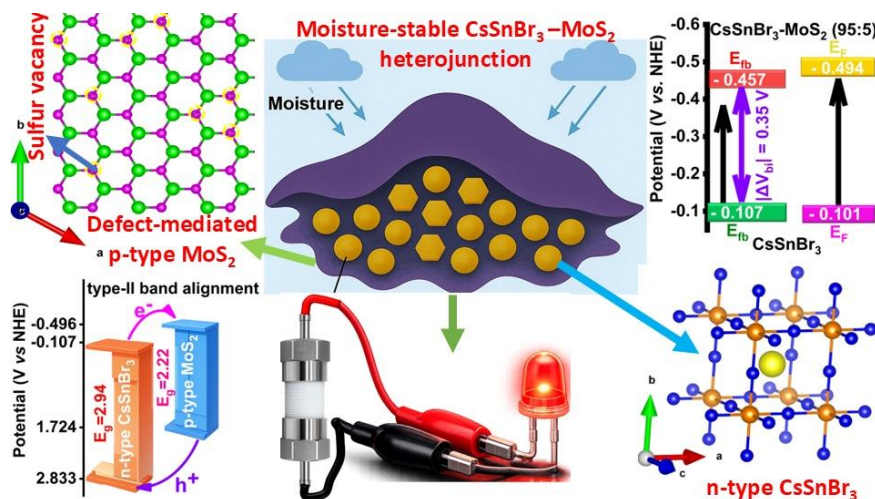


Figure 3. Defect-engineered MoS_2 containing sulfur vacancies forms a moisture-resistant, built-in-field-enhanced type-II heterojunction with n-type CsSnBr_3 . This interface stabilizes Sn^{2+} , directs charge transport, and enables a 2.8 V aqueous energy-storage device capable of powering an LED.

Broader Impact: Capacity, Leadership, and Sustainability

While this journey has advanced materials innovation, its significance extends well beyond performance metrics. In a developing-country context, scientific progress must also be measured by strengthened institutions and empowered individuals.

The establishment of NRL and EMSRL has enhanced Bangladesh's experimental capacity in nanoscience and sustainable energy research, reducing reliance on external facilities and demonstrating that globally competitive research can thrive within our own academic environment.

Equally important has been the cultivation of human capital. Numerous postgraduate researchers trained in these laboratories now contribute to academia and industry both nationally and internationally. Their growth represents the most enduring dimension of sustainability.

Beyond research, this journey has involved broader responsibilities. Recognition as a Fellow of the Institute of Physics (UK) and the Royal Society of Chemistry reflects interdisciplinary engagement across physics and chemistry. Yet leadership is defined not by titles, but by mentorship, ethical practice, and meaningful collaboration. Sustainable research must be accompanied by sustainable scientific culture—where institutions, ideas, and individuals evolve together.

Conclusion: Toward Generalizable Sustainable Materials Design

From transforming a small storeroom into a functioning laboratory in 2013 to establishing a dedicated energy materials research facility in 2025, this journey reflects an evolution not only in technology, but in perspective.

What began as materials synthesis matured into interface engineering. What began as nanostructure refinement evolved into defect modulation and electrostatic design.

What began as laboratory construction grew into complementary research platforms devoted to sustainable innovation.

Today, our work seeks not only to enhance individual materials, but to articulate broader design principles—synthesis-driven heterointerface formation, defect-regulated band alignment, built-in electric-field engineering, moisture-stable lead-free platforms, and multifunctional materials addressing energy and environmental challenges. These principles offer a framework for sustainable materials design that extends beyond any single system.

The journey from laboratory foundations to sustainable materials solutions continues. Its message, however, is enduring: impactful science does not depend solely on abundant resources or sophisticated infrastructure. It depends on clarity of vision, perseverance in the face of constraint, and the thoughtful alignment of fundamental physics with societal need.

Above all, science must serve people—and contribute to a future that is technologically advanced, environmentally responsible, and socially sustainable.

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