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NANOINNOVATION WITH PURPOSE: ADVANCING MATERIALS, ENERGY, AND FORENSICS ACROSS BORDERS AND DISCIPLINES

Jingbo Louise Liu
Texas A&M Energy Institute, Texas A&M University-Kingsville,
and Louise Nanoinnovation North American
Email: Jingbo.Liu@tamuk.edu

Jingbo Louise Liu is a Professor of Chemistry at Texas A&M University-Kingsville, Faculty Affiliate at the Texas A&M Energy Institute, and Director of Louise Nanoinnovation North American. Her research spans sustainable energy, advanced materials, and forensic science, with a strong commitment to mentoring the next generation of innovators. Her HYDROGENISE initiative exemplifies this mission, developing non-precious catalysts and composite electrolytes that accelerate water splitting, improve fuel mileage, and reduce hydrogen production costs. Her research integrates solid-state batteries, microbial fuel cells, and carbon capture technologies, all guided by a four-phase R&D4 framework: Research, Design, Demonstration, and Deployment. She pioneered halide ceramic electrolytes synthesized via green nano-emulsion methods, achieving superionic conductivity and stable cycling. In microbial fuel cells, she engineered nanocatalyst-enhanced systems with red-light stimulation to boost power density. Her carbon management work uses clay-based sorbents for low-cost CO_2 capture. Dr. Liu's forensic innovations include β-POLICE nanocomposites for fingerprint detection and BEST simulants for crime scene reconstruction, both of which align with DHS priorities. Her LouiseSix metabolic boosters support mitochondrial health, bridging nanoscience with human wellness. She has taught over 14,500 students, supervised 285 researchers, and produced more than 380 scholarly outputs, including patents, peer-reviewed journal publications, books/book chapters, and invited and contributed presentations at professional conferences. She has led and participated in projects funded by NSF, DOE, DHS, NSERC, and faculty fellowships sponsored by the AFOSR and ONR. Her leadership and contributions to energy, materials and public service have earned her nomination for the Presidential Award for Excellence in Science, Mathematics, and Engineering Mentoring, and recognition from the National Small Business Association, the International Union of Pure and Applied Chemistry, the Japan Society for the Promotion of Science and elected fellow distinctions by the American Chemical Society, the Royal Society of Chemistry, and the Linnean Society.

Foundations in Ice and Curiosity: A Transnational Scientific Awakening.–I was born in Harbin, a city renowned for its ice-crystalline winters, into a family of police officers. My childhood was shaped by duty, ethics, a love of motion (running, gymnastics, and heptathlon), and early leadership, a trajectory that enabled boldness in sports, speech, and self-expression. While my parents led the “Up to the Mountains and Down to the Countryside” youth movement, my grandmother became my universe. Her stories amazed me as I drifted off to sleep, wrapped in warmth and wonder. Every day, my grandfather carried me on his shoulders, singing and dancing as he called me his little moon, a name wrapped in love. At school, I was a disciplined child, entrusted to speak, compete, and lead, based on the teachings of my grandparents. These moments planted the seeds of courage, public voice, and quiet determination. Though I lacked formal training, I embraced gymnastics with fearless joy, earning awards on the balance beam and parallel bars simply because others hesitated. In table tennis, I found rhythm and resolve, winning women's singles and doubles championships. And on ice, I soared, a small burst of flight beneath the northern sky, skating with the spirit of a bird in motion. My academic journey began with curiosity and a desire to question, culminating in my B.S. and M.S. degrees in Chemistry and Chemical Engineering from Heilongjiang University. Later, I pursued my Ph.D. in Materials Science and Engineering at the University of Science and Technology Beijing to bridge the gap between theory and practice. At the National Library of China, I immersed myself in the legacies of Nobel Laureates Einstein and Fleming, absorbing the genius of their molecular insights and nanotechnological visions. From Beijing’s historic corridors, I journeyed across continents to Calgary, Alberta, a city where the prairie winds meet the Rockies, and where the horizon itself invites exploration. As a postdoctoral fellow, I entered the world of solid oxide fuel cells, hydrogen vehicles, and advanced materials. In Dr. Birss’s laboratories at the University of Calgary's Chemistry Department, I learned to balance theory with application. The work demanded rigor, the careful layering of ceramics, the delicate calibration of electrochemical systems, and the scientific pursuit of efficiency in energy conversion.

Laboratories, Lecterns, and Leadership: From Clarkson to Texas A&M-Kingsville.–At Clarkson University, I entered the laboratory alive with metal, metal oxide catalysts, and polymers and explored novel polymer-metal hybrid composites through the elegance of wet-chemistry at the nanoscale (Fig. 1a). On the second floor of the

Materials Processing Building, I had access to the full arsenal of state-of-the-art instrumentation, Zeta potential analysis, scanning electron microscopy, transmission electron microscopy, X-ray diffraction, and many other tools that opened windows into the “small worlds” for me to communicate with the nanoscale. Afterwards, I moved to West Virginia University Institute of Technology, where I held my first position as a Visiting Assistant Professor (Fig. 1b). This marked a significant milestone, the threshold moment that opened the door to a professorship. In the classroom, I discovered the power of teaching not as transmission, but as transformation by providing high-quality education and the courage to question, innovate, and lead. I began creating leading-edge teaching materials, weaving research into pedagogy so that students could see science not as static knowledge, but as a living, evolving field of inquiry. I worked on chitosan-based natural product extracts for the absorption of heavy metals, particularly mercury. This work had a societal impact by offering a sustainable, low-cost, and environmentally friendly approach to mitigating toxic metal pollution in water systems and advancing green remediation technologies. In 2006, I arrived at Texas A&M University (TAMU)-Kingsville and have been affiliated with the TAMU Energy Institute. This institution shaped me into a professor (Fig. 1c). I invented and led projects that spanned the spectrum of my scientific passions: from energy materials to functional devices, from disinfection science to forensic nanotechnology. Each project was not an isolated effort, but part of a larger vision to advance science that serves both society and truth, as Chemistry is a pursuit of truth. My work was recognized and supported by the NSF, DOE, AFOSR, ONR, and the DHS. These grants and fellowships served as endorsements of my research and affirmations of their relevance to national needs and global challenges. TAMU-Kingsville became the fulcrum, where my research matured into leadership. I learned to balance the laboratory with the lecture hall, the grant proposal with the mentoring session, the pursuit of discovery with the responsibility of stewardship. My identity as a professor is often defined by the number of products and graduates I have trained. These metrics also enable empowering students' lives, launching projects, and translating knowledge into meaningful impact.

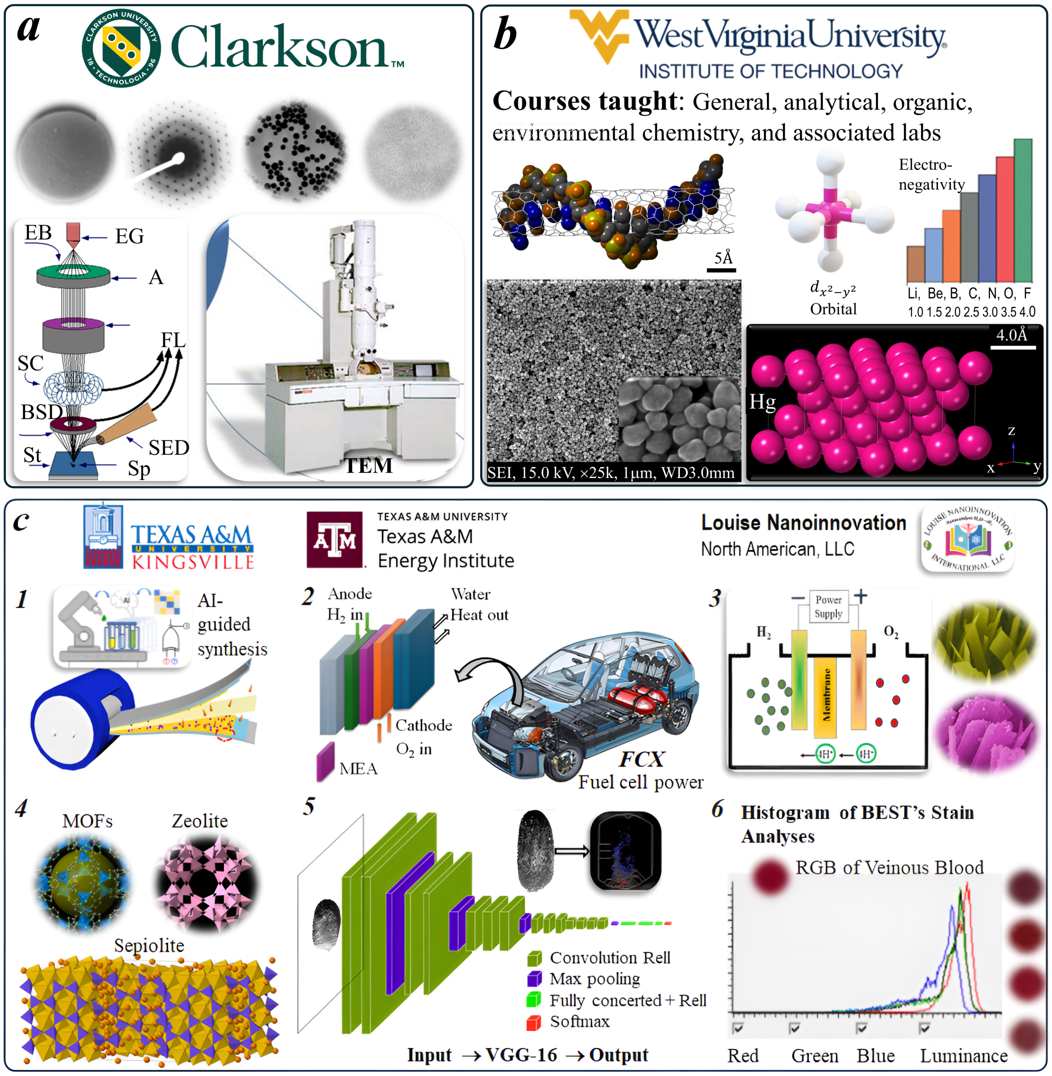


Figure 1. Professional progression across institutions, highlighting research, teaching, and innovation. (*a*) Clarkson University: Development of polymer-metal hybrid composites; (*b*) West Virginia University Institute of Technology: Initial faculty appointment emphasizing transformative pedagogy and applied research in water remediation; and (*c*) TAMU-Kingsville: multidisciplinary research spanning energy materials, functional devices, carbon management, and nano-forensics, supported by NSF, DOE, DHS, and ONR & AFOSR Summer Faculty Fellowship: (*c1*) solid-state batteries, (*c2*) microbial fuel cells, (*c3*) green hydrogen production, (*c4*) carbon management, (*c5*) fingerprint nano-agents, (*c6*) blood simulants.

From Battery System to Forensics: Research Across Multi-disciplines.–This research portfolio spans two decades of innovation at the intersection of materials science, energy systems, and forensic technology, unified by a commitment to reproducibility, sustainability, and societal impact. In energy storage, all-solid-state lithium batteries were advanced using Li_3InCl_6-based halide electrolytes, achieving superionic conductivity, a wide electrochemical window, and stable cycling. Microbial fuel cells were enhanced using nanocatalysts, polymeric membranes, and biofilm engineering, with red-light stimulation boosting power density. The green hydrogen project demonstrated high production via non-Pt catalysts in proton exchange membrane electrolysis cells, reducing costs and enabling scalable, carbon-free fuel. Carbon management emphasized clay minerals as sorbents for CO_2 capture, integrating experimental and simulation insights to improve storage and reduce capture costs. In forensics, β-POLICE improved fingerprint detection accuracy by 40%, while BEST replicated human blood rheology and patterns using artificial intelligence (AI)-enabled pattern recognition. Together, these projects illustrate nanoinnovation with purpose, bridging laboratory breakthroughs to practical applications in defense, security, and public health.

All-Solid-State Lithium Batteries: Ceramic Electrolytes for Safer High-Density Storage.–The rapid electrification of transportation and grid storage demands energy systems that combine high energy density with uncompromising safety. Conventional lithium-ion batteries (LIBs) rely on flammable liquid electrolytes, which pose risks of leakage, dendrite-induced short circuits, and thermal runaway. All-solid-state lithium batteries have emerged as a transformative alternative, leveraging solid electrolytes that function as both ionic conductors and electronic insulators. Our research focuses on Li_3InCl_6-based halide ceramic solid-state electrolytes (SSEs), synthesized via green emulsion methods and optimized through orthogonal design, to achieve superionic conductivity and long-term stability. An *in-situ* nanoengineering was employed using aqueous media and Aloin as a bio-capping agent. This route adheres to the 12 Principles of Green Chemistry, minimizing the use of hazardous solvents while enabling precise control over nucleation and growth. Orthogonal Taguchi arrays reduced the experimental burden from 625 to 48 runs, allowing systematic exploration of precursor concentration, emulsion temperature, sintering temperature, and dopant type (F^-, $Ce^{3+/4+}$, $Mo^{3+/5+}$). Half-cells were assembled using a trilayered pressing approach (TPA, 50-600 MPa) with lithium, indium, and copper blocking electrodes. Structural characterization was performed using X-ray absorption near-edge structure (XANES), X-ray photoelectron spectroscopy (XPS), powdered X-ray diffraction (PXRD), and Laue diffraction (Figs 2a-1 to 2a-3). At the same time, electrochemical performance was evaluated through electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (CV), as shown in Fig 2b. XANES/XPS revealed distinct oxidation states of In and Cl, with dopants introducing mid-gap states that facilitated Li^+ transport. The XRD and Laue diffraction confirmed the triclinic Li_3InCl_6 structure, characterized by corner- and edge-sharing octahedra, which enables an understanding of the ion transport phenomenon. The EIS data demonstrated a reduction in interfacial resistance under a half-cell assembly (Li/solid electrolyte/In). The CV results confirmed expansive electrochemical stability windows (> 4.5 V), indicating low interfacial resistance in the half-cells. The TPA improved electrode-electrolyte cohesion, mitigating interfacial degradation. These findings highlight the potential of halide SSEs to overcome dendrite formation while enabling high-voltage cathode compatibility. The dependence of current density on applied potential further demonstrated the influence of temperature, with higher temperatures enhancing ionic transport and electrochemical performance. Linear fitting of the current response confirmed the predictable relationship between applied voltage and current flow, underscoring the reliability of the electrolyte's behaviors. This study demonstrates that Li_3InCl_6 crystallizes into a triclinic corundum-derived structure that supports efficient Li^+ transport. Electrochemical tests confirm that selective doping with F, Mo, and Ce enhances ionic conductivity by modifying local bonding and electronic states. The CV of $Li_3InCl_{4.8}F_{1.2}$ and other formulated electrolytes at various sweep rates (64 mV s^{-1}) revealed well-defined oxidation and reduction peaks, characteristic of a reversible redox process. At elevated sweep rates, however, the voltammograms exhibited peak broadening and a noticeable shift in potential, indicating a transition toward semi-reversible reaction kinetics. To conclude, our work

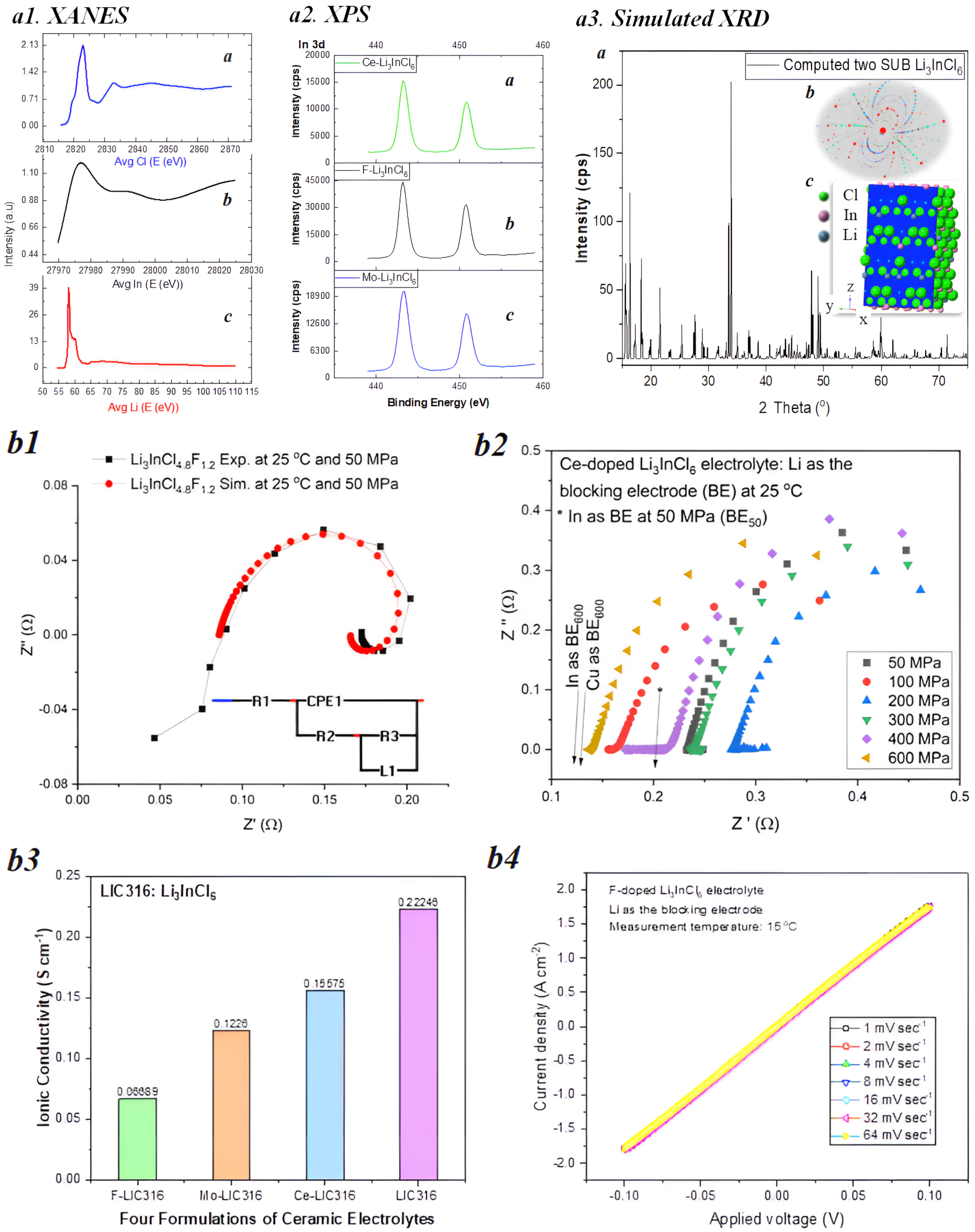


Figure 2. Solid-state battery study. *a*. Spectroscopic analyses: (a-1) XANES data, (a-2) XPS for indium 3d core levels, (a-3) Simulated XRD pattern; and *b*. Electrochemistry of LIB half-cells: (b-1) EIS under ambient conditions, (b-2) EIS under various pressures, (b-3) Ionic conductivity of four Li_3InCl_6-based electrolytes, and (b-4) CV performed across different sweep rates.

demonstrates that green nano-emulsion synthesis and orthogonal design optimization can yield scalable, high-performance ceramic electrolytes. These results highlight Li_3InCl_6 as a promising SSE for high-performance batteries, with doping strategies offering pathways to lower activation energies and enhanced efficiency. Future work should refine dopant selection and apply computational tools to accelerate optimization. These materials bridge the gap between laboratory prototypes and practical, safer, denser, and greener energy storage.

Microbial Fuel Cells: Nanocatalysts, Polymeric Membranes, and Biofilm Engineering.– Microbial fuel cells (MFCs) represent a unique convergence of microbiology, electrochemistry, and materials science. By harnessing the metabolic activity of microorganisms, MFCs convert organic substrates into electricity with near-zero carbon emissions. Our research encompasses catalyst design, polymeric membranes, and biofilm engineering, with a focus on scalable device performance. Cathodic oxygen reduction remains the rate-limiting step in MFCs. We developed hierarchically porous catalysts and N-doped carbon nanostructures, achieving power densities exceeding 1600 mW m^{-2}, which rival those of Pt/C benchmarks. Anodic performance was enhanced using graphene quantum dots (GQDs), which facilitated extracellular electron transfer from *Saccharomyces cerevisiae* biofilms. We synthesized crosslinked poly(vinyl alcohol) (PVA), sulfosuccinic acid (SSA), and tetraethyl orthosilicate (TEOS) membranes (PTS) via sol-gel chemistry (Fig. 3a). The three reactants interact through covalent bonding and intermolecular forces, particularly via the -OH groups in PVA, leading to an increase in chain length and network formation. The TEOS undergoes hydrolysis and subsequent condensation reactions with water, producing stoichiometric SiO_2 nanoparticles and ethanol; these silica nanoparticles contribute to enhanced structural stability within the composite. Simultaneously, SSA functions as a crosslinking agent, reacting with the -OH groups of PVA to form ester linkages (-COO-). The sulfonic acid groups ($-SO_3H$) introduced by SSA further improve proton conductivity by providing additional proton-conducting sites (Figs 3a-1 and a-2). Collectively, these interactions yield a mechanically robust and ionically conductive hybrid network, well-suited for electrochemical applications. The

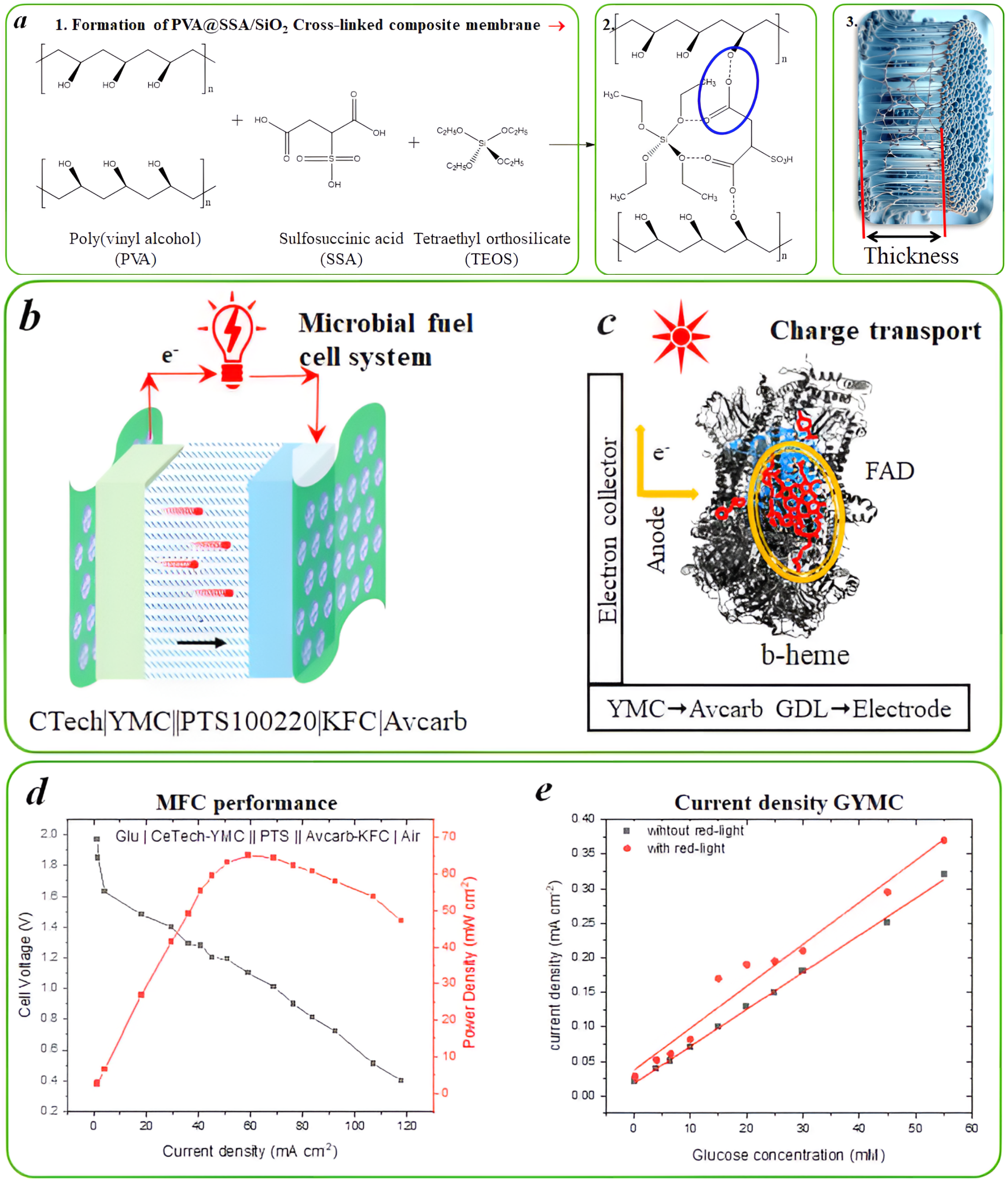


Figure 3. Performance of microbial fuel cells (MFCs). *a*. Schematic of the proton exchange membrane formation, (a-1) Formation of the PTS proton exchange membrane, (a-2) Hydrogen bonding interactions among the precursor network, (a-3) Morphology and film thickness; and *b*. MFC configuration; *c*. Proposed charge transfer mechanisms; *d*. Electrochemical performance of PTS-based MFCs; *e*. Influence of red-light exposure on accelerating electron transfer kinetics.

membrane with tunable thickness (Fig. 3a-3) exhibited a water uptake capacity of up to 120%, highlighting its strong hydrophilic character and ability to retain water, which is essential for sustained proton transport. Under dry conditions, the material exhibited an ionic conductivity of 2.815 mS cm^{-1}, underscoring its potential for efficient ion conduction without the need for external humidification. The presence of a tunable pore network not only facilitated efficient proton cohesion between microbial biofilm and electrolytes. The power density improvements of 40 - 340% were achieved depending on the device configurations. Device durability was enhanced by mitigating oxidative stress on yeast biofilms under red light (RL) stimulation. One MFC configuration, named Tech|YMC||PTS100220|KFC|Avcarb (Fig. 3b), exhibited a high maximum power density (1200 A m^{-2}) after 20 minutes of operation with red light exposure (2.88 J cm^{-2}). The mixed cell cultures increased MFC electrochemistry due to the synergistic effects of different components (Figs 3c-d). The nano-emulsions of graphene-yeast form interactive nanomaterials, securing a homogeneous tunability of structure and properties from the molecular level. The modified biofilm anodes are anticipated to directly contact the microorganisms, further promoting electron transfer due to graphene's high conductivity. A microorganism capable of forming nanowires can extend its proteinaceous filaments into the extracellular matrix to facilitate electron transport. This study suggested that redox-active microbial membrane proteins enable short-range electron transfer without physical contact between the microbe and the electrode.

Single-electron reduction of flavin adenine dinucleotide dihydride ($FADH_2$): The redox protein $FADH_2$ undergoes a one-electron oxidation to form FADH, releasing a proton (H^+) and a single electron (e), which can participate in downstream electron transfer processes, $FADH_2 \leftrightarrow FADH^+ + e^-$. *Two-electron reduction of $FADH_2$*: In a full two-electron oxidation pathway, $FADH_2$ is converted to FAD with the concomitant release of two protons ($2H^+$) and two electrons ($2e^-$), facilitating redox cycling in metabolic and bioelectrochemical systems. The reaction is represented as $FADH_2 \leftrightarrow FAD + 2H^+ + 2e^-$. *Reduction of ferric heme iron*: Ferric heme (Fe^{3+}) accepts one electron to form ferrous heme (Fe^{2+}), a key step in electron transport chains and catalytic redox reactions involving cytochromes, $Fe_{(heme)}^{3+} + e^{-} \leftrightarrow Fe_{(heme)}^{2+}$. We pioneered the use of *S. cerevisiae* biofilms anchored on graphene, combined with red-light (RL, 635 nm) stimulation. RL exposure enhanced cytochrome c activity by up to 1700%, shortening electron transfer pathways and boosting power density by 80% (Fig. *3e*). Methylene blue (MB) mediation further increased the current density by 340%, demonstrating synergistic effects of direct and indirect electron transfer. These trinary PTS membranes exhibited superior proton conductivity in solution and comparable dry-state conductance to Nafion. At the device level, MFCs incorporating PTS membranes demonstrated a 110% increase in power and current output compared to Nafion-based systems. *S. cerevisiae* was employed as the biocatalyst in MFC construction. Among the tested variables, the combination of MB mediation and RL exposure yielded the highest power densities. In its reduced form (MBH_2), it effectively mediated electron transfer to cytochrome *c* and was subsequently re-oxidized, sustaining the redox cycle. Mechanistic studies have revealed that strategic adjustments to device configuration, particularly those promoting direct electron transfer, can enhance power output by up to 300%. These findings underscore the potential of PTS-based MFCs as a cost-effective and environmentally sustainable platform for bioelectrochemical energy generation.

Hydrogen Production from Electrolysis: HYDROGENISE Technology.–Hydrogen is a cornerstone of the clean energy transition; however, current production is dominated by carbon-intensive steam methane reforming. Proton exchange membrane electrolysis cells (PEMECs) offer a sustainable alternative, splitting water into hydrogen and oxygen with high efficiency. The hydrogen generation through integrated sustainable electrolysis (HYDROGENISE) project advances decentralized hydrogen production using non-precious metal catalysts and green electrolysis. Non-platinum metal oxide composite catalysts were synthesized using wet-chemistry methods (Fig. 4a) as replacements for conventional platinum-group metals (PGMs), offering a cost-effective and sustainable alternative without compromising catalytic activity. To evaluate their performance at scale, a 10 MW electrolyzer prototype was constructed and tested with the aim of on-board hydrogen production for vehicles (Fig. 4b). The system operated at an energy consumption of approximately 50 kWh per kilogram of hydrogen produced, achieving a production rate of nearly 200 kg/hr of H_2. Electrochemical characterization demonstrated Faradaic efficiencies in the range of 90-100%, accompanied by low overpotentials and excellent operational durability. These results highlight the potential of non-PGM catalysts and advanced PEMEC design to enable efficient, large-scale hydrogen generation for clean energy applications. The catalytic system demonstrated a significant improvement in efficiency, with water-splitting rates measured at nearly 50% higher than those achieved by commercial catalysts under identical conditions, without the need for pre-treatment. To further validate its performance, prototype miniature model cars powered by hydrogen fuel cells were tested. The results (Fig. 5c) indicated that validated cars exhibited a 45% increase in mileage and a 52% extension in drivetime compared with conventional systems, highlighting the practical benefits of the improved catalyst design. This technology achieved a 35% reduction in hydrogen production costs, lowering the price to approximately $ 2.60/kg of H_2, which represents a substantial step toward economic viability. Finally, the system's scalability was demonstrated through decentralized production, which eliminates the need for costly preprocessing and long-distance transport, thereby enabling flexible, regionally TX hydrogen deployment. The HYDROGENISE initiative showcases a decentralized hydrogen production platform based on PEMFCs, operating at ~50 kWh $kg^{-1}{}_{H2}$ with a production capacity of 200 kg h^{-1}. Utilizing non-PGM/metal oxide composite catalysts, the system achieves Faradaic efficiencies of 90-100% with low overpotentials, enabling efficient water splitting without costly pretreatment. Compared to commercial benchmarks, HYDROGENISE delivers higher catalytic activity, improved vehicle mileage, and longer driving time in model hydrogen fuel cell vehicle tests. Production costs are reduced by 35%, supporting economic scalability. By integrating advanced catalyst design, optimized electrochemical kinetics, and decentralized deployment, HYDROGENISE provides a sustainable and cost-effective pathway for clean H_2 generation, aligning with the NSF I-Corps' mission to accelerate the commercialization of transformative energy technologies.

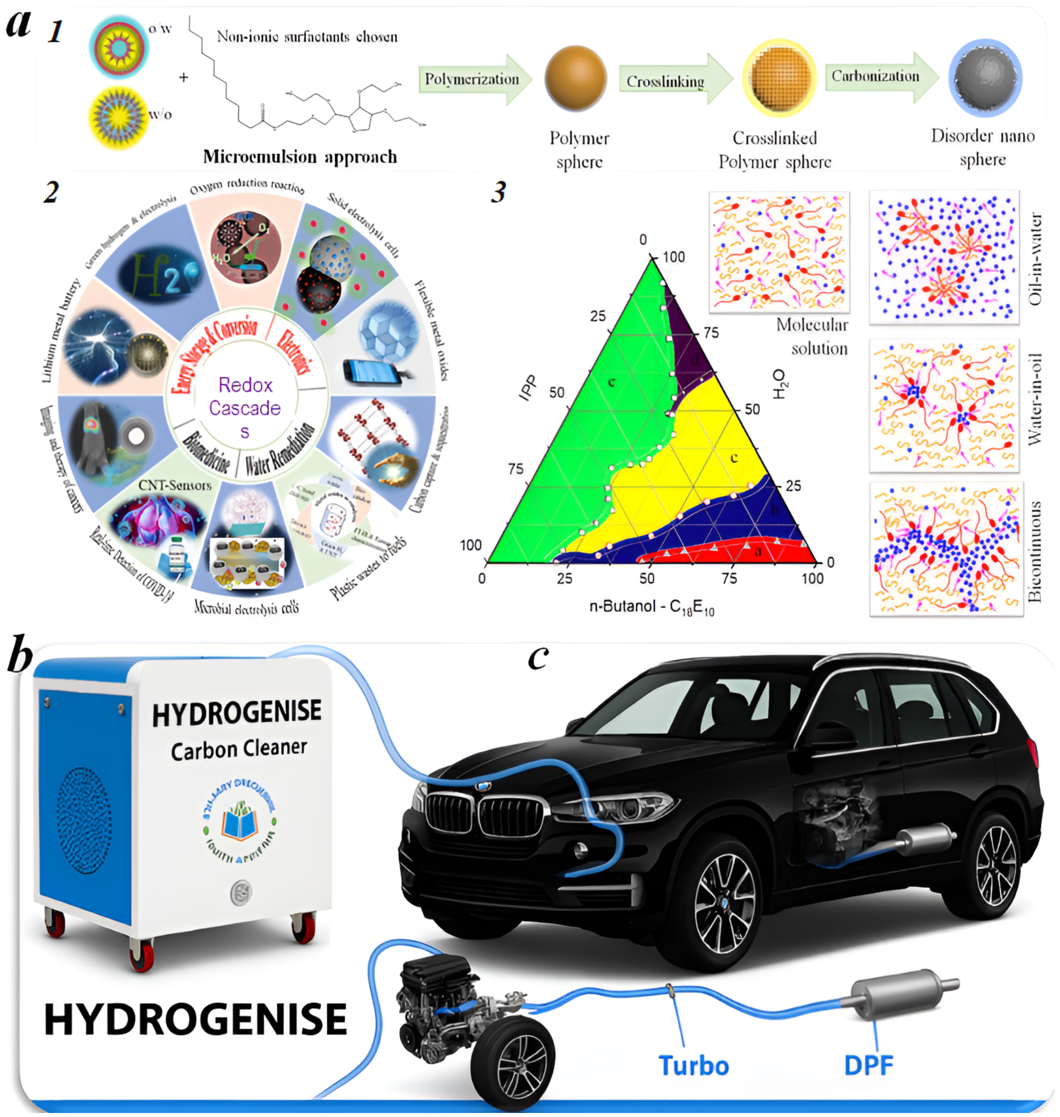


Figure 4. Integrated framework for hydrogen production and utilization. *a*. Wet-chemistry nanoemulsion synthesizing non-Pt metal composites: (a-1) Optimization of emulsion variables, (a-2) Applications of emulsion-derived materials, and (a-3) Theoretical studies guiding emulsion performance; *b*. Schematic of an electrolyzer, and *c*. on-board production of H_2 as vehicle fuels.

Carbon Management with Cost-Effective Porous Materials.– Carbon capture, utilization, and storage remain a cornerstone of global decarbonization strategies; however, the scalability of current sorbent technologies is limited by cost, stability, and deployment challenges. While metal-organic frameworks (MOFs) offer high uptake capacities due to their tunable pore architectures, their synthesis and scale-up remain expensive. Clay minerals are abundant, low-cost, and structurally adaptable, making them promising candidates for large-scale CO_2 management. The Texas Louisiana Carbon Management Center (TXLACMC), supported by the U.S. Department of Energy, has advanced integrated experimental and simulation studies to evaluate the performance of montmorillonite, illite, sepiolite, and palygorskite as cost-effective porous sorbents. Clay minerals were subjected to acid and base activation treatments to enhance surface area and interlayer accessibility. Acid activation nearly doubled Brunauer-Emmett-Teller (BET) surface areas, while base activation improved interlayer swelling and cation exchange capacity, facilitating deeper CO_2 penetration. Powdered X-ray diffraction (PXRD) was employed to probe crystallographic transitions and interlayer expansion. Comparative adsorption studies were conducted under ambient conditions, benchmarking activated clays against high-performing MOFs, such as PPN-6, PPN-6-SO_3H, and PPN-6-SO_3Li. The adsorption of CO_2 onto swelling clays, such as montmorillonite, induces an expansion of the basal spacing from ~9-10 Å to greater than 15 Å, accompanied by the interlayer reorganization of water molecules and exchangeable cations. These structural shifts altered porosity, permeability, and hydraulic conductivity, with implications for stress propagation and microfracture formation in subsurface storage environments. The PXRD and simulations (Figs. 5a-1 to a-4) revealed octahedral-to-tetrahedral coordination transitions in montmorillonite upon CO_2 uptake, reflecting changes in electron density and lattice strain. Unit cell volumes varied across clay types: ~697 $Å^3$ for montmorillonite, ~468 $Å^3$ for illite, ~1910 $Å^3$ for sepiolite, and ~1172 $Å^3$ for palygorskite, correlating with swelling potential and cation exchange capacity. Activated montmorillonite achieved 60-80 $cm^3 \cdot g^{-1}$ (2.0-2.5 mmol$\cdot$ g^{-1}, ~9 wt%), while illite exhibited lower uptake due to rigid interlayers (Figs. 5b-1 and b-2). The fibrous clays such as sepiolite and palygorskite demonstrated moderate uptakes (10-60 $cm^3 \cdot g^{-1}$), enhanced by fibrous channels and microporous networks (Figs. 5b-3 & b-4). By comparison, MOFs exhibited higher absolute uptakes due to their functionalized pore networks (Figs. 5b-5 to b-7); however, activated clays approached similar ranges at significantly lower costs and with superior geological compatibility. Molecular simulations have

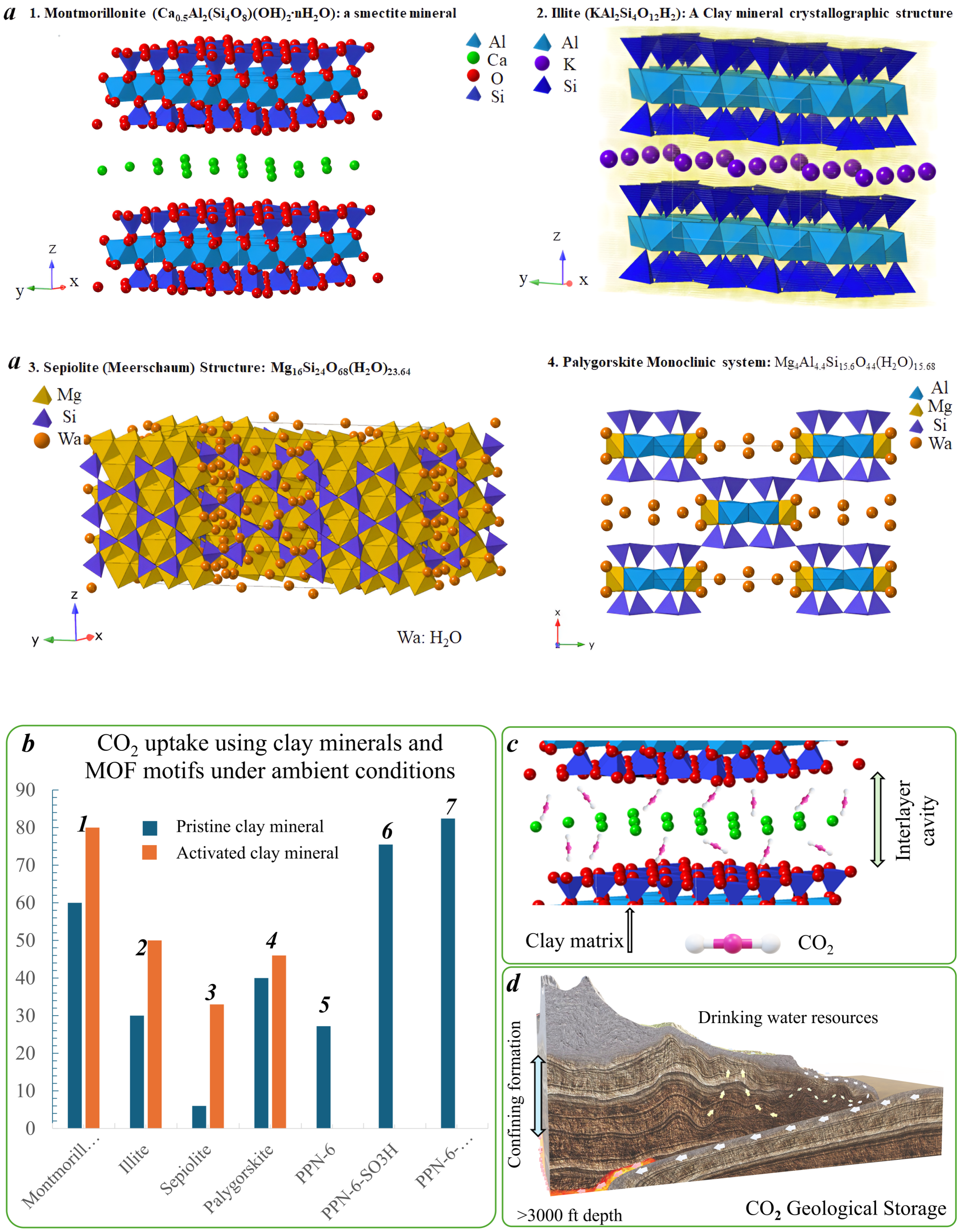


Figure 5. Crystallographic transitions and CO_2 uptake in porous sorbents. *a*. Crystallographic Analyses, (a-1) Montmorillonite, (a-2) Illite, (a-3) Sepiolite, and (a-4) Palygorskite; and *b*. Gas uptake using clay minerals and MOFs; *c*. Proposed mechanism for CO_2 capture; and *d*. CO_2 geological storage through subsurface injection.

confirmed that cation exchange capacity and hydration dynamics influence CO_2 binding energies (Fig. 6c). In montmorillonite, CO_2 interacts with interlayer Ca^{2+} ions through ion-dipole intermolecular forces, reconfiguring the electrostatic potential, expanding the basal spacing, and redistributing charge density across the tetrahedral and octahedral sheets. In fibrous clays, anisotropic swelling and confined water clusters facilitated selective CO_2 transport through nanochannels. These atomic-scale rearrangements influenced stress accumulation, fracture nucleation, and caprock integrity, underscoring the importance of mineral-specific mechanistic models for long-term geological storage (Fig. 5d). By combining adsorption experiments with molecular dynamics, TXLACMC established a validated predictive framework for reservoir performance. This dual methodology enhances accuracy in forecasting fault activation thresholds, microfracture risks, and containment resilience under cyclic injection scenarios. The TXLACMC initiative demonstrates that clay minerals, particularly montmorillonite and palygorskite, represent cost-effective, scalable alternatives to MOFs for CO_2 capture and storage. Acid- and base-activated clay minerals exhibit enhanced CO_2 uptake, underscoring the adaptability of clays. These findings support DOE's mission to de-risk CCUS deployment by providing predictive insights into mineral-fluid interactions, swelling behavior, and caprock integrity.

Fingerprint Development Agents: Bio-Polymeric Ligated Iron-Oxide Composite Enhancers (β-POLICEs).–Latent fingerprint detection remains one of the most critical techniques in forensic science; however, conventional agents, such as iodine fuming or ninhydrin, suffer from low sensitivity, substrate limitations, and poor reproducibility. To address these challenges, we developed POLICEs, synthesized via green nano-emulsion chemistry, and optimized through orthogonal design. These nanostructured composites exhibit tunable surface chemistry, high affinity for fingerprint residues, and enhanced fluorescence under ultraviolet (UV) illumination, enabling more accurate and reliable forensic identification. A modified nano-emulsion method was employed, using shrimp shell extract (chitin) as a natural polymer ligand. An orthogonal design enabled systematic variation of $FeCl_2/FeCl_3$ concentrations, emulsion temperature, $Fe^{2+/3+}$ ratios, and heating conditions. CrystalMaker simulations, XRD, and Laue diffraction were used to probe crystalline phases and electron density distributions. These β-POLICE nano-powders were applied to porous and non-porous substrates using a "powder sprinkling" method, followed by visualization under visible and UV light. Comparative tests were performed against standard red, bi-chromatic, and magnetic powders. These include the measurement of the sensitivity, selectivity, and retention of the latent fingerprint pattern, which were quantified by image analysis and fluorescence intensity measurements. The β-POLICEs exhibited Fe_3O_4 spinel phases (Fig. 5a-1) ligated with chitin monomer (Fig. 5a-2). The enhanced performance of nanostructured β-POLICEs in latent fingerprint detection can be attributed to their

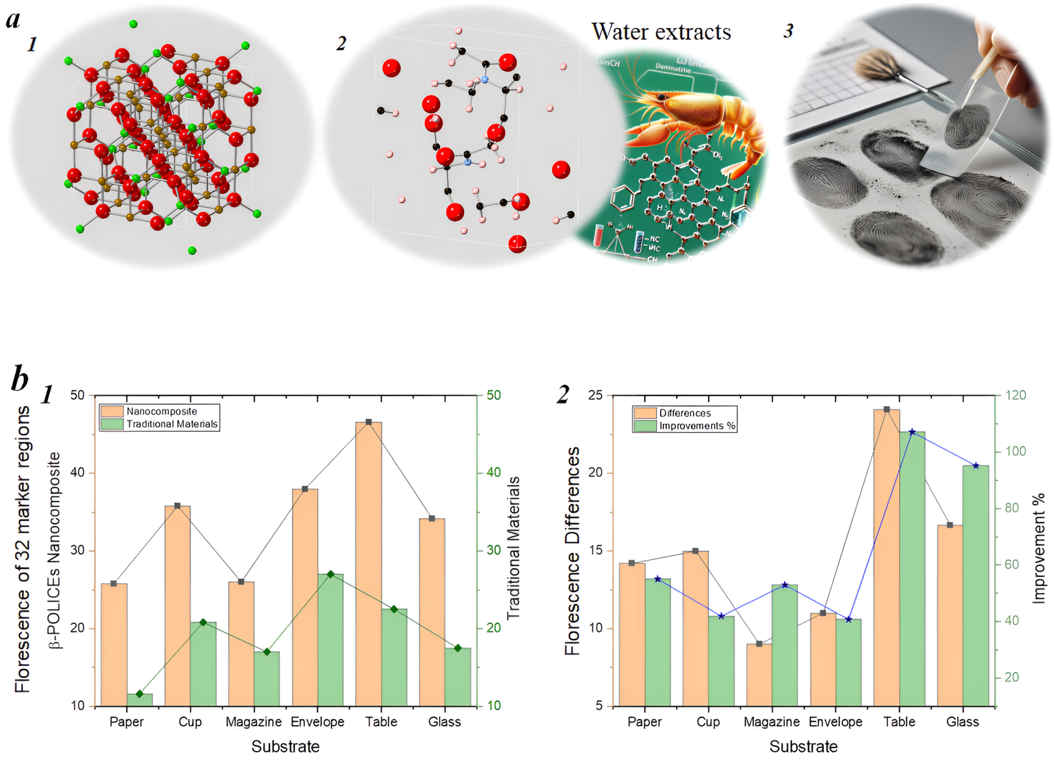
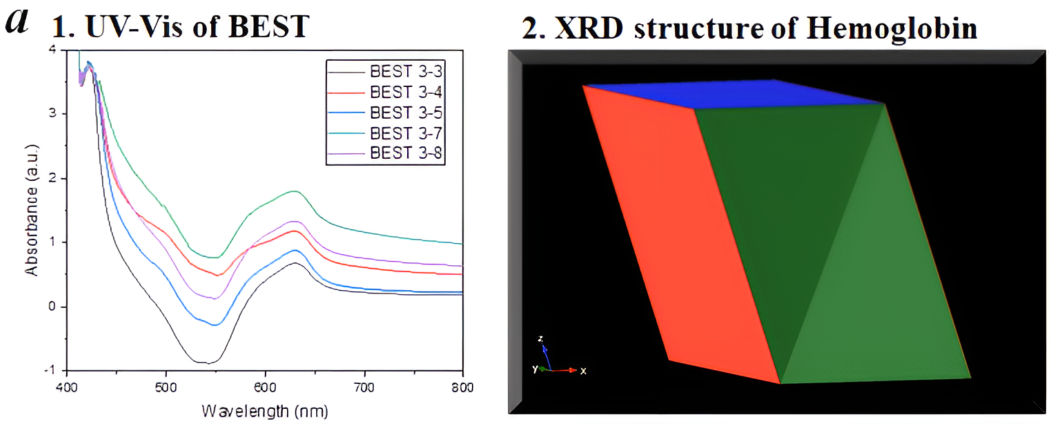
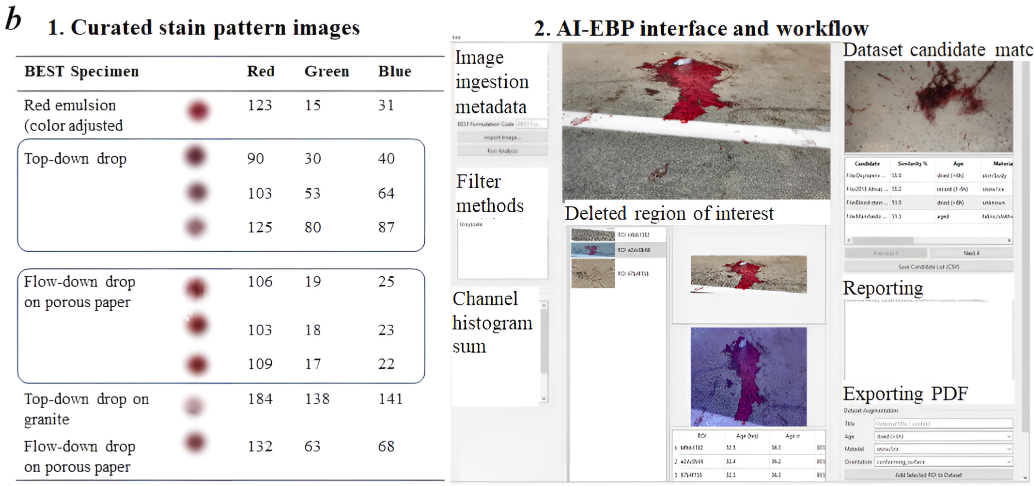


Figure 6. Statistical validation of β-POLICE nanomaterials for latent fingerprint detection. *a*. Crystallographic characterization, (a-1) Crystalline Fe_3O_4 spinel phases, (a-2) Ligation with chitin monomers, (a-3) Fingerprint extraction through interaction-enhancing adhesion, polarity, and uniform particle deposition; and *b*. Kruskal-Wallis statistical analysis, (b-1) Confirming superior sensitivity, contrast, (b-2) Resolution in latent fingerprint detection applications.

ability to form sub-unit building blocks, such as FeO_4 tetrahedra and FeO_6 octahedra, within the crystalline lattice, which directly influence the electron density distribution and surface reactivity. The coexistence of tetrahedral and octahedral coordination sites creates localized variations in charge density, generating active binding domains that interact strongly with the organic and inorganic residues present in latent fingerprints. These coordination environments facilitate electrostatic attraction and hydrogen bonding with amino acids, lipids, and salts. The shrimp shell extract coating introduces amine and hydroxyl functional groups, further enhancing adhesion through complementary surface chemistry. The redistribution of electron density across Fe-O bonds enhances surface polarity, thereby improving the affinity of the nanomaterial for fingerprint residues and facilitating more uniform particle deposition. This dual mechanism, achieved through structural coordination coupled with tailored surface chemistry, yields sharper ridge detail, higher contrast, and improved resolution of latent fingerprint extracts across various substrates (Fig. 5a-3). The β-POLICEs improved fingerprint extraction accuracy by 40% compared to conventional graphitic powders. Enhanced fluorescence under UV light enabled clear visualization of smudged, partial, or overlapping prints. By adjusting the polymer content and $Fe^{2+/3+}$ ratios, the binding affinity and regeneration capacity can be optimized. The technology provides law enforcement agencies with a sustainable, low-cost, and environmentally friendly alternative to traditional agents, directly supporting criminal investigations in South Texas and beyond. Statistical validation using the Kruskal-Wallis Test confirmed significant improvements in fingerprint detection across diverse substrates, with nanomaterials consistently outperforming traditional commercial powders (Fig. 6b). This test indicates significant differences in the mean ranks of latent fingerprint detection between nano β-POLICE and traditional powders across various surfaces. For example, paper surfaces treated with nanomaterials exhibit an integrated fluorescence value of 13% using graphitic powder. In contrast, the corresponding value for β-POLICE was 26%, which is statistically significant at a 0.05 level of uncertainty using a t-test. These superior outcomes are attributed to the enhanced surface area, strong adhesive interactions from chitin-derived nitrogen donors with eccrine amine groups, and the ability of magnetic nanostructures to form finer, more uniform coatings. Together, these features improve fluorescence, reactivity, and overall fingerprint visibility. β-POLICEs composed of nanostructured Fe_3O_4, coated with shrimp shell extract, demonstrate promise as a next-generation latent fingerprint development agent. The synergy between the magnetic, stable, and high-contrast properties of metal oxides and chitin's biocompatibility, adhesive strength, and eco-friendly nature yields a material that is both effective and sustainable. These findings establish β-POLICEs as a sensitive, stable, and environmentally responsible alternative, advancing forensic science toward more reliable, efficient, and sustainable fingerprint detection technologies. Their adoption can improve the sensitivity and reliability of fingerprint analysis, strengthening the evidentiary chain in criminal justice.

Blood Simulants: Biologically Equivalent Simulant for Forensic Tracedrop (BEST).–Blood spatter analysis helps investigators understand events involving gunshots or blunt force trauma by examining how blood droplets form patterns. These patterns offer clues about movement and impact. However, current methods often assume straight-line droplet paths, ignoring factors such as gravity, air resistance, and surface effects, which can lead to errors in locating the origin. Preserving blood evidence is also tricky due to degradation, contamination, or health risks. To improve accuracy and safety, better tools and models are needed. The BEST project addresses this need by developing nano-emulsion-based simulants that mimic the properties of real blood, including viscosity, density, and oxygen-carrying capabilities. These simulants are designed to be safe, consistent, and easy to use for training and analysis. The BEST approach replicates blood's rheological properties for realistic fluid dynamics while incorporating minimal oxygen-carrying capacity to approximate biological venous function. A dualistic strategy was implemented to satisfy forensic fluid dynamics while ensuring close resemblance to authentic blood. The simulant was synthesized to replicate the viscosity, density, and color coding of blood using green wet-chemistry methods. Cross-linked hemoglobin nanoparticles were concurrently fabricated through N-succinimide 3-maleimidopropionate (SMP) chemistry, combined with betalain as a stabilizing, biocompatible agent. These nanoparticles were subsequently incorporated into the base simulant, fine-tuning its physical and chemical properties to enhance forensic applicability. An orthogonal design was optimized to examine five synthesis variables: concentration, pH, drop rate, agitation speed, and temperature. UV-Vis spectroscopy assessed stability, XRD probed crystalline phases, rheometry, and red-green-blue (RGB) color analysis of blood teardrops. The BEST agents were applied to porous and non-porous substrates to generate bloodstain patterns. Convolutional neural networks (CNNs) were trained to classify stains by age, substance differentiation, and pattern type. Comparative analyses were performed against natural blood and conventional simulants to evaluate accuracy in fluid dynamics and stain morphology. BESTs exhibited viscosities and densities closely matching those of human blood, with tunable rheology achieved through variation in cross-linker concentration. Storage stability was enhanced by hemoglobin-polymer crosslinking, which prevented degradation, as determined by analyses using ultraviolet spectroscopy (Fig. 7a-1) and X-ray powder diffraction (Fig. 7a-2). Betalain provides adjustable coloration reflecting oxygenation states, enabling realistic visual simulation. BEST agents reproduced spatter, drip, and transfer patterns with high fidelity, supporting accurate reconstruction of crime scenes (Fig. 7b-1). The artificial intelligence-enhanced blood pattern (AI-EBP) prototype integrates a streamlined technical framework that combines user interface design, machine learning, dataset integration, and reporting features into a cohesive workflow (Fig. 7b-2). A PySide6 desktop interface supports scrollable regions of interest (ROIs), saliency overlays, and prediction tables. Its OpenCV-VGG16 (16-layer-weighted visual geometry group (VGG-16) pipeline enables age estimation, substance differentiation, and pattern classification with gradient-based saliency maps. Annotated datasets and k-nearest neighbor (knn) scoring enhance CNN outputs. Analysts can append ROI samples with metadata, while portable document format (PDF) and comma-separated values (CSV) exports provide forensic-ready summaries and candidate lists with similarity metrics and source references for documentation. The BEST approach provides safer





BEST Specimen		Red	Green	Blue
Red emulsion (color adjusted	●	123	15	31
Top-down drop	●	90	30	40
	●	103	53	64
	●	125	80	87
Flow-down drop on porous paper	●	106	19	25
	●	103	18	23
	●	109	17	22
Top-down drop on granite	●	184	138	141
Flow-down drop on porous paper	●	132	63	68

Figure 7. Evaluation of BESTs and AI-EBP integration for forensic applications. *a*. Storage stability confirmed through ultraviolet spectroscopy and X-ray powder diffraction analyses, (a-1) UV-Vis results, (a-2) XRD of Hemoglobin analog; and *b*. AI-EBP prototype integrates preprocessing, (b-1) Curated stain pattern images on diverse substrates, (b-2) The AI-EBP interface integration of ROI previews, CNN predictions, dataset augmentation, and reporting.

training tools for students, detectives, and forensic professionals, reducing reliance on human or animal blood while improving reproducibility and accessibility. The BEST project developed nano-emulsion-based blood simulants that replicate key properties of human blood, including viscosity, density, and oxygen-sensitive color coding using betalain. Cross-linked with SMP for enhanced stability, these simulants remain viable for up to three weeks and scale reliably from 1 mL to 500 mL. RGB-based colorimetric analysis enables differentiation of oxy- and deoxyhemoglobin states, supporting source identification and age estimation. BESTs produce realistic spatter patterns across various substrates, offering a safe and reproducible alternative to natural blood. Integrated with AI-EBP, the system combines machine learning, forensic datasets, and automated reporting to improve pattern recognition, evidence visualization, and crime scene interpretation in forensic investigations.

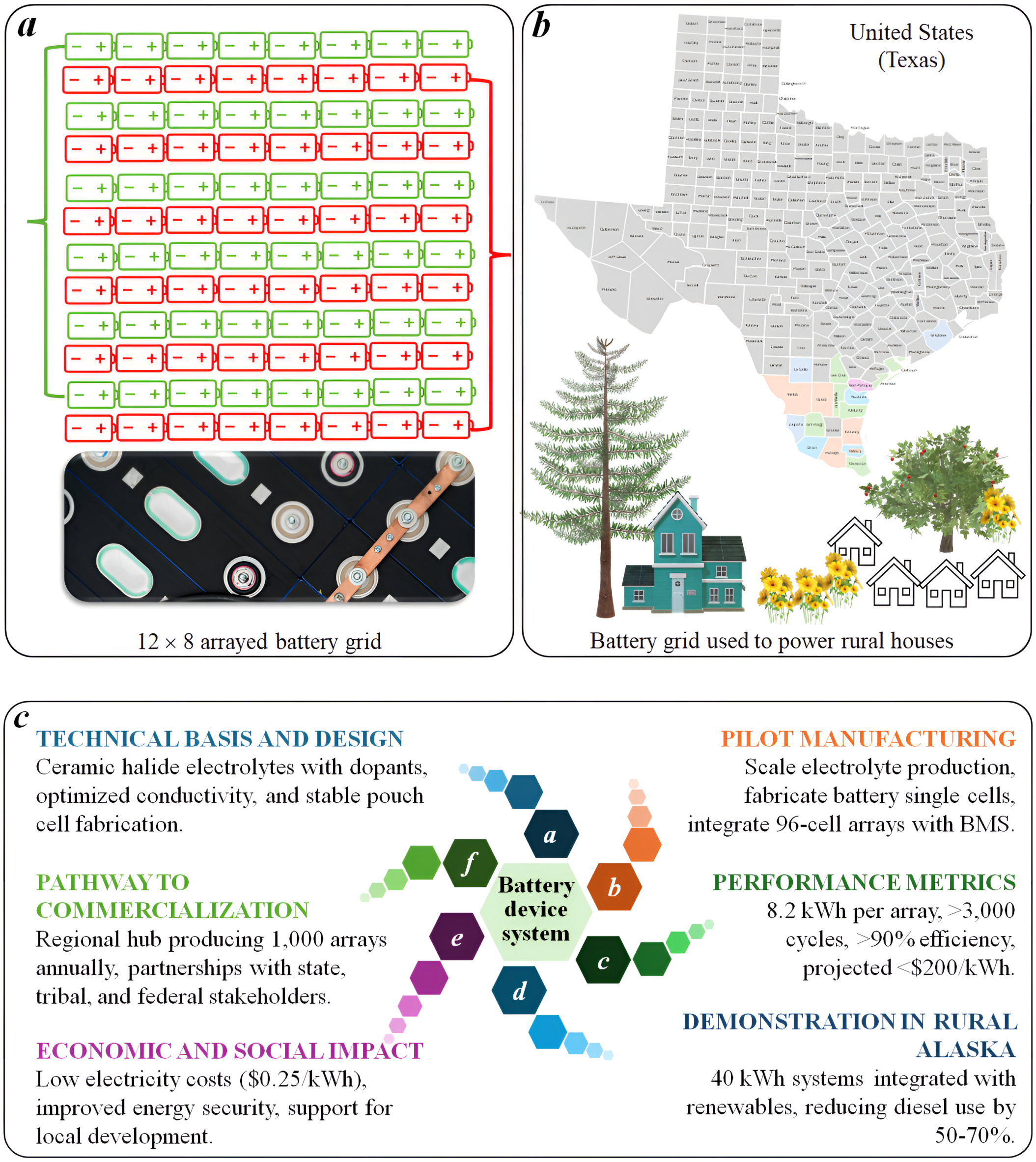
Over the past twenty years, my research has evolved into a multidisciplinary program dedicated to advancing science. I have pursued six interconnected fields: battery systems, fuel cells, hydrogen production, carbon management, fingerprint detection, and blood simulants, each selected for its potential to address urgent challenges in sustainability, security, and public health. In energy, I have led teams that have advanced all-solid-state lithium batteries through green halide electrolytes and explored microbial fuel cells, where nanomaterials and extremophiles generate clean electricity. The hydrogen project demonstrated decentralized electrolysis with non-precious catalysts, lowering costs and enabling carbon-free fuel, while clay-based sorbents provided a practical route for scalable CO_2 capture. In forensics, our team developed β-POLICE latent fingerprint agents with 40% higher accuracy and the BEST agents, a safe and reproducible training tool. Together, these six areas reflect a vision of science that is directed toward solutions and deployment.

Innovation with Impact: Entrepreneurship and Fellowships in Translational Science.–Over the past two decades, our research enterprise has bridged fundamental nanoscience with translational technologies supported by federal agencies and entrepreneurial initiatives. The unifying theme has been the design of tunable materials, whether electrolytes, catalysts, or biopolymers that can be optimized through orthogonal design, validated through advanced characterization (technical readiness level, TRL4-6), and scaled toward pilot manufacturing (TRL7-9). This integrated approach has enabled us to advance projects in clean energy, forensic science, and human health, with a focus on reproducibility, sustainability, and societal impact.

Pilot Manufacturing of 96-Arrayed Solid-State Battery Devices for Rural Electrification.–Since 2000, I have advanced cathode, anode, and electrolyte materials for energy storage using bottom-up and top-down approaches. These efforts laid the foundation for TRL 1-3, enabling the development of reproducible lab-scale solid-state battery prototypes. At TRL 4 (Fig. 8a), we validated performance through cycling, impedance spectroscopy, and mechanical testing. Our entrepreneurship team is advancing toward TRL 9, with 96-cell arrayed modules configured in 12×8 grids, delivering ~68 volts for portable microgrids. These modular systems, comparable in footprint to a queen-sized bed, are deployed in rural Alaska (Fig. 8b) and South Texas, offering scalable, off-grid electrification. The technology combines solid-state safety with modular resilience, supporting commercialization and energy access in underserved communities. Solid-state battery program progressed from technical readiness level (TRL) 4 to TRL 9 through systematic validation, pilot manufacturing, and field deployment. Each 96-cell array module delivers 8.2 kWh at 68 V, with over 3,000 cycles, 92-94% efficiency, and projected costs of below $200/kWh. Electrolytes are synthesized via bio-assisted nano-emulsion methods and doped to enhance conductivity through the orthogonal design optimization of thickness, porosity, and sintering conditions. Cells are pressed, laminated, and assembled under dry-room conditions, then packaged with battery management systems for fault detection and thermal regulation. Pilot lines produce 100 modules annually, enabling deployment in rural areas. Field demonstrations integrate 40 kWh systems with renewables, reducing diesel use by 50-70% and lowering electricity costs to $0.25/kWh. Arrays operate safely in sub-zero conditions and scale from single-building backup to community microgrids. Commercialization will involve regional manufacturing hubs, federal support, and private investment, extending the impact of disaster relief and defense. This resilient technology offers a sustainable alternative to diesel, enhancing energy access and economic development (Fig. 8c).

Pilot Manufacturing of Fingerprint Development Agents for FBI and Police Officers.–Latent fingerprint detection remains a cornerstone of forensic science; however, traditional agents such as iodine and ninhydrin suffer from limited sensitivity and reproducibility. To address these challenges, we developed β-POLICE nanocomposites using eco-friendly nano-emulsion methods. Ligated with chitin from natural sources, these materials exhibit tunable surface chemistry and strong affinity for fingerprint residues. Laboratory trials demonstrate a 40% improvement in detection accuracy over conventional powders, with strong UV fluorescence enabling the visualization of smudged or partial prints (Fig. 9). The production of β-POLICEs ensures a uniform particle size, high surface area, and substrate versatility across various materials, including glass, metal, paper, and plastic. Pilot manufacturing follows a three-phase pathway: (1) scaling synthesis to kilogram batches using 10-liter reactors with in-line monitoring; (2) standardizing powder formulations for shelf life and humidity resistance; and (3) assembling field-ready kits with brushes, UV flashlights, and protocols. Each kit is designed for ease of use by FBI agents and forensic technicians. The pilot line is expected to produce over 500 kits annually. Performance metrics include 18-month shelf life, broad substrate compatibility, and projected costs below $150 per kit at scale. Field trials conducted with the FBI and police departments have confirmed improved detection rates and reduced false negatives. The modular design supports scaling from patrol kits to lab packs. Commercialization will involve a regional hub producing 5,000 kits annually, supported by DHS, FBI, and private investment. Certification under American Society for Testing and Materials (ASTM) and FBI standards ensures regulatory compliance. Training programs for police academies and FBI centers will support adoption. Supply chain strategies will secure raw materials and maintain cost stability. β-POLICE represents a transformative forensic tool, scalable, safe, and impactful, bridging nanotechnology with public safety and justice. *Pilot*

Manufacturing of LouiseSix: Synergistic Formula for Holistic Wellness and Vitality.–LouiseSix is a next-generation metabolic booster developed by Louise Nanoinnovation North American, combining branched-chain amino acids, polyols, and polyphenolic ligands to support mitochondrial function, redox balance, and systemic wellness. Laboratory studies demonstrate enhanced electron transfer,



TECHNICAL BASIS AND DESIGN
Ceramic halide electrolytes with dopants, optimized conductivity, and stable pouch cell fabrication.

PATHWAY TO COMMERCIALIZATION
Regional hub producing 1,000 arrays annually, partnerships with state, tribal, and federal stakeholders.

ECONOMIC AND SOCIAL IMPACT
Low electricity costs ($0.25/kWh), improved energy security, support for local development.

PILOT MANUFACTURING
Scale electrolyte production, fabricate battery single cells, integrate 96-cell arrays with BMS.

PERFORMANCE METRICS
8.2 kWh per array, >3,000 cycles, >90% efficiency, projected <$200/kWh.

DEMONSTRATION IN RURAL ALASKA
40 kWh systems integrated with renewables, reducing diesel use by 50-70%.

Figure 8. Technology readiness levels from laboratory materials to energy systems powering rural communities. *a*. Deployment of arrayed solid-state battery for electrification, *b*. Integration of battery systems with village homes; ***c***. Pathway from battery innovation to commercialization.

glucose hydrolysis, and lipid mobilization, leading to improved energy homeostasis, reduced oxidative stress, and favorable body mass index (BMI) regulation. Its six bioactive components work synergistically to promote adenosine triphosphate (ATP) generation, stabilize lipid

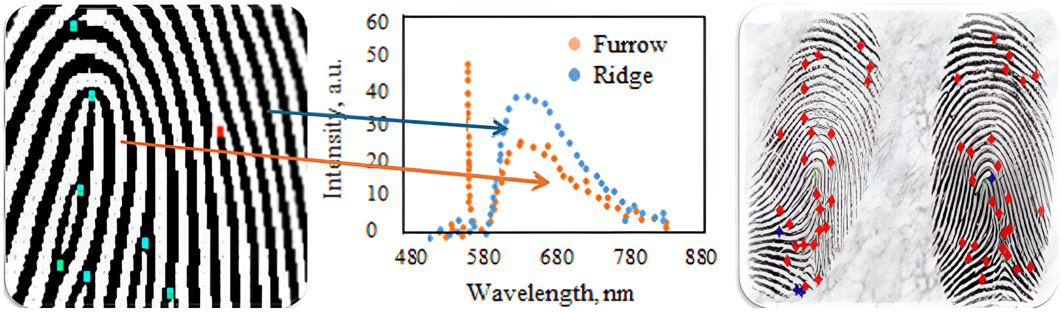


Figure 9. Pilot manufacturing of β-POLICE nanocomposites with a focus on performance metrics indicates a 40% improvement in detection using nanoagents and based on CNN AI-guided pattern recognition.

membranes, and support metabolic flexibility. The formulation stimulates hormone-sensitive and adipose triglyceride lipases, accelerating fat breakdown and increasing nitric oxide bioavailability for vascular function. Enhanced mitochondrial efficiency supports neurotransmitter synthesis (acetylcholine and dopamine), cognitive performance, and cardiovascular health by reducing systemic vascular resistance and mean arterial pressure. Antioxidant polyphenols protect mitochondrial membranes from lipid peroxidation, delaying age-related decline. By contributing to acetyl-CoA pools, LouiseSix also supports epigenetic regulation and metabolic adaptability. Pilot manufacturing includes scale-up in 10-liter bioreactors, formulation into capsules and powders and packaging into wellness kits aligned with FDA dietary supplement guidelines. The pilot line is designed to produce 10,000 units annually for validation of weight loss. Performance metrics indicate enhanced ATP synthesis, improved fatty acid oxidation, and modulation of cardiovascular markers. Stability exceeds 24 months; unit cost is projected to fall below $20 at scale. Clinical demonstrations show benefits in exercise performance, cognitive resilience, and vascular health. Commercialization will expand production to 100,000 units, supported by regulatory partnerships, practitioner training, and global market entry. LouiseSix offers a reproducible, science-based approach to preventive health and long-term vitality.

In summary, the research I undertook spanned continents, disciplines, and decades of inquiry. My scientific mind has evolved from foundational academic training in chemistry and materials science to the development of translational technologies in energy, forensics, and wellness. My team has designed and synthesized advanced materials, including halide electrolytes, nanocatalysts, and biopolymer composites, which have been optimized through orthogonal design and validated by spectroscopic, electrochemical, and structural characterization. These materials have been integrated into functional devices for solid-state batteries, water electrolysis to produce hydrogen, microbial fuel cells, and forensic detection systems, each engineered to address national priorities in sustainability, security, and public health. As an educator, I have mentored emerging scientists and embedded research into transformative pedagogy, fostering intellectual independence and scientific rigor. In my current role as R&D4 director and entrepreneur, I lead pilot manufacturing and commercialization efforts, ensuring reproducibility, scalability, and operational relevance across sectors. This continuum, from molecular design to societal deployment, defines a career committed to innovation with a purpose philosophy, advancing science that bridges laboratory control with global impact, and serving both knowledge and humanity through reproducible, mission-driven research.

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