Details of completed project

1. **Project details**

a. *Title*: "Development of Indigenous Sodium-ion Battery: An Analogous to Lithium-ion System"

b. *Institute*: Pondicherry University

2. **Aim / Objectives:**

- To develop doped-Layered Sodium Manganese Oxide (SMO) ($NaMn_{1-x}M_xO_2$) cathodes using lyophilizing method with and without conductive graphene-layer coating.
- To fabricate and evaluate half-cell using the afore-synthesized doped-SMO with and without conductive graphene-layer coating.
- To fabricate CR-2032 coin-type and evaluate sodium-ion battery with the use of doped-SMO as cathode and highly porous bio-derived disordered carbon.
- To fabricate and evaluate Large Size pouch cell battery device using doped-SMO as cathode and highly porous bio-derived disordered carbon for application to consumer electronics.

3. **Executive Summary (*One page*):**

In line with the project objective of developing doped layered sodium manganese oxide (SMO, $NaMn_{1-x}M_xO_2$) cathodes via a lyophilization route and integrating them into practical sodium-ion battery (SIB) configurations, a comprehensive suite of anode and cathode materials has been designed, synthesized and evaluated. On the cathode side, Fe- and multi-metal-doped layered Na-Mn-O compositions (NFMO and NFAM, corresponding to $NaMn_{1-x}M_xO_2$-type SMO) were successfully obtained by a solution/lyophilization-assisted synthesis. Structural (XRD, Raman, FT-IR) and surface (XPS) analyses confirmed phase-pure layered frameworks with mixed-valence Ni/Fe/Mn redox centres and, in NFAM, Al^{3+} acting as a structural stabiliser. FE-SEM and EDAX revealed porous, agglomerated/fine-grained particles with homogeneous elemental distribution, which are favourable for electrolyte access and Na^+ transport. Electrochemical investigations (CV, GCD and kinetic analysis) in CR-2032 half-cells demonstrated reversible Na^+ intercalation/de-intercalation, good rate capability and a mixed diffusion–pseudocapacitive charge-storage mechanism. In particular, Fe-doped layered Na-Mn-O cathodes showed stabilized discharge capacities of ~140 mA h g^{-1} (NFMO-0.1) and ~160 mA h g^{-1} (NFMO-0.5), confirming that doped-SMO systems synthesized by the lyophilizing route are promising cathode candidates for sodium-ion batteries and are suitable for pairing with highly porous bio-derived disordered carbon anodes in full cells.

Complementary to the core doped-SMO cathode development, a series of high-performance anode materials was established to build a robust electrode library and deepen understanding of Na^+ storage mechanisms relevant to the eventual doped-SMO/bio-carbon full cells. Sn-based chalcogenide heterostructures (SnO-SnS, SnO-SnSe, SnS-SnSe) prepared by a hydrothermal/annealing route, as well as $NiCo_2S_4$-$NiCo_2O_4$ (NCS-NCO) heterostructures anchored on GO, NiO-CoS heterostructures, and Mo-based heterostructures (MoO_2-MoS_2, MoO_2-$MoSe_2$, MoS_2-$MoSe_2$), were thoroughly characterized (XRD, FT-IR/Raman, FE-SEM, HRTEM) and evaluated as SIB anodes. These systems delivered high reversible capacities (e.g., ~716 mAh g^{-1} for SnO-SnSe and ~740 mAh g^{-1} for MoO_2-$MoSe_2$ at 0.1 C), good rate capability and excellent long-term cycling stability (capacity retention >90% over 100 cycles in MoO_2-$MoSe_2$), with performance gains traced to synergistic heterostructure interfaces, improved electronic conductivity and effective accommodation of volume changes. Together, the doped-SMO layered cathodes (with lyophilization-enabled microstructure control and a clear pathway to conductive graphene-layer coating) and the high-capacity anode platforms provide a strong scientific and technological foundation for the next phases of the project: (i) fabrication and optimization of CR-2032 sodium-ion coin cells using doped-SMO cathodes with and without conductive graphene coatings paired with highly porous bio-derived disordered carbon anodes, and (ii) subsequent scale-up to large-size pouch cell devices for consumer electronics applications.

4. Scope for further work

Further research can focus on optimizing the electrochemical performance and scalability of the developed sodium-ion battery materials. In particular, systematic studies on conductive graphene-layer coating of doped layered sodium manganese oxide ($NaMn_{1-x}M_xO_2$) cathodes can be carried out to improve electronic conductivity and structural stability during prolonged cycling. Optimization of electrolyte compositions and electrode-electrolyte interfaces will also be essential to enhance cycling stability and rate capability.

Additionally, integration of the optimized cathode materials with highly porous bio-derived disordered carbon anodes in full sodium-ion battery configurations should be further investigated. Scaling up from CR-2032 coin cells to large-format pouch cell prototypes will enable evaluation of practical performance parameters such as energy density, safety, and long-term cycling stability. Advanced in-situ/operando characterization techniques (such as operando XRD, Raman spectroscopy, and electrochemical impedance analysis) may also be employed to understand sodium-ion storage mechanisms and structural evolution during cycling.

5. Benefits visualized

The successful development of doped layered sodium manganese oxide cathodes and compatible high-capacity anode materials provides a promising pathway toward cost-effective and sustainable sodium-ion battery technologies. Since sodium is abundant and inexpensive compared to lithium, the developed system has strong potential for large-scale energy storage applications.

The project contributes to the advancement of indigenous sodium-ion battery technology, which can support energy storage solutions for renewable energy integration, grid stabilization, and consumer electronics. Furthermore, the development of scalable electrode materials and fabrication strategies can promote domestic battery manufacturing capabilities and reduce dependence on imported lithium resources. The outcomes of this work also provide fundamental insights into sodium-ion storage mechanisms, which will aid in designing next-generation electrode materials with improved performance and durability.