FINAL REPORT: PERFORMANCE-ENABLING SOYBEAN-DERIVED MATERIALS FOR NEXT-GENERATION SOLID-STATE LITHIUM-SULFUR BATTERIES

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The Kansas Soybean Commission (KSC) supported our project of developing performance-enabling soybean-derived materials for next-generation solid lithium-sulfur (Li-S) batteries. The Li-S batteries can suppress Li dendrites and prevent them from penetrating the solid electrolyte since the penetration due to Li dendrite growth is one of the reasons for solid-state Li-S failures. Leveraged by this KSC-supported research, we've secured two research awards from NASA. They are, (1) Enhancing Sustainability and Resilience of Solid-State Battery Systems for Space Exploration via Precision Prognostics and Health Management (07/2022-12/2023, $196,721), and (2) Physics-Informed-AI Enabled Smart Electrospinning of Nanofiber Membranes Towards In-Space Manufacturing (05/2023- 04/2026, $1,072,000). **Fig. 1** summarizes the generic procedure for battery electrodes utilizing large amounts of soy protein concentrate (SPC). In detail, the battery anode includes SPC (80%), Carbon Black (CB) (5%), and polyvinylidene fluoride (PVDF) (10%). The samples were uniformly mixed sequentially using a Ball mill machine and SFM-7 vacuum mixer machine. Then, the samples were transported for casting and dried overnight in a vacuum oven. The electrochemical performance of the SPC-based electrodes was investigated through 2032-type coin cells fabrication. Lithium metal was used as a counter electrode. The range of mass loading of the active materials 0.0069-0.0251 g. Celgard 2400 membrane was used as a Seperator and 1M $LiPF_6$ in a 1:1 (w/w) EC: DMC used as an electrolyte. The coin cell assembled in a glove box (H20< 0.1 ppm, O2 < 0.1 ppm) using a compact hydraulic crimping machine and cell performance experiments were conducted on a Neware Battery Testers. This process is illustrated in **Fig. 2**. We utilized CCCV (constant current constant voltage)

Fig. 1 Battery SPC preparation

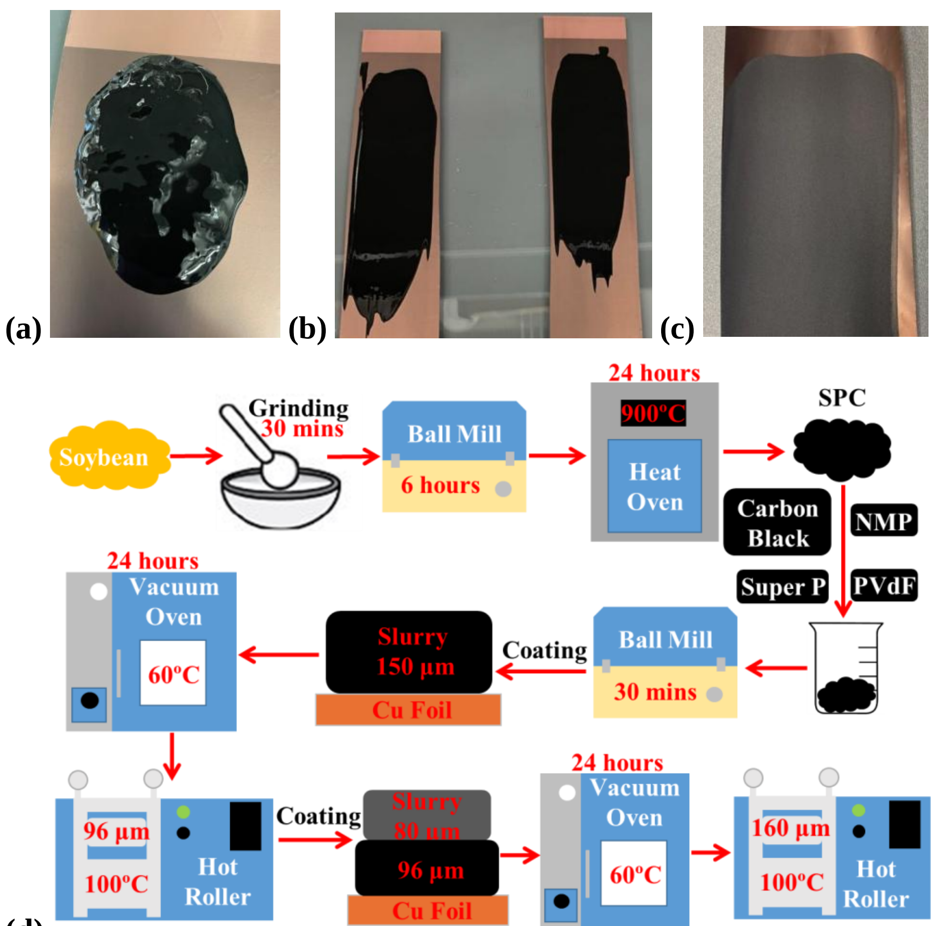

Fig. 2 Battery SPC preparation (a) Mixed SPC sample, (b) Sample Casting, (c) Dried Electrode Sample, and (d) Solid-reaction Synthesis

charging, a typical method of charging rechargeable batteries. Operation switches between CC charging, which charges with a constant current, and CV, which charges at a constant voltage, depending on the voltage of the rechargeable battery. The open circuit voltage (OCV) was set at 2.99V for all tests. The test shows that the SPC-enriched lithium metal batteries show stable and long cyclic electrochemical performance, as shown in **Fig. 3**. It is worth mentioning that many of the tests are still ongoing. We also performed material characterization of the developed SPC-enriched batteries.

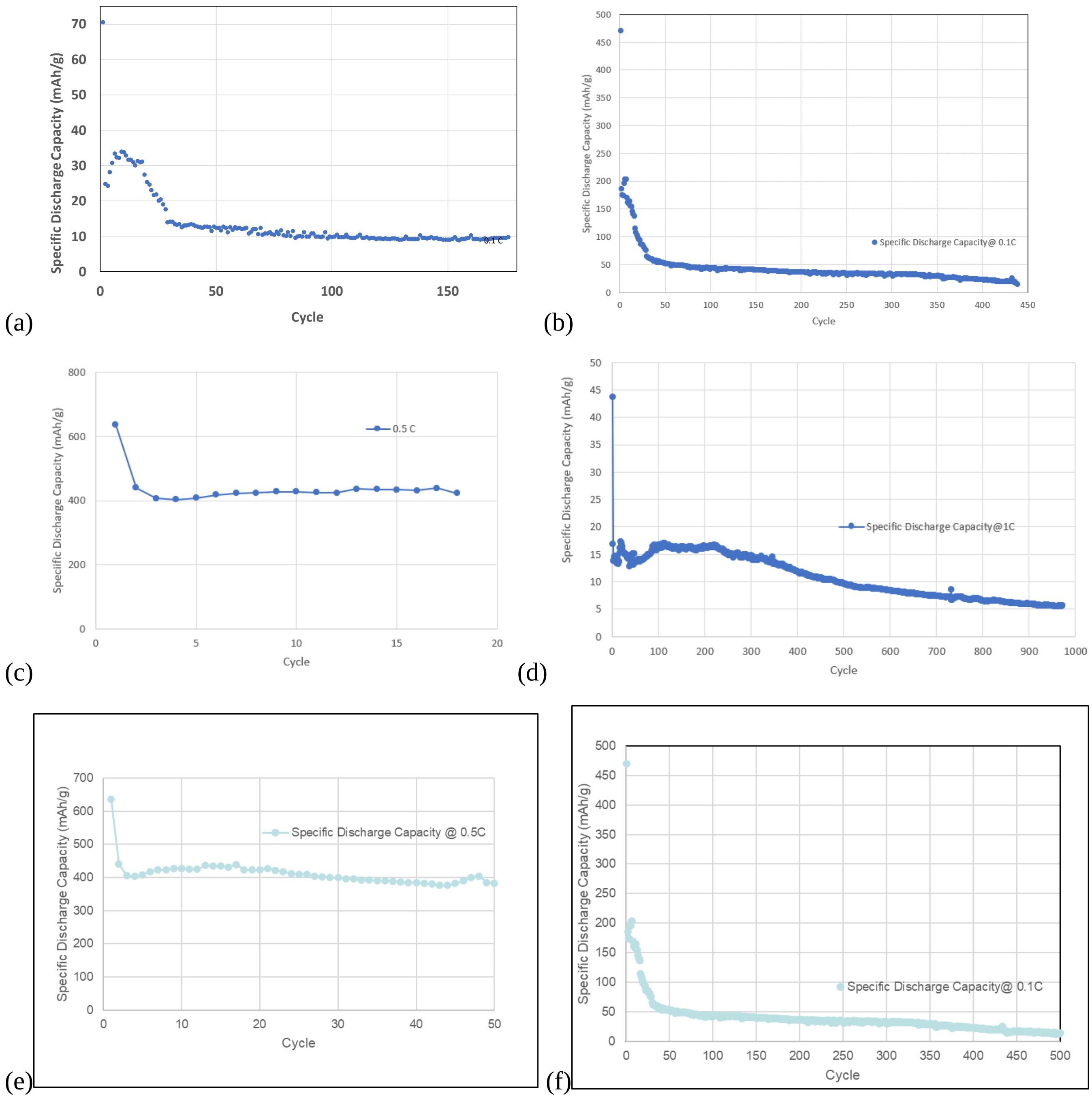

Fig. 3 Cyclic performance @ (a) 0.1C , (b) 0.1 C (max. capacity 469.8 mAh/g), (c) 0.5C (max. capacity 635.34 mAh/g), (d) 1C , (e) 0.1C @ 0.0137 mg-active material, (f) 0.0069 mg-active material (many of the tests are still running)

Utilizing the Phenom ProX desktop Scanning Electron Microscope (SEM), **Fig 4.** shows the microstructures of SPC-enriched electrodes. The porous structure of the electrodes with different grain sizes were observed. The porous structure of the electrodes promotes electrolyte penetration and Li–ion transportation throughout the interior structure. Besides, the interconnection between the porous structures prohibits less resistance to ion transfer and consequent improvement in conductivity and cell capacity.

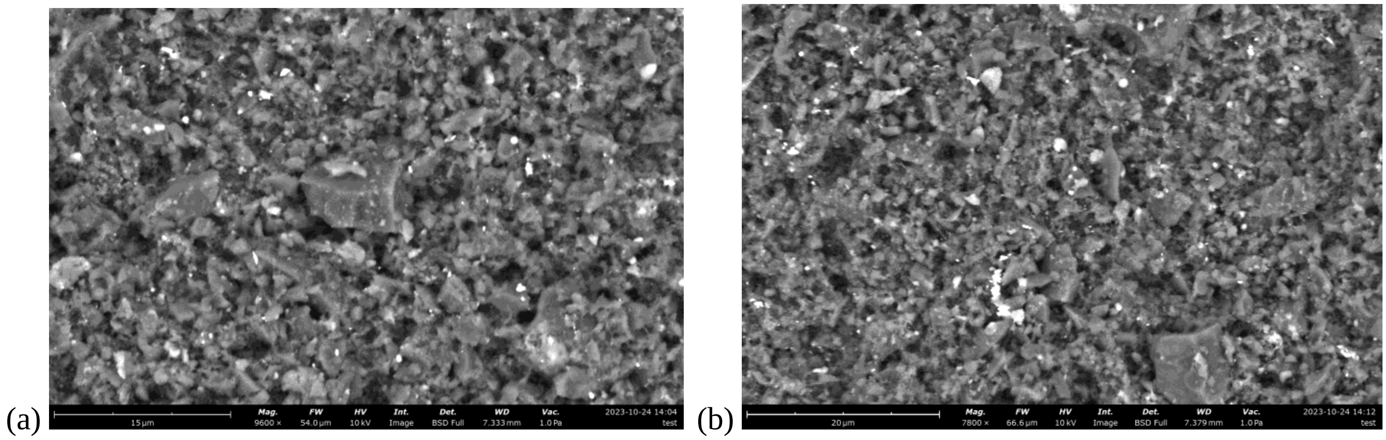

Fig. 4 Microstructures of SPC-enriched electrodes (a) top view, (b) bottom view.

Fig. 5 shows the Energy Dispersive Spectroscopy (EDS) tests of material compositions and elements weight concentrations.

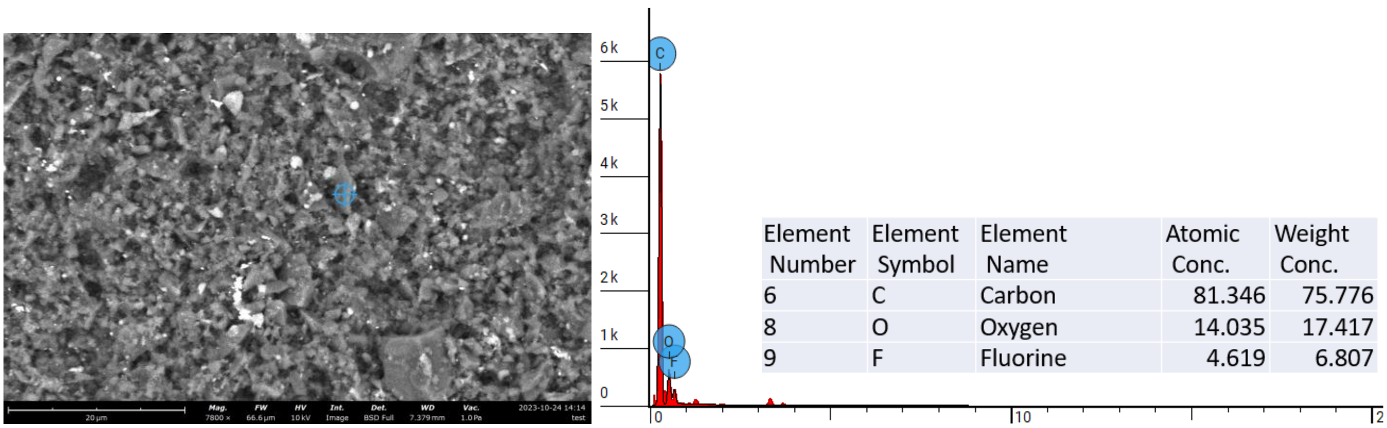

Fig. 5 EDS tests of Material Composition of SPC-enriched electrodes

The demand for energy storage and generation materials is expected to remain strong through at least 2040.

Teaming up with Radiation Monitoring Devices (RMD), Inc. to estimate the overall market size of the rechargeable lithium batteries market, and according to *MarketsandMarkets Research* (i.e., a market research company), the battery electrode material is forecast to grow at a Compound Annual Growth Rate (CAGR) of 16.2 percent from 2018 to 2024, which translates to a global rechargeable lithium battery market of $92.2 billion in 2024. Utilize a 3 percent CAGR to forecast the market size beyond the published market research. We aim to reach a 0.05% market share by 2032 with a 2 percent licensing fee. The advantage of licensing this technology is that partner(s) will have the name recognition and infrastructure to build market share quickly. Once the market adopts this technology, the related market share will rapidly increase. Table 1 below shows our initial forecast of market size and revenue estimate.

Table 1: Revenue Forecast	**2028**	**2029**	**2030**	**2031**	**2032**
Market Size					
Potential Market ($ Billion)	**$103.77**	**$106.88**	**$110.09**	**$113.39**	**$119.06**
License Revenue					
- RMD Market Share Goal	**0.01%**	**0.02%**	**0.03%**	**0.04%**	**0.05%**
- Market Value ($ Million)	**$10.38**	**$21.38**	**$33**	**$45**	**$60**
- Royalty Percentage	**2.0%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**
Revenue Goal ($ Million)	**$0.21**	**$0.43**	**$0.66**	**$0.91**	**$1.19**