Book of Abstracts

1st K IC-25
1st Potassium-based batteries International Conference
25 and 26 September 2025, Madrid (Spain)

1st Potassium-based batteries International Conference

25 and 26 of September 2025

Madrid – Spain

1st KIC-25

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1st Potassium-based batteries - International Conference (KIC-25)

We cordially invite you to the free registration of the 1st edition of the Potassium-based batteries International Conference (KIC-25), held in Madrid (Spain) from 25 to 26 September 2025, within the 2nd edition of “Sustainable Energy Storage Days In Madrid—SESDIM” (22-26 September), hosted by CSIC, Universidad Complutense of Madrid and Helmholtz Institute Ulm.

KIC-25 is the first conference fully dedicated to potassium-based technologies. It aims to strengthen global collaboration in this emerging technology and fully discuss the fundamental understanding of materials (cathode, anode and electrolyte). It focuses on the challenges and how to overcome them to accelerate potassium-based technology to the next level by fruitful discussion among academia and industry.

The KIC-25 will cover the latest research findings and developments in potassium-based batteries, which are the next technology beyond lithium- and sodium-based batteries. The conference will be composed of plenary (invited) talks and posters on materials research, electrochemistry, advanced characterization methods and full-cell development by international experts. The KIC-25 will cover the following topics:

- Research materials: cathodes, anode, liquid/solid electrolytes
- Interfaces(-phases) understanding
- Advance characterization methods
- Full cells prototype

The conference will be held on CSIC premises, in the heart of Madrid's financial area, next to the Museum of Natural Sciences. It is well connected by public transport to its well-known art galleries, such as the Prado Museum, Thyssen or Reina Sofia, or to its historic neighbourhoods, where visitors can enjoy typical Spanish gastronomy.

Looking forward to meeting you,

On behalf of the organizing committee

Dr. Javier Carretero-González (ICTP-CSIC - Spain)
Dr. Elizabeth Castillo-Martínez (Universidad Complutense Madrid – Spain)
Dr. Maider Zarrabeitia (Helmholtz Institute Ulm - Germany)

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Organizing Committee

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Day 1: Thursday, 25th of September 2025	
8:15-8:45	Registration
8:45-9:00	Opening - Welcome
PLENARY A	
9:00-9:50	**Michel Armand** (CIC energiGUNE) *The choices beyond Lithium*
SESSION A: ELECTROLYTES - LIQUID AND SOLIDS ***Chair: Shinichi Komaba***	
9:50-10:20	**Guiomar Hernández** (Uppsala University) *Polycarbonate-based polymer electrolytes for potassium-batteries*
10:20-10:35	**Andrea Balducci** (Friedrich Schiller University Jena) *Glyoxal-based electrolytes for potassium-ion batteries and potassium-ion capacitors*
10:35-10:50	**Jinyu Chen** (Helmholtz Institute Ulm) *Anion-Cation Engineering of Quasi-Solid Ternary Polymer Electrolytes for High-Performance K-Ion Batteries*
10:50-11:05	**Alexander Botschek** (Forschungszentrum Jülich GmbH) *Structure and ionic transport in kinetically stabilised* $K_{2-x}Ta_{1-x}Zr_xCl_6$
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SESSION B: CATHODE MATERIALS AND TRANSPORT PROPERTIES ***Chair: Jelena Popovic-Neuer***	
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12:00-12:15	**Marco Carlotti** (University of Pisa) *Precursor Strategies for the Preparation of High-Molecular Weight Redox-active Conjugated Polymers and Their Use as Organic Cathodes in K-ion Batteries*
12:15-12:30	**Lorenzo Stievano** (Institut Charles Gerhardt Montpellier) *Looking for new Mn-based cathode materials for potassium batteries:* K_xMnO_4
12:30-12:45	**Tomooki Hosaka** (Tokyo University of Science) *Transition metal silicates and fluorides as potassium insertion hosts*
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SESSION C: DEGRADATION MECHANISM AND INTERFACIAL PROPERTIES ***Chair: Yang Xu***	
14:15-14:45	**Fabian Jeschull** (Karlsruhe Institute of Technology) *Cycle Life Limitations of Graphite Electrodes in Potassium-Ion Batteries*
14:45-15:00	**Ezzoubair Bendadesse** (Humboldt Universität zu Berlin) *Enhancing Alloy-Based Anodes in PIBs via Localized High-Concentration Electrolytes*
15:00-15:15	**Ayaka Mochizuki** (Tokyo University of Science) *Electrochemical behaviour and potassium insertion mechanism of K_2TiF_6*
15:15-15:45	**Cofree break**
SESSION D: ANODE MATERIALS ***Chair: Guiomar Hernández***	
15:45-16:15	**Laure Monconduit** (Institut Charles Gerhardt Montpellier) *Some advancements about Carbon negative electrodes for K-ion batteries*
16:15-16:30	**Alexandre Urbano** (Universidade Estadual de Londrina) *Optimizing Potassium-Ion Storage: Sputtering Techniques for High-Performance*
16:30-16:45	**Louiza Larbi** (Université de Haute-Alsace) *Impact of Hard Carbon Properties on Their Performance in KIBs*
16:45-17:00	**Group photo**
17:00-18:30	**Poster session**
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Day 2: Friday, 26th of September 2025	
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9:00-9:50	**Shinichi Komaba** (Tokyo University of Science) *Potassium-ion battery as "post sodium- and lithium-ion*
Session E: REFERENCES & INTERFASES ***Chair: Mauro Pasta***	
9:50-10-20	**Jelena Popovic-Neuer** (University of Stavanger) *Electrolytes and interphases in alkali metal batteries*
10:20-10:35	**Ben Jagger** (University of Oxford) *Potassium Alloy Reference Electrodes for Potassium-Ion Batteries*
10:35-10:50	**Sabrina Trano** (Politecnico di Torino) *Unveiling the Unexpected: Electrolytes, Anode and Interfaces in Potassium Batteries*
10:50-11:05	**Gleb Zhekeznov** (University Bayreuth) *Evaluation of KTP-type Polyanionic Cathode Materials for Potassium-based Batteries*
11:05-11:30	**Coffee break**
Session F: (METAL) BATTERIES ***Chair: Fabian Jeschull***	
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12:00-12:15	**Max Wacha** (Justus-Liebig-Universitaät GieBen) *Investigation of the Potassium Metal Anode for the Use in Solid-State Batteries*
12:15-12:30	**David Peralta** (CEA Liten) *Gr-PBA full cells development: from the PBA synthesis development until K-ion pouch cells manufacturing*
12:30-12:45	**Elizabeth Castillo-Martínez** (Universidad Complutense de Madrid) *Sustainable anode materials for potassium ion batteries*
12:45-13:00	Poster awards Closing remarks

Location information

Institute of Ciencias Agrarias,

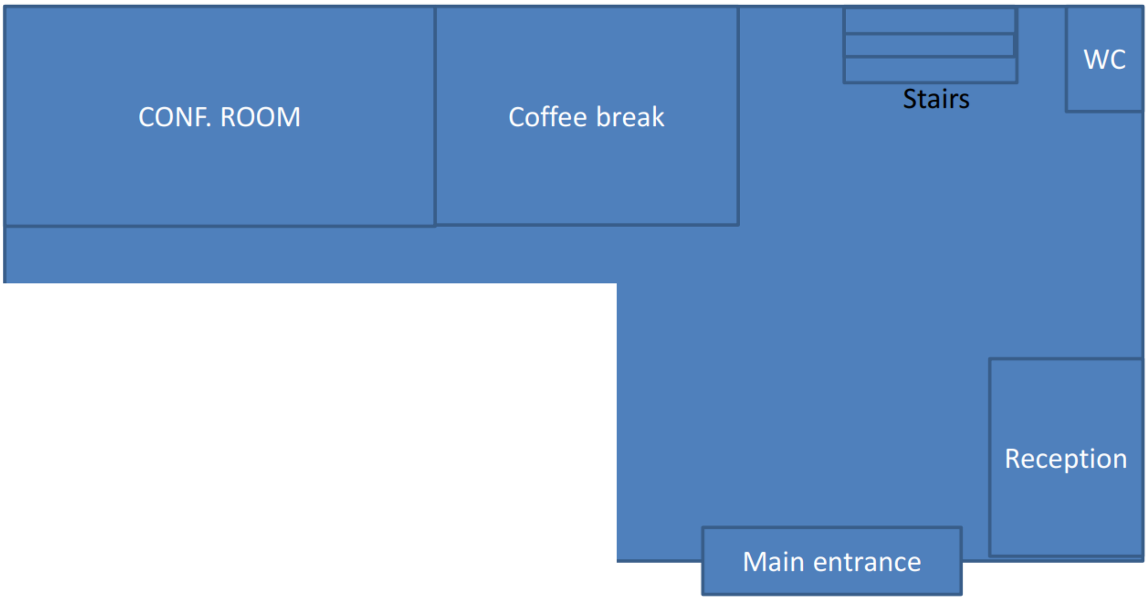
C. de Serrano, 115b

Chamartín, 28006 Madrid

The closest Metro Madrid stops are “Gregorio Marañon” (**Line 7** and **Line 10**) and “República Argentina” (**Line 6**).

Please do not hesitate to contact us if you need more details about how to reach Madrid, and /or the Institute of *Ciencias Agrarias*.

Institute of Ciencias Agrarias,



Relevant information

Lunch at Cafeteria Serrano 117 (not mandatory)

Main entrance of the cafeteria /restaurant (Lunch)

KIC-25 Conference

Abstracts: Plenary speakers

- **Michel Armand** (CIC energiGUNE)

The choices beyond Lithium

- **Shinichi Komaba** (Tokyo University of Science)

Potassium-ion battery as "post sodium- and lithium-ion

The choices beyond Lithium

Michel Armand

CIC energiGUNE, Parque Tecnológico de Álava, Albert Einstein 48, 01510 Vitoria-Gasteiz, Álava, Spain

The main driving forces to develop batteries beyond lithium are primarily the scarcity of its resources and the need, for the negative electrode current collector, to use non-alloying copper, also in short supply. Though there is limited activity on fluoride-ion systems, the main emphasis is put on cations as vectors of the electrochemical reaction. Na, K, Mg, Ca, Zn, Al are the subject of intense research and carry the hopes of energy densities comparable to LIBs.

All these new systems depend on the discovery/development of suitable electrolytes and electrode materials working by intercalation at least for the positive electrode, as in the case of Mg, Ca and Zn, there are hopes to harness the plating/dissolution of the metal. In all options, we consider as a key parameter the respective rate of ligand exchange around the cation. This intrinsic property of cations has been measured by Eigen in the case of water exchange and spans 18 orders of magnitude for the representatives of the Mendeleev chart. Too slow cations are unable to desolvate at the interface (plate the metal) and their diffusion is hindered inside the intercalation material. It is thus important to select cations with the exchange rate greater than 10^7 s^{-1}, for electrode/electrolyte acceptable kinetics. All the alkali metals at > 10^8 s^{-1} fit in this category of fast exchangers.

Sodium corresponds to the most advanced systems and is seen as the chemistry powering grid storage batteries and possibly plug-in hybrids. Several companies, especially HiNa in China have made MWh size batteries, with cycle life comparable to that of LIBs (2000 -3000 cycles) and excellent low temperature performances, a secondary benefit of the fast exchange of ligands. Na^+ with a radius of 0.095 nm cannot fit in many of the electrode materials suitable for Li^+ and 3D, and lattices with large openings like the Nasicon structure ($Na_3V_2(PO_4)_3$ and fluoro equivalents) or the Prussian White $Na_{2-x}Fe_2(CN)_6$. Intense activity is devoted to the lamellar oxides $Na_xT^MO_2$, with octahedral (O) or prismatic (P) coordination of the cation. The negative electrode material is almost inevitably hard carbon as graphite does not intercalate Na^+.

Potassium is even a faster ligand exchanger but the larger size of K^+ (0.133 nm), the choice of electrode materials able to accommodate the cation is even more limited. Interestingly, K^+ intercalates in graphite to KC_8 with high rates possible, but with a large volume change (50%) that fractures the SEI during cycling. Again, Prussian White analogues allow the operation of a positive electrode, as the cavities inside this framework structure have *ad-hoc* size. Low dimensionality organic electrode materials offer also a wide choice of positive electrode candidates.

Magnesium has the same radius as Li^+ but double the charge and is a slow exchanger (5×10^5 s^{-1}), making the diffusion in intercalation electrodes cripplingly sluggish, directing the choice to organic redox molecules as positive. However, with a large effort from the scientific community, electrolytes that reversibly plate Mg° without dendrites have been found.

Aluminium does not move as Al^{3+}, with a ligand exchange rate of $10^0 s^{-1}$ and thus no intercalation materials is known. Only with the ligand Cl^-, aluminium plating is possible, and the most suitable positive electrode material was graphite able to give C_nAlCl_4 but with a large equivalent weight, and low specific energy.

The pro and cons of these different chemistries will be reviewed and discussed.

Potassium-ion battery as “post sodium- and lithium-ion”

Shinichi Komaba, Tomooki Hosaka, Daisuke Igarashi, and Changhee Lee

Department of Applied Chemistry, Tokyo University of Science, Shinjuku, Tokyo 162-8601, Japan.

Over the past decade, our research has focused on establishing potassium-ion batteries (PIBs) as a viable "post-lithium and sodium-ion" energy storage technology through comprehensive studies of electrode and electrolyte materials. For positive electrodes, while typical 3d transition metal layered oxides like P2-K_xCoO_2 show limited capacities, low operating potentials, and multiple phase transitions with K^+/vacancy ordering,[1] Prussian blue analogues (PBAs) have been recognised as superior candidates.[2,3] Their 3D open frameworks provide ideal channels and interstitial sites for large K^+ ion diffusion and insertion, enabling enhanced cycle and rate performance.[3] Polyanionic compounds[4,5] and metal-organic phosphates,[6] which share similar beneficial 3D open framework structures, also show promise as positive electrode materials due to their high ionic conductivities and operating potentials.

For negative electrodes, graphite stands out as a highly promising material for PIBs.[7,8] Our investigations show that its physical characteristics (d_{002} and L_c values) significantly influence electrochemical performance, with optimal properties distinct from those needed in lithium systems.[9] Furthermore, our rationally designed ZnO-template hard carbon has achieved an exceptionally large capacity of 381 mAh g^{-1} ($KC_{5.8}$), surpassing the alkali content of stage^{-1} graphite intercalation compounds.[10]

The use of advanced electrolytes or additives—including KFSA superconcentrated electrolytes,[11,12] KPF_6-KFSA mixed salt electrolytes,[13] fluorosulfonamide-type additives,[14] and polymer electrolytes[15]—has significantly improved the cycle life of K-ion full cells. These advances demonstrate the promising potential of PIBs as a competitive next-generation battery system.

1. Y. Hironaka, K. Kubota and S. Komaba, *Chem. Commun.*, 2017, **53**, 3693.
2. X. Bie, S. Komaba, et al., *J. Mater. Chem. A*, 2017, **5**, 4325.
3. T. Hosaka, T. Fukabori, H. Kojima, K. Kubota and S. Komaba, *ChemSusChem*, 2021, **14**, 1166.
4. T. Hosaka, T. Shimamura, K. Kubota and S. Komaba, *Chem. Rec.*, 2019, **19**, 735.
5. P. R. Kumar, T. Hosaka, T. Shimamura, D. Igarashi and S. Komaba, *ACS Appl. Energy Mater.*, 2022, **5**, 13470.
6. A. S. Hameed, A. Katogi, K. Kubota and S. Komaba, *Adv. Energy Mater.*, 1902528.
7. S. Komaba, T. Hasegawa, M. Dahbi and K. Kubota, *Electrochem. Commun.*, 2015, **60**, 172.
8. H. Onuma, S. Komaba, et al., *J. Mater. Chem. A*, 2021, **9**, 11187.
9. D. Igarashi, S. Komaba, et al., *Electrochemistry*, 2021, **89**, 433.
10. D. Igarashi, S. Komaba, et al., *Adv. Energy Mater.*, 2023, **13**, 2302647.
11. T. Hosaka, K. Kubota, H. Kojima and S. Komaba, *Chem. Commun.*, 2018, **54**, 8387.
12. T. Hosaka, T. Matsuyama, K. Kubota, R. Tatara and S. Komaba, *J. Mater. Chem. A*, 2020, **8**, 23766.
13. T. Hosaka, T. Matsuyama, K. Kubota, S. Yasuno and S. Komaba, *ACS Appl. Mater. Interfaces*, 2020, **12**, 34873.
14. Z. T. Gossage, T. Hosaka, T. Matsuyama, R. Tatara and S. Komaba, *J. Mater. Chem. A*, 2023, **11**, 914.
15. M. Hamada, R. Tatara, K. Kubota, S. Kumakura and S. Komaba, *ACS Energy Lett.*, 2022, 2244.

Abstracts: Invited speakers

- **Guiomar Hernández** (Uppsala University)
Polycarbonate-based polymer electrolytes for potassium-batteries

- **Mauro Pasta** (University of Oxford)
Ion transport in K-ion batteries

- **Fabian Jeschull** (Karlsruhe Institute of Technology)
Cycle Life Limitations of Graphite Electrodes in Potassium-Ion Batteries

- **Laure Monconduit** (Institut Charles Gerhardt Montpellier)
Some advancements about Carbon negative electrodes for K-ion batteries

- **Jelena Popovic-Neuer** (University of Stavanger)
Electrolytes and interphases in alkali metal batteries

- **Yang Xu** (University College London)
Achieving stable potassium electrodeposition for energy dense potassium metal batteries

Polycarbonate-based polymer electrolytes for potassium-batteries

Guiomar Hernández[a], *Isabell Lee Johansson*[a,b], *Anna Khudyshkina*[b], *Ulf-Christian Rauska*[b], *Timofey I. Kolesnikov*[b], *Daniel Brandell*[a], *Jonas Mindemark*[a], *Fabian Jeschull*[b]

[a]*Uppsala University (Sweden)*, [b]*Karlsruhe Institute of Technology (Germany)*

The reactive nature of potassium metal and high redox potentials of positive electrodes poses tough challenges for liquid electrolytes. Solid polymer electrolytes are considered a solution to these challenges due to their cathodic stability at the negative K-metal electrode and potentially battery safety. As with Li and Na chemistries, poly(ethylene oxide) is also dominating the field of potassium batteries with promising performance [1]. However, the same drawbacks arise, one of them the need for high temperature operation above the melting temperature (around 60 °C) and the strong coordination to the alkali metal cations that decreases the transference number.

On the other hand, carbonyl-based polymer host materials are known for their weaker coordination to the alkali metal cations. The semicrystallinity of poly(ε-caprolactone) (PCL) is decreased with the addition of salt or by copolymerization with poly(trimethylene carbonate) (PTMC) allowing high ionic conductivity at room temperature. On the other hand, PTMC is fully amorphous with lower ionic conductivity but higher mechanical stability. Both PTMC and P(CL-TMC) have mostly been studied with lithium- and sodium-based salts [2,3], and to a lesser extent with other post-lithium systems aiming at the investigation of ion coordination in these systems [4,5,6].

Herein, the physical and electrochemical properties of PTMC and P(CL-TMC) and potassium bis(trifluoromethanesulfonyl)imide (KTFSI) solid polymer electrolytes with different salt concentrations have been investigated. The best performing compositions have been further studied in different cell set-ups to investigate the anodic and cathodic stability against different electrode materials: K‖K symmetrical cells, K-metal‖$K_2Fe[Fe(CN)_6]$ and $Fe[Fe(CN)_6]$‖$K_2Fe[Fe(CN)_6]$. Overall, PTMC shows higher stability against potassium metal than P(CL-TMC), although lower capacity is obtained due to the higher cell resistance. Changing the anode from K-metal to $Fe[Fe(CN)_6]$ the cycling stability of P(CL-TMC) is much improved. This highlights the challenges with potassium metal compatibility and stability also for polymer electrolytes.

[1] Khudyshkina, A. D. et al. *ACS Appl. Polym. Mater*. **4**, 2734–2746 (2022) "Poly(ethylene oxide)-Based Electrolytes for Solid-State Potassium Metal Batteries with a Prussian Blue Positive Electrode", 10.1021/acsapm.2c00014

[2] Sångeland, C., et al. *Energy Storage Mater*. **19**, 31–38 (2019) "Towards room temperature operation of all-solid-state Na-ion batteries through polyester–polycarbonate-based polymer electrolytes" 10.1016/j.ensm.2019.03.022

[3] Andersson, R., et al. *Phys. Chem. Chem. Phys*. **24**, 16343–16352 (2022) "Quantifying the ion coordination strength in polymer electrolytes" 10.1039/D2CP01904C

[4] Andersson, R., et al. *Phys. Chem. Chem. Phys*. **24**, 16343–16352 (2022) "Quantifying the ion coordination strength in polymer electrolytes" 10.1039/D2CP01904C

[5] Park, B. et al. *Energy Mater. Adv.* 2021, (2021) "Ion Coordination and Transport in Magnesium Polymer Electrolytes Based on Polyester-co-Polycarbonate" 10.34133/2021/9895403

[6] Kolesnikov, T. I., et al. *Eur. Polym. J.* **217**, 113315 (2024) "Synthesis of Polyimide-PEO Copolymers: Toward thermally stable solid polymer electrolytes for Lithium-Metal batteries" 10.1016/j.eurpolymj.2024.113315

Ion transport in K-ion batteries

Mauro Pasta[a]

[a] *University of Oxford, Department of Materials (UK)*

Potassium-ion batteries are emerging as a promising complementary technology to lithium-ion batteries, owing to their potential for lower cost and high-rate capability[1]. In my talk, I will discuss the progress our group has made in probing ion transport in K-ion batteries by characterising the transport and thermodynamic properties of electrolytes[2,3], the structure-electrochemistry relationship in Prussian Blue analogue cathodes and graphite anodes[4–6], and in modelling full cell performance[7].

1. Dhir, S., Wheeler, S., Capone, I. & Pasta, M. Outlook on K-Ion Batteries. *Chem* **6**, 2442–2460 (2020).
2. Dhir, S., Jagger, B., Maguire, A. & Pasta, M. Fundamental investigations on the ionic transport and thermodynamic properties of non-aqueous potassium-ion electrolytes. *Nat. Commun.* **14**, 3833 (2023).
3. Zhao, J. *et al.* Transport and Thermodynamic Properties of KFSI in TEP by Operando Raman Gradient Analysis. *ACS Energy Lett.* **9**, 1537–1544 (2024).
4. Cattermull, J., Roth, N., Cassidy, S. J., Pasta, M. & Goodwin, A. L. K-Ion Slides in Prussian Blue Analogues. *J Am Chem Soc* **145**, 24249–24259 (2023).
5. Jagger, B. et al. Potassium alloy reference electrodes for potassium-ion batteries: The K-in and K-bi systems. *ACS Mater. Lett.* 4498–4506 (2024).
6. Cattermull, J., Pasta, M. & Goodwin, A. L. Structural complexity in Prussian blue analogues. *Mater Horiz* **8**, 3178–3186 (2021).
7. Dhir, S. *et al.* Characterisation and modelling of potassium-ion batteries. *Nat. Commun.* **15**, 7580 (2024).

Cycle Life Limitations of Graphite Electrodes in Potassium-Ion Batteries

Celine Röder[a], Iurii Panasenko[a], Sandro Schöner[a], Tamara Donate[a], Fabian Jeschull[a]

[a]*Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76133 Karlsruhe, Germany*

K-ion battery (KIB) systems follow in the footsteps of Li-ion batteries (LIBs) and share a common material bases. For instance, both cations intercalate into graphite that can serve as negative electrode in both cell chemistries. Especially in half cells, the degradation of graphite electrodes in KIBs is significantly accelerated in comparison to LIBs, which appears to be related to the formation of a less protective solid electrolyte interphase (SEI) that is paramount for long cycle life[1,2]. Recently reported crosstalk phenomena in half cell configurations due to the highly reactive potassium counter electrode make the analysis of surface layers a particular challenge[3,4].

In this presentation, we discuss various failure modes of graphite in carbonate electrolytes in the context of particle properties, binder contents in electrode formulations, choice of electrolyte formulation and additives and SEI formation and composition. The latter was investigated by in-house and synchrotron-based photoelectron spectroscopy (PES) depth profiling, performed on cycled graphite electrodes from half and full cells configurations. Our results suggest fundamental differences in surface layer composition under the influence of a reactive counter electrode and challenge interpretations of SEI layer properties derived from half cell samples. Furthermore, they highlight the need for more full cell testing with reliable cathodes and/or reference electrodes.

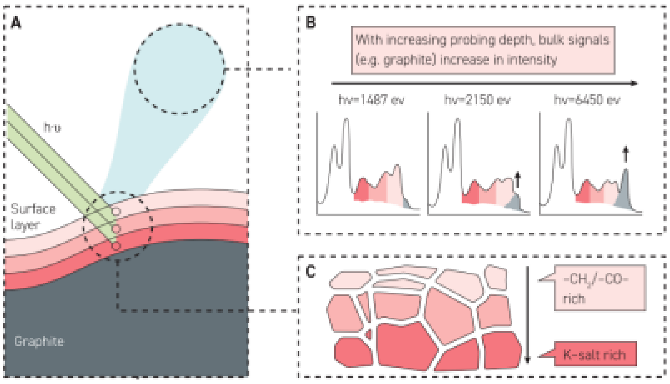


Figure 1. Illustration of PES depth profiling on graphite electrodes

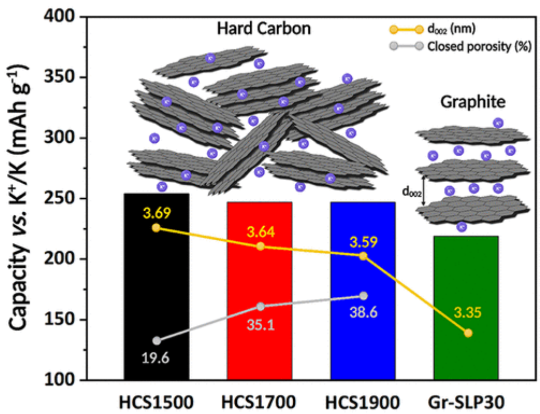
1 Jeschull, F. & Maibach, J., *Electrochemistry Communications* **121**, 106874 (2020). 10.1016/j.elecom.2020.106874
2 Hofmann, A., Müller, F., Schöner, S. & Jeschull, F., *Batteries & Supercaps* **6**, e20230032 (2023). 10.1002/batt.202300325
3 Panasenko, I., Bäuerle, M. & Jeschull, F. *Electrochimica Acta* **513**, 145551 (2025). 10.1002/batt.202300325
4 Jeschull, F. *et al*. *Advanced Energy Materials* **2403811**, 1–14 (2024). 10.1002/aenm.202302745

Some advancements about Carbon negative electrodes for K-ion batteries

L. Larbi [a,c], B. Larhrib [d], L. Madec [b,d], H. Martinez [b,d], C. Ghimbeu [b,c], L. Monconduit [a,b]

[a]ICGM, Univ. Montpellier, CNRS, ENSCM, Montpellier, France
[b] RS2E, CNRS, 80039 Amiens, France
[c]Université de Haute-Alsace, IS2M, Mulhouse, France
[d]Universite de Pau et des Pays de l'Adour, E2S UPPA, CNRS, IPREM, Pau, France

In the urgency to find alternatives to Li-ion batteries, K-ion batteries (KIBs) could well position themselves. They combine several promising features: (i) energy density, (ii) power density, (iii) abundance of constituent elements of electrode materials, (iv) lower cost with the use of available precursors (K_2CO_3) and Al current collectors at both electrodes, (v) safety during storage and transport (at 0 V). However, the transition from LIBs to KIBs is not without obstacles. The higher mass and size of K^+ ions strongly impact the electrochemical mechanisms and structural integrity of electrode materials, volumetric and gravimetric capacities, and ultimately cycling performance. We have recently explored new carbon negative electrodes for KIB, especially the understanding of the correlation of electrode and electrolyte materials and their respective performance. Due to the size of K^+ (1.38 Å) as compared to Li^+ (0.76 Å), a much larger volume expansion (60% vs. 13%) is expected during the potassiation/depotassiation, which can irreversibly damage the electrode. Controlling the volume expansion of the electrode upon cycling is thus essential. For this reason, we studied an electrode formulation of different carbon black contents and electrode calendaring protocols to optimize the ionic and the electronic percolation networks.[1] Moreover, we investigated 4 graphite samples to evaluate the impact of particle sizes, specific surface area (SSA), active surface area (ASA) and surface oxygen functional groups on their performance in KIB.[2] Hard carbons (HCs), able to accommodate insertion/extraction of the large K^+ ions with limited volume expansion were also studied and compared to graphite. HCSs, with a spherical morphology and a disordered structure, were synthesized and annealed. The pyrolysis temperature (1500 to 1900 °C) has shown a strong influence on the HC properties (structure, porosity and surface chemistry) and on their electrochemical performance in KIBs. Like Li- and Na-ion batteries, electrolyte reactivity has strong impact on the KIB electrochemical performance. We provided a reliable XPS study without K-metal, on the electrochemical performance of $KVPO_4F_{0.5}O_{0.5}$/graphite full cells, investigating the impact of various parameters, including open-circuit voltage (OCV) temperature, upper cut-off voltage (UCV), depth of discharge (DOD), and vanadium dissolution.[3]



[1] B. Larhrib et al *Electrochimica Acta*, 2022, 425, 140747, "Optimized electrode formulation for enhanced performance of graphite in K-ion batteries", 10.1016/j.electacta.2022.140747
[2] L. Larbi et al ACS *Applied Energy Materials*, 2023, 6 (10), 5274-5289, "Impact of Hard Carbon Properties on Their Performance in KIB", 10.1021/acsaem.3c00201
[3] B. Larhrib et al, Journal of Power Sources 588, 2023, 233743, "A novel K-ion $KVPO_4F_{0.5}O_{0.5}$/graphite full cell: Correlation between XPS SEI studies and electrochemical testing results", 10.1016/j.jpowsour.2023.233743

Electrolytes and interphases in alkali metal batteries

Jelena Popovic-Neuber

University of Stavanger, Norway

Alkali metals, including potassium, when employed as anodes in battery cells suffer from continuous solid electrolyte interphase (SEI) formation, dendrite growth, and general issues related to interphase degradation including formation of porosity, roughness, and "dead" electrode mass.[1, 2] Electrochemical methods such as impedance spectroscopy (EIS) and galvanostatic polarization are complementary, and when used in model symmetric cells, can elucidate effective cationic transference numbers in the electrolyte bulk (liquid electrolytes), but can also be used to understand ion transport in the interphase, as well as the time and temperature evolution of SEI (liquid and solid electrolytes) and charge-transfer resistance.[3] In the first part of this talk, I will showcase the current understanding of ion transport and SEI evolution on Li, Na, K, as well as Al and Mg metal electrodes in contact with variety of relevant liquid battery electrolytes based on EIS, as well as related bulk behaviour of liquid electrolytes based on galvanostatic polarization.[4-6] In addition, I will give an overview of a possibility to form artificial SEIs on alkali metals. In the second part of the talk, I will showcase different classes of potential high-performance potassium electrolytes, including liquid-solid composites based on anodic alumina, sulfide-based solid-state electrolytes, and highly concentrated electrolytes.[7-10]

[1] Popovic, J. Review—Recent Advances in Understanding Potassium Metal Anodes. *J. Electrochem. Soc.* 2022, *169* (3),030510.
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Achieving stable potassium electrodeposition for energy dense potassium metal batteries

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Potassium (K) metal batteries (PMBs) hold great promise for next-generation rechargeable batteries due to the low redox potential of K^+/K and the earth abundance of K, but the problematic K metal anodes – K dendrite growth and unstable solid-electrolyte interphase (SEI) – are a major roadblock.[1,2] A great deal of effort has been made to suppressing K dendrite growth and stabilizing SEI via various approaches such as surface coating, artificial SEI, and electrolyte/additive innovation. There has been little investigation at the basic aspect here – the surface of K and the substrate that K electrochemically deposits on, the latter of which is also the central point for realizing anode free PMBs. In this talk, I will discuss our recent work investigating the surface properties of K and the K plating substrate to improve K electrodeposition. I will talk about the optimization of the K metal surface properties through K processing methods and how they amplify the benefits of a robust SEI properties via tuning the electrolyte concentration. This enables a synergy of the K surface and SEI properties in improving K metal plating/stripping behavior.[3] I will introduce an approach of creating surface nanotexture on K plating substrates based on the energetics point of view and show how the approach can be transfered. In addition, I will show that our investigations focusing on the surface of K and substrates enable energy dense PMBs in the form of coin cells by pairing the K anodes showing improved electrodeposition with high mass loading cathodes.

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Abstracts: Oral presentations

- **Andrea Balducci** (Friedrich Schiller University Jena)

Glyoxal-based electrolytes for potassium-ion batteries and potassium-ion capacitors

- **Jinyu Chen** (Helmholtz Institute Ulm)

Anion-Cation Engineering of Quasi-Solid Ternary Polymer Electrolytes for High-Performance K-Ion Batteries

- **Alexander Botschek** (Forschungszentrum Jülich GmbH)

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Looking for new Mn-based cathode materials for potassium batteries: K_xMnO_4

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Transition metal silicates and fluorides as potassium insertion hosts

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Enhancing Alloy-Based Anodes in PIBs via Localized High-Concentration Electrolytes

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- **Alexandre Urbano** (Universidade Estadual de Londrina)

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- **Louiza Larbi** (Université de Haute-Alsace)

Impact of Hard Carbon Properties on Their Performance in KIBs

- **Ben Jagger** (University of Oxford)

Potassium Alloy Reference Electrodes for Potassium-Ion Batteries

- **Sabrina Trano** (Politecnico di Torino)

Unveiling the Unexpected: Electrolytes, Anode and Interfaces in Potassium Batteries

- **Gleb Zhekeznov** (University Bayreuth)
Evaluation of KTP-type Polyanionic Cathode Materials for Potassium-based Batteries

- **Max Wacha** (Justus-Liebig-Universitaät GieBen)
Investigation of the Potassium Metal Anode for the Use in Solid-State Batteries

- **David Peralta** (CEA Liten)
Gr-PBA full cells development: from the PBA synthesis development until K-ion pouch cells manufacturing

- **Elizabeth Castillo-Martinez** (Universidad Complutense de Madrid)
Sustainable anode materials for potassium ion batteries

Glyoxal-based electrolytes for potassium-ion batteries and potassium-ion capacitors

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Potassium-ion batteries (PIBs) are currently considered as a promising alternative to lithium-ion and sodium-ion batteries (LIBs and SIBs). The growing interest in PIBs is primarily motivated by the natural abundance of potassium and the possibility of achieving high energy and power densities due to the low standard redox potential of K^+/K, as well as the fast K^+ ion diffusion in the electrolyte.

To realize advanced PIBs the development of novel electrolytes is essential, as this component is influencing not only their performance, but also their safety and their sustainability. A carefully design of the electrolyte is therefore mandatory for the development of these devices.

In this paper we report about the use of the glyoxal solvents tetraethoxy-glyoxal (TEG) for the design of advanced electrolytes for PIBs and potassium-ion capacitors (PICs). TEG displays lower flashpoint and higher thermal stability than linear carbonates, can dissolve conducting salts in molar amounts and support the formation of a stable SEI layer. For these characteristics, glyoxal-based electrolytes are considered as a very interesting class of alternative electrolyte for energy storage devices. We show that the electrolyte containing 1.5 M potassium bis(fluorosulfonyl)imide (KFSI) dissolved in a propylene carbonate (PC)/ (TEG)/ vinyl ethylene carbonate (VEC) mixture (62:36:2 vol.%) displays very good transport and thermal properties, and it can prevent the anodic dissolution of Al current collectors. LIBs and LIC containing this electrolyte display high performance and high cycling stability. Furthermore, utilizing *in situ* Raman spectroscopy and *operando* XRD, we report the first experimental evidence of the formation of KC_{16} as an intermediate phase during the potassium intercalation into graphite[1]. Very interestingly, we also showed that using this electrolyte K^+ ions intercalate alone into the graphite lattice and no co-intercalation of the solvents occur. These results are clearly showing the importance of electrolyte selection not only for the optimization of the devices performance, but also for a thorough understanding of the potassium intercalation into graphite.

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Anion-Cation Engineering of Quasi-Solid Ternary Polymer Electrolytes for High-Performance K-Ion Batteries

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Potassium-ion batteries (KIBs) have garnered significant attention in recent years, indicating that KIBs can be an alternative to lithium- and sodium-ion batteries for high power applications [1]. Solid electrolytes represent a key solution to enhancing battery safety and energy density. Among these, polymer electrolytes are promising candidates due to their good flexibility, ease of processing and low interfacial resistance. However, their inherent poor chain flexibility at room temperature results in low ionic conductivity. Incorporating ionic liquids (ILs) as plasticizers into quasi-solid polymer electrolytes (QSPEs) significantly enhances ionic conductivity while ensuring thermal stability and safety [2,3].

This work investigates the influence of distinct anion and cation combinations on QSPE performance. Salts and ILs incorporating the bis(fluorosulfonyl)imide anion (FSI^-) combined with ILs based on the 1-butyl-1-methylpyrrolidinium cation (Pyr_{14}^+) demonstrated superior ionic conductivity. Specifically, the QSPE formulated with KFSI and Pyr_{14}FSI (denoted Pyr_{14}FSI:FSI) achieved an ionic conductivity of 1.84 mS cm^{-1} at 20 °C. Coin cell tests employing Pyr_{14}FSI:FSI as the polymer electrolyte, Prussian White (PW) as the cathode, and K metal as the anode delivered a specific capacity of 112 mAh g^{-1} with 73% capacity retention at 20 °C. The development of these polymers clearly indicates the great potential of ILs as plasticizers for developing potassium solid-state batteries that can operate at room temperature.

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Structure and ionic transport in kinetically stabilised $K_{2-x}Ta_{1-x}Zr_xCl_6$

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Double perovskite chlorides with the general formula $Na_{3-x}M_{1-x}M'_xCl_6$ (M, M' = Transition metal cations) are promising materials as electrolytes in all-solid-state-batteries exhibiting a good compromise between oxidation stability and high ionic conductivity.[1] While well investigated for sodium, few potassium-containing compounds have been analysed towards the crucial ion transport properties.[2,3] This work presents the structure and electrochemical performance of the kinetically stabilised system $K_{2-x}Ta_{1-x}Zr_xCl_6$. The endmembers $KTaCl_6$ and K_2ZrCl_6 were found to exhibit minor structural deviations from the previously reported double perovskite structures, which could be resolved by a combination of X-ray and neutron powder diffraction, pair distribution function analysis and nuclear magnetic resonance spectroscopy. We observe a symmetry reduction from $Fm\bar{3}m$ > $P4/mnc$ > $C2/c$ with increasing Zr^{4+} content, as well as at reduced temperatures. Utilising impedance spectroscopy, the highest ionic conductivity was observed in $KTaCl_6$ with $6 \cdot 10^{-5}$ S cm^{-1}, decreasing to $2.5 \cdot 10^{-7}$ S cm^{-1} in K_2ZrCl_6. However, the activation energy ist highest at 10% Zr^{4+} content with 0.65 eV, while levelling off at around 0.55 eV at higher Zr^{4+S} substitution degrees. Our findings suggest a vacancy-driven increase of ionic conductivity: In $KTaCl_6$, 50% of the K- sites are unoccupied, while structural bottlenecks seem to play a minor part.

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Precursor Strategies for the Preparation of High-Molecular Weight Redox-active Conjugated Polymers and Their Use as Organic Cathodes in K-ion Batteries

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Conjugated polymers, characterized by small bandgaps and accessible states, are exceptionally versatile materials that find use in numerous technological applications. Synthetic chemistry is the most powerful tool a chemist has to control the electronic properties and the arrangements of the polymeric chains, thus allowing the preparation of materials with tailored properties and enhanced performances.
However, their aggregation-prone nature often hinders the synthetic process and reduces their processability, resulting in materials with a low degree of polymerization, which may exhibit different properties compared to their high-MW analogues, and limiting their scope in device fabrication.
When the use of solubilizing side chains to circumvent these problems is not possible or ineffective – as in those cases where a high specific density of responsive units is beneficial or when immobilization of the active material is needed – the use of processable polymeric precursors and reliable transformation strategies (that can form rapidly and quantitatively the target active materials) offer an efficient way to access high molecular weights conjugated polymers with a high density of functional units.
To address this issue, we designed novel strategies for the preparation of high-molecular weight fully-conjugated polymers comprising functional redox moieties either in-chain or as pendant groups.[1] Thanks to their nature, these materials are intrinsically insoluble, even in the charged state, and can offer improved charge transport kinetics because of their extended conjugation.
In this contribution, I will describe novel approaches based on the use of different polymeric precursors for the preparation of fully-conjugated materials with a high density of active centres. In particular, these precursors comprise either reversibly-masked quinoid groups, which allow the insertion of expendable solubilizing chains, or aromatic units connected via succinyl linkers, that can undergo pyrrolization in the presence of a primary amine, thus allowing for the insertion of active side groups. Finally, the fully-conjugated materials obtained through this strategy are employed as active material in organic cathodes for K-ion batteries, as well as in the preparation of OFETs with different polarities and multicolored electrochromic surfaces.

Part of this study was carried out within the POLiBATT project – funded by European Union – Next Generation EU within the PRIN 2022 PNRR program (D.D.1409 del 14/09/2022 Ministero dell'Università e della Ricerca) and the European Union's Horizon 2020 Research and Innovation Program under the Marie Skłodowska-Curie Grant Agreement MP3 – No. 885881.

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Looking for new Mn-based cathode materials for potassium batteries: K_xMnO_4

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Potassium-ion batteries (KIBs) are promising alternatives to lithium-based systems due to potassium's abundance and low cost. Developing suitable cathode materials is critical for their commercialization. Among candidate systems, the non-toxic and inexpensive K-Mn-O system is appealing, yet only 2D K_xMnO_2 materials have been explored to date. We focused on K_3MnO_4, a composition with a theoretical capacity of 227 mAh/g upon removing two K^+ ions. Previous work identified two polymorphs: cubic γ-K_3MnO_4 and tetragonal β-K_3MnO_4, both composed of isolated MnO_4 tetrahedra in 0D frameworks.

A new polymorph, α-K_3MnO_4, was synthesized via a solid-state reaction of KO_2 and MnO under vacuum. Its orthorhombic *Pnma* structure, with a zig-zag arrangement of MnO_4 tetrahedral units (Figure 1a), is isostructural to K_3FeO_4. The blue powder, consistent with the presence of tetrahedrally coordinated Mn^{5+} ions, shows a reversible capacity of 70 mAh/g between 1.6–3.5 V vs. K^+/K at C/20.

In this presentation, we will detail the electrochemical behaviour of α-K_3MnO_4, its peculiar electrochemical mechanism studied by operando techniques (Figure 1b) and its structure–property relationships, highlighting the potential of this material family for KIB cathodes.

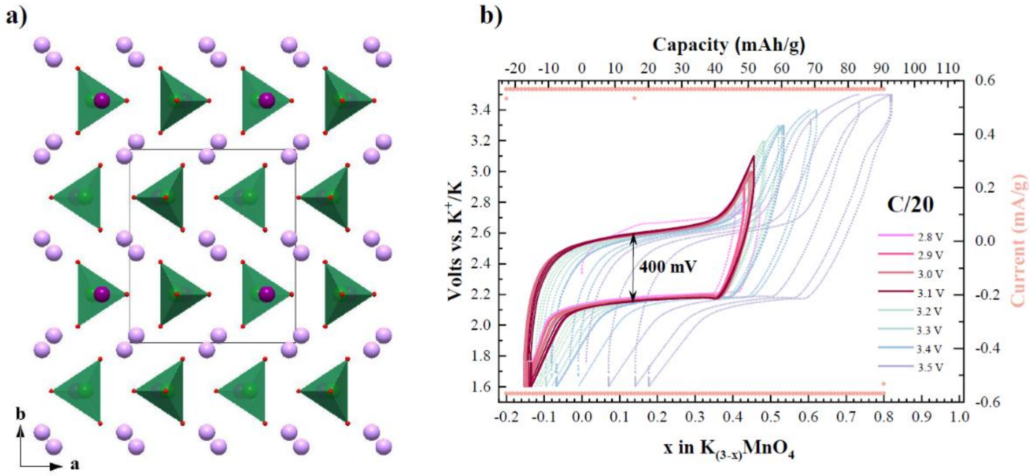

Figure 1: (a) α-K_3MnO_4 crystal structure following (001) axis. (b) Incremental voltage vs. composition curves for K_3MnO_4 at C/20 in the potential range 1.6V-3.5V vs. K^+/K

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Transition metal silicates and fluorides as potassium insertion hosts

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Potassium insertion materials are crucial for enabling a "rocking-chair" type K-ion battery (KIB).[1] While materials such as Prussian blue analogues,[2-4] $KTiOPO_4$-type,[5,6] and $K_3V_2(PO_4)_2F_3$-type[7] compounds have demonstrated potential as potassium insertion hosts, the exploration of new frameworks is vital for designing better insertion materials. This presentation will discuss our recent investigations into the potassium insertion properties and mechanisms of a series of transition metal silicates and fluorides.

We explored several potassium vanadium fluorides, including $K_5V_3F_{14}$, K_3VF_6, and KVF_4.[8] While $K_5V_3F_{14}$ and KVF_4 exhibited limited electrochemical activity, K_3VF_6 demonstrated promising performance, delivering a reversible capacity of 95 mAh g^{-1} with a distinct voltage plateau at 3.7 V (Fig. 1a). X-ray absorption spectroscopy confirmed a reversible one-electron $V^{3+/4+}$ redox process. Building on the reversible behavior observed in K_3VF_6, we investigated commercially available K_2TiF_6, which shares a similar framework to the charged product K_2VF_6. K_2TiF_6 demonstrated highly reversible potassium insertion/extraction based on the $Ti^{4+/3+}$ redox couple (Fig. 1a).

Furthermore, we synthesized K_2CoSiO_4 and K_2FeSiO_4 via a solid-state route. Both silicate compounds exhibited high reversible capacities of ~120 mAh g^{-1}, corresponding to reversible one-electron redox processes of $Co^{2+/3+}$ and $Fe^{2+/3+}$, respectively (Fig. 1b). These findings highlight the potential of these novel fluoride and silicate materials to broaden the range of viable potassium insertion hosts for KIBs.

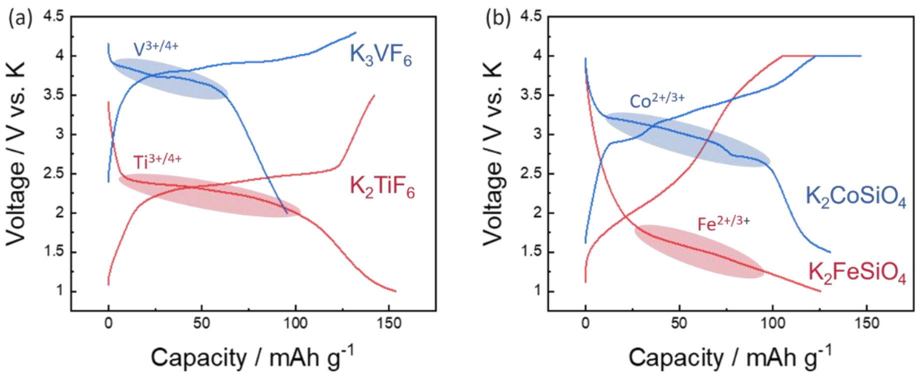

Figure 1 Charge-discharge curves of (a) K_2CoSiO_4 and K_2FeSiO_4 and (b) K_3VF_6 in K cells.

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Enhancing Alloy-Based Anodes in PIBs via Localized High-Concentration Electrolytes

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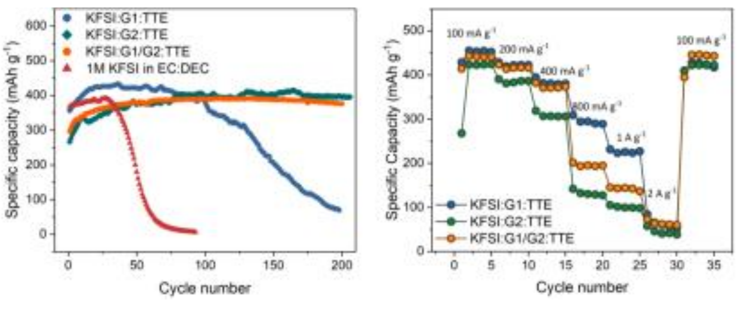
The advancement of practical potassium-ion batteries hinges on the development of high-capacity anode materials. Due to the relatively low capacity of graphite (279 mAh g^{-1}), alloy-based anodes have gained attention as promising alternatives. Among them, antimony stands out with a high theoretical capacity of 660 mAh g^{-1}. However, practical use is hindered by severe volume expansion during cycling.[1] Embedding antimony in a carbonaceous matrix has proven effective in mitigating this issue by enhancing structural stability.[2] Yet, electrolyte selection remains critical for optimizing performance. Conventional carbonate-based electrolytes often suffer from flammability, unstable SEI formation, poor compatibility with alloy anodes, and limited cycling life. Due to the larger ionic radius and higher reactivity of potassium, PIBs require tailored electrolyte solutions. Localized High Concentration Electrolytes (LHCEs) have gained attention for their unique anion-rich solvation structures, which promote inorganic-rich SEI formation and enhance stability. Unlike Highly Concentrated Electrolytes (HCEs), LHCEs use an inert diluent to retain favorable solvation features while reducing viscosity and improving ionic mobility.[3,4]

In this study, we investigate LHCE formulations using ether solvents—dimethoxyethane (DME) and diglycol methyl ether (DGME)—to evaluate their effects on solvation structure, cycling stability, rate performance, and the (de)potassiation mechanism of antimony/graphite (Sb@Gr) composite electrodes. Through X-ray photoelectron spectroscopy (XPS), in-situ Raman spectroscopy, and electrochemical testing, we analyze solvent effects on SEI composition and battery performance. Results show that DME enables higher-rate charging, DGME offers superior long-term cycling, and their combination provides a balanced performance. Raman analysis confirms a shared solvation shell in the mixed solvent system. Notably, LHCEs offer more pronounced benefits for alloy-based electrodes than for potassium metal, as demonstrated in symmetric cell studies. These findings provide valuable insights into the synergistic role of LHCEs and alloy anodes, advancing the design of high-performance PIB systems.



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Electrochemical behaviour and potassium insertion mechanism of K_2TiF_6

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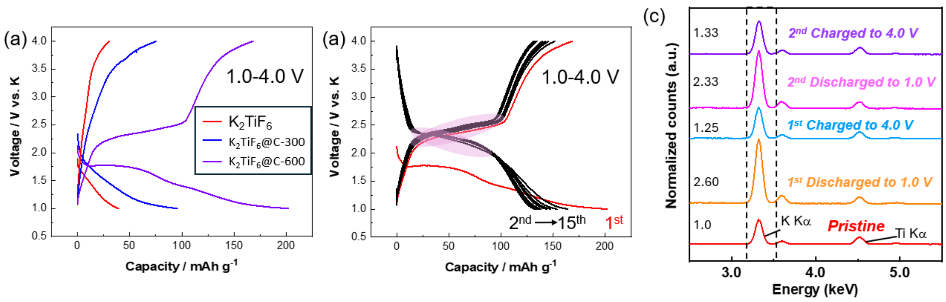
Potassium-ion batteries (PIBs) have attracted significant attention as potential high-voltage and high-power secondary batteries [1]. Fluoride-based materials have been investigated as potential electrode materials for PIBs due to their high theoretical capacity and their diverse crystal structure [2]. We have recently reported K_3VF_6 as a reversible K^+ ion insertion/extraction host, showing a reversible capacity of ~95 mAh g^{-1} with a plateau at 3.8 V (vs. K/K^+) [3]. However, K_3VF_6 shows a large capacity degradation during cycling, and the degradation mechanism has not been fully understood. K_2TiF_6 has a similar framework as K_2VF_6, which is obtained by removing potassium from K_3VF_6. There have been no reports of its electrochemical performance, although commercial K_2TiF_6 is widely available. We here investigate the electrochemical performance of K_2TiF_6 for PIBs to gain deeper insight into designing high-capacity, long-life transition metal fluorides.

The commercial K_2TiF_6 is a white powder with a particle size of 80 µm. In order to improve the electronic conductivity and reduce the particle size, K_2TiF_6 was ball milled with Ketjen black at 300 or 600 rpm to form carbon-composite active materials (K_2TiF_6@C-300 and K_2TiF_6@C-600). The average particle sizes were 6 and 2 µm for K_2TiF_6@C-300 and K_2TiF_6@C-600, respectively. K_2TiF_6@C-600 showed much higher potassium insertion (discharge) capacity of 202 mAh g^{-1} with a voltage plateau at ~2.0 V (Fig. 1a). The capacity was much higher than that of K_2TiF_6 (39 mAh g^{-1}) and K_2TiF_6@C-300 (95 mAh g^{-1}). It should be noted that the capacity exceeds the $Ti^{4+/3+}$ redox capacity of 111 mAh g^{-1}, suggesting additional reactions. The discharge capacity in the second cycle reached 164 mAh g^{-1}, and unlike the first cycle, relatively low-polarization electrochemical reactions were observed (Fig. 1b). From Ex-situ EDS measurements, the amount of K changes during the charge/discharge process (Fig. 1c). Therefore, we further investigate the crystal structure and oxidation state evolution during the K ion insertion process in K_2TiF_6.



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Optimizing Potassium-Ion Storage: Sputtering Techniques for High-Performance Electrode Development

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The growing demand for sustainable and efficient energy storage solutions has spurred increasing interest in potassium-ion batteries (KIBs) as promising alternatives to lithium-ion technologies. Potassium offers significant advantages, such as abundant natural reserves, low cost, and similar intercalation chemistry to lithium, making it highly attractive for large-scale applications. However, the development of high-performance KIB electrodes remains a major challenge, particularly regarding structural stability and electrochemical efficiency.In this context, sputtering deposition emerges as a powerful tool for the investigation and optimization of new potassium-based electrode materials. Sputtering allows precise control over film composition, thickness, and morphology at the atomic level, enabling the fabrication of thin films with tailored properties. It also facilitates the exploration of metastable phases, gradient compositions, and doping strategies that are difficult to achieve through conventional synthesis. The capability of sputtering to produce uniform, binder-free, and additive-free electrodes is particularly advantageous for fundamental electrochemical studies, eliminating variables that could obscure the intrinsic behavior of active materials. Moreover, the compatibility of sputtered films with flexible and unconventional substrates opens new opportunities for the development of next-generation KIBs for wearable and portable devices. This work aims to prospect collaborations focused on the investigation and production of thin films to optimize the use of potassium ions in energy storage applications, contributing to the advancement and commercial viability of potassium-ion battery technology.

Impact of Hard Carbon Properties on Their Performance in KIBs

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Potassium-ion batteries (KIBs) have emerged as a promising energy storage system in the recent years. However, finding the suitable negative electrode material is a real scientific challenge. Since carbonaceous materials allow the insertion / extraction of potassium-ions (K^+), and are safe, nontoxic, abundant, and inexpensive, they are promising choice for KIBs. Among those carbon materials, hard carbon is an attractive choice because it may achieve better rate performance as electrode material owing to its structure containing graphitic and pseudo-graphitic domains. Herein, we propose the synthesis of hard carbon spheres (HCS) and the study of the pyrolysis temperature influence (1500 to 1900 °C) on their properties as well as the relationship with electrochemical performance[1]. A comparison with a commercial graphite (Gr) was provided as well. Spherical morphology, disordered structure, and low surface area (SSA) were obtained for the HCSs. Most properties (interlayer space (d_{002}), active surface area, and oxygen-based functional groups (CO_x) were found to decrease with increasing pyrolysis temperature, except for the helium density and closed porosity (C_p), which increase. However, Gr presents a flake-like morphology, a larger particle size, a higher helium density, an ordered structure with a smaller d_{002}, and no C_p. Electrochemical tests showed that HCSs perform better than Gr with higher initial Coulombic efficiency (ICE) and better specific capacities. The HCSs pyrolyzed at 1500 and 1700 °C exhibit the best ICEs, and specific capacities, respectively. The ICE is affected by multiple surface and bulk parameters but also by electrolyte formulation. The capacity is governed by diffusive phenomena, and a larger d_{002} and defects favour a better insertion of K^+. Closed pores did not lead to an improvement in capacity. Furthermore, HCSs exhibit significantly better capacity retention than Gr when cycled at high current rates (up to 10C depotassiation rate).

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Potassium Alloy Reference Electrodes for Potassium-Ion Batteries

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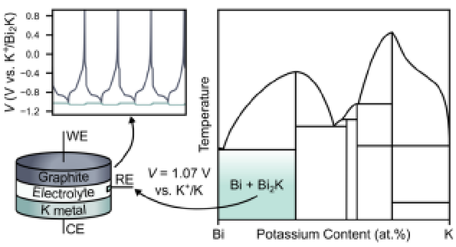
Potassium-ion batteries (KIBs) represent a promising complementary technology to lithium-ion batteries (LIBs) due to the availability and low cost of potassium. KIBs could also be produced with graphite anodes and Prussian blue analogue cathodes, reducing the demand for rare, costly elements necessary in LIBs.[1] However, accurate characterisation of KIB electrode materials is impeded by a lack of suitable reference electrodes. A reference electrode should have a stable rest potential, should be chemically inert, and should operate within the electrochemical stability window of KIB electrolytes.

Many studies currently use potassium metal as a reference electrode out of necessity, which does not satisfy any of the above criteria. The potential of potassium metal has been shown to be irreproducible and it can drift over time,[2] which we demonstrated may be caused by the high concentrations of sodium and other impurities present in commercially available potassium metal.[3] Potassium metal pre-treatment has therefore been necessary to achieve satisfactory reliability of rest potential.[2, 3] Potassium metal is also highly reactive, decomposing electrolyte on contact and forming resistive solid electrolyte interphase (SEI) layers. Electrolyte decomposition products formed at potassium metal electrodes have further been observed to travel across cells and deposit on the other electrode as a result of crosstalk.[4] The development of a stable reference electrode for KIBs is therefore of critical importance.

Here, we explore the K-In and K-Bi binary alloy systems as potential reference electrode materials and synthesize promising two-phase alloys. These are metallic, and hence electronically conductive, and the two-phase nature should provide a stable potential, independent of random composition fluctuations. The In-In_4K system displays a rest potential of 0.64 V vs. K^+/K but takes tens of hours to stabilise, indicating a kinetic limitation. On the other hand, the Bi-Bi_2K system displays a rest potential of 1.07 V vs. K^+/K, greatly reducing the driving force for electrolyte reduction, and stabilises within a few hours.[5] We prove the use of Bi-Bi_2K as a reference electrode by cycling graphite in three-electrode cells and demonstrate that it results in significantly less electrolyte reduction than potassium metal,[5] facilitating the accurate electrochemical characterisation necessary to accelerate KIB development.



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Unveiling the Unexpected: Electrolytes, Anode and Interfaces in Potassium Batteries

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The energy transition relies on efficient storage solutions, with Li-ion batteries (LIBs) dominating research and industry. However, Li scarcity limits their large-scale adoption, driving interest in K-ion batteries (KIBs) as a cost-effective alternative, especially for stationary storage. K 900 times more abundant than Li, it features a similar redox potential (-2.93 V vs. SHE), and is compatible with Al current collectors, even for anodes. However, their electrochemical behavior challenges many established paradigms derived from Li systems, particularly at the electrode-electrolyte interface. A key factor in these differences is the distinct ionic nature of K. The large ionic radius of potassium limits the use of conventional graphitic anodes with narrow interlayer spacing. To address this, we synthesized an amorphous lignin-derived carbon anode with an exceptionally high surface area (2000 m^2/g), designed to maximize capacitive charge storage. Interestingly, while the initial potassium storage mechanism is predominantly capacitive[1], the capacity significantly increases upon cycling. This enhancement is attributed to a structural reordering of the disordered carbon matrix, induced by repeated K^+ intercalation and deintercalation. This transition from a capacitive to a more intercalation-dominated behavior was demonstrated by operando X-ray diffraction (XRD) and Raman spectroscopy. While K^+ has a larger ionic radius than Li^+, its smaller Stokes radius in common solvents influences solvation dynamics and transport properties in ways that diverge from LIBs. The resulting higher diffusion rate of K-ions allows the use of thicker electrolytes, which can effectively suppress dendrite growth while maintaining high ionic conductivity, leading to enhanced cycling stability in potassium-based cell. To harness these properties, we have developed tailored gel polymer electrolytes (GPEs) for KIBs[2-3]. One formulation prioritizes mechanical strength crosslinking pre-oxidized lignin with PEGDGE, achieving high ionic conductivity despite increased thickness and enabling long-term cycling stability. Another one employs lignin as a filler, increasing the conductivity (approaching 10^{-1} S cm^{-1}) and fostering a more favorable GPE/K-metal interface. Beyond electrolyte engineering, a fundamental understanding of interfacial chemistry in potassium batteries is mandatory to unlock their potential and ensure their safety. Unlike lithium systems, where SEI formation and composition are relatively well understood, potassium batteries exhibit a highly dynamic and evolving SEI. Our investigations reveal that the charge transfer resistance at open circuit voltage is initially extremely high, but dramatically drops below 100 Ω within the first few cycles. This behavior suggests a progressive transformation of the SEI, leading to a thinner, more conductive layer over time - contrary to what is commonly expected in lithium-based systems. To systematically investigate these interfacial transformations, a combination of X-rays photoelectron spectroscopy, in operando gas chromatography, 3D tomography and atomic force microscopy is needed. Our findings demonstrate that the decomposition potential as well as the SEI layer composition in potassium batteries are highly dependent on the electrolyte chemistry and significantly evolves upon cycling. This work contributes to the characterization of potassium battery interfaces, an area that remains relatively unexplored. By revealing unexpected interfacial processes, we offer new insights that can support the future development of stable and high-performance potassium-based energy storage systems.

Evaluation of KTP-type Polyanionic Cathode Materials for Potassium-based Batteries

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Potassium-ion batteries (KIBs) have emerged as a viable alternative to lithium- and sodium-ion systems, offering potential advantages in resource availability and electrochemical performance. Interest in KIBs was sparked by the discovery that potassium can reversibly intercalate into graphite to form KC_8, making it an ideal anode material with a high theoretical capacity of 273 mAh/g[1]. Polyanionic frameworks based on the $Pna2_1$ space group, such as $K_xVPO_4F_{1-y}O_y$ (0< y<1) and K_xFeSO_4F have demonstrated good electrochemical properties in KIBs, surpassing layered oxide and rivaling Prussian Blue alternatives, with capacities of up to 120 mAh/g and 103 mAh/g, respectively, and high average voltages of 4.5 V and 3.6 V vs K^+/K[2,3]. These materials share a $KTiOPO_4$ (KTP)-type structure, which provides structural stability and tunability through substitution of oxygen/fluorine, but also of different transition metals for Ti and of the polyanionic groups as well. While liquid electrolytes impose limitations at high potentials, strategies such as composition tuning, surface coatings, and the use of solid electrolytes could enable their full potential. Current research on Cathode Active Materials (CAMs) for potassium solid-state batteries (K-SSBs) remains scarce, with most studies focusing on organic CAMs or Prussian blue analogs, which achieve low energy densities[1]. Given the parallels between KIBs and K-SSBs, polyanionic compounds are expected to be key to enhancing energy density in solid-state systems. However, additional factors must be considered, including the optimisation of CAM morphology for mechanical contact with the solid electrolyte, investigation of CAM/solid electrolyte stability, and the application of protective coatings to mitigate interfacial degradation. Lessons from lithium- and sodium-based solid-state batteries suggest that these design strategies will be critical for achieving long-term stability and high-performance K-SSBs.

Presented herein are initial efforts focused on synthesising cathode materials for further use in K-SSBs. $KVOPO_4$, a KTP-type polyanionic structure, was initially selected due to its adequate performance in literature[1,2]. Of the three tested synthesis methods, a multi-step solid-state approach was found to be the most effective, yielding a pure product that was scaled up for delivery to project partners. Fluorinated $KVPO_4F_yO_{1-y}$ materials, specifically $KVPO_4F$ and $KVPO_4F_{0.5}O_{0.5}$, were subsequently targeted for their reported superior performance at the same voltages. A modified multi-step solid-state method enabled their successful synthesis, optimisation, and reproduction. Electrochemical testing in liquid potassium half-cells showed that while $KVOPO_4$ matched literature performance, the fluorinated variants underperformed, with $KVPO_4F_{0.5}O_{0.5}$, however, still demonstrating the best capacity retention and phase stability. High-resolution XRD at the ALBA synchrotron confirmed the increase in unit cell size and decrease in crystallite size with fluorination, as well as the presence of minor impurity phases. Operando XRD have been performed to characterise phase evolution, with preliminary results indicating that $KVPO_4F_{0.5}O_{0.5}$ undergoes the most gradual phase transitions. Further work focuses on optimising $KVPO_4F_yO_{1-y}$ synthesis and performance while expanding research to $KFeSO_4F$ and Mg-doped variants, which operate at lower voltages and eliminate vanadium use[3]. Initial solid-state synthesis of $KFeSO_4F$ will be reported, and its electrochemical performance evaluated comparing differing processing methods.

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Investigation of the Potassium Metal Anode for the Use in Solid-State Batteries

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Solid State Batteries (SSB) have experienced a major rise of interest in the past years due to the ability to implement a metal anode (MA) resulting in a higher capacity than other conventional active materials and a comparable performance to batteries with liquid electrolyte, only to name a few advantages.[1] In SSBs it is more crucial to understand the behaviour of contact areas between electrodes and the solid electrolyte (SE) than in the case of liquid electrolytes, since the absence of a liquid makes contacting more difficult. This results in major challenges of these systems e.g. pore formation. Therefore, the interfaces Li|SE and Na|SE have already been investigated thoroughly, showing that pore formation during stripping of the MA eventually leads to cell failure due to loss of contact and dendrite formation.[2,3] The occurrence of vacancies and accumulation to pores takes place when the replenishment of the pores is slower than the insertion of vacancies by stripping. It has been shown that the property trends within the group of alkaline elements cause increasing critical current densities with increasing periodicity of the metal.[4] The aforementioned clarifies that interfacial behaviour such as pore formation between the SE and the Potassium Metal Anode (K-MA) have to be further investigated.

In this study we first confirm that K-β"-Alumina (KBA) is a suitable SE for the investigation of the K-MA since it shows good stability in contact with Potassium in contrast to e.g. sulfidic SE with narrower stability windows. To analyse and understand interfacial processes like pore formation we use our in-house developed dilatometric measurement setup to precisely measure the formed pore volume operando during stripping. The pore volume is calculated from the dilatometric height change.[5] Combining this method with Galvanostatic Electrochemical Impedance Spectroscopy (GEIS), we answer, which of the two competing effects – higher vacancy diffusion alongside higher molar volume of the K-MA – prevail and lead to the observed properties. We demonstrate that already small external pressure (<0.1 MPa) reduces pore formation and measurable constrictions and allows therefore to completely strip the potassium from the current collector. Combining EIS, Dilatometry, SEM and FIB-SEM we want to give a comprehensive overview over critical pore formation and point out possible mitigation strategies for the future use of KSSBs with a K-MA and an oxide SE.

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Gr-PBA full cells development: from the PBA synthesis development until K-ion pouch cells manufacturing

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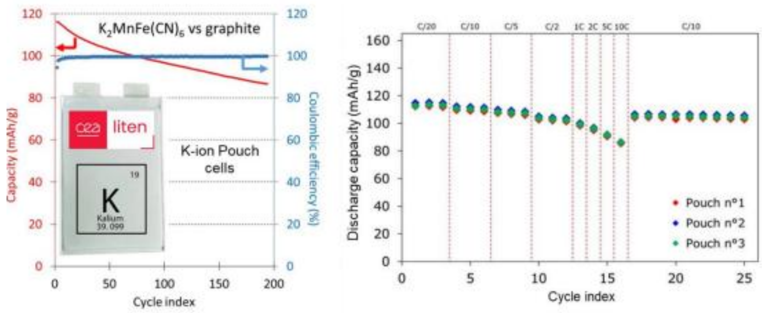
With the aim of offering a complete system free of critical metals and with the lowest possible environmental footprint, our team focuses for developing K-ion batteries composed of $K_2Mn[Fe(CN)_6]$ (cathode) and graphite (anode).

The four main components of the electrochemical system were first optimized in half-cell using potassium metal as anode.[1-4] Extensive work was carried out to limit the number of crystalline defects in the Prussian White structure by adding a chelating agent. Then, fine-tuning of the ratio and type of carbonaceous additive, as well as the cellulose binder, has enabled electrodes to be manufactured using an aqueous process, with an active material loading up to 90%. The addition of an additive such as vinylene carbonate to the electrolyte allows to counteract potassium reactivity and results in a robust and functional system. Finally, the comparison and evaluation of different grades of graphite enabled the selection of an anode material with a capacity of 250 mAh/g, sufficiently stable in terms of lifetime to enable its use in complete cells.

In a second phase, the study was finalized by merging all the developments carried out in half-cells into complete 4 mAh potassium-ion cells. The first full-cell prototypes are showing very promising results, with discharge capacities of 116 mAh/g at 3.6 V. Residual capacity is still 80% after 120 cycles, suggesting that cells with long lifetimes may be possible once optimizations have been finalized. In addition to a successful initial proof-of-concept, the feedback from these first prototypes has enabled us to better target and prioritize future research on the technology.



Electrochemical results of first CEA K-Ion cells (cycle life and Crate behaviour)

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2 D. Peralta, N. Dautain; patent FR2312443
3 D. Peralta, N. Dautain; patent FR2312447

Sustainable anode materials for potassium ion batteries

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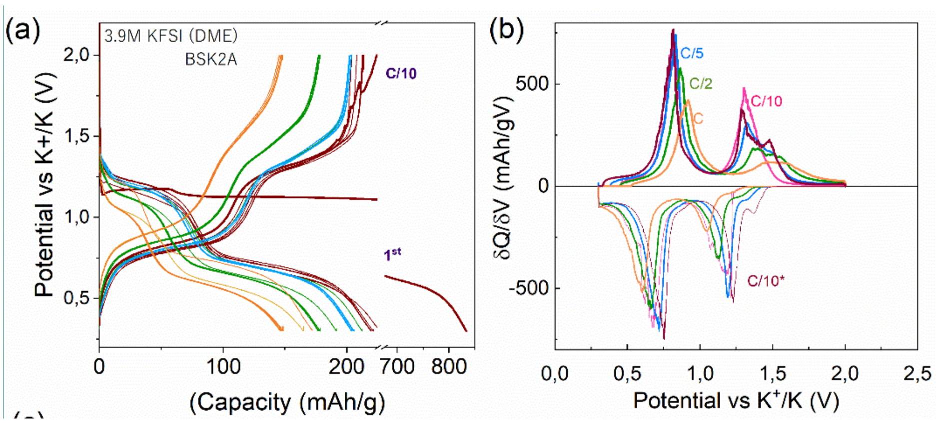
Na and K ion batteries (SIBs and KIBs), represent lower cost and more sustainable energy storage technologies than Li ion batteries (LIBs) and are critical for large scale applications. [1] The scientific communitie continue to search for efficient battery materials which comply with this sustainable approach, with materials based on non-critical raw elements, that are easily synthesised, mostly by low energy consumption synthesis routes. Biomass produced carbons are one type of electrode material that attracts considerable attention due to its natural abundance, and good electrochemical performance of biomass derived carbon anodes. [2] The use of organic materials produced at low temperatures is very appealing. Conjugated carboxylates have shown to be promising anode materials for LIBs, SIBs and KIBs with reversible alkali ion insertions at voltages low enough to be used in batteries. Schiff Bases have shown better performance in SIBs than in LIBs, however understanding their mechanism of reaction remains elusive, in part due to the poor crystallinity of electroactive materials. We show here that Schiff Bases are electrochemically active at adequate voltages for anode materials in KIBs, and we are solving the crystal structure of an electrochemically active Schiff base by means of powder X-ray diffraction data deploying Rigid bodies units. [3]



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Abstracts: Poster presentations

- *Poster #1* - **Irene Gomez Berenguer** (Universidad Complutense de Madrid)
Carboxylate-Derived Fluorenones as Electrode Materials in Potassium-Ion Batteries

- *Poster #2* - **Noemi Hernandez** (Helmholtz Institute of Ulm)
Designing Bio-waste Hard Carbon Anodes via Template Approaches for K-ion Batteries

- *Poster #3* - **Alejandro Ares** (Institute of Polymer Science and Technology)
Effects of additive salts with voluminous cations on polymer electrolytes for fluorine free K ion batteries

- *Poster #4* - **Jesús Prado Gonjal** (Universidad Complutense de Madrid)
Mechanistic Insights and Electrochemical Performance of Microwave-Synthesized SnS for K-Ion Batteries

- *Poster #5* - **Xinyao Ma** (University of Oxford)
Transport and Thermodynamic Properties of Potassium-ion Electrolytes by Operando Raman Gradient Analysis

- *Poster #6* - **Timofey Kolesnikob** (Karlsruhe Institute of Technology)
Polyimide-Powered PEO Electrolytes for Potassium Metal Batteries

- *Poster #7* - **Victor Duran** (Universidad Complutense de Madrid)
Supramolecular and Honeycomb Iron-Chloranilate MOFs: Low-Cost Cathodes for Alkali-Ion Batteries

- *Poster #8* - **Celine Roeder** (Karlsruhe Institute of Technology)
Synergistic Effects of Electrolyte Additives in High-Voltage Potassium-Ion Full Cells

- *Poster #9* - **Ulf-Christian Rauska** (Karlsruhe Institute of Technology)
Operando HAXPES Investigation of the Anode Interphase in Solid-State Potassium Cells Comprising Block-Copolymer Electrolytes

- *Poster #10* - **Andre Lammiduk Lubis** (*University of Limerick*)
Facile synthesis of composite Cu3P-ppy nanofibers as anode for Potassium-ion batteries

- *Poster #11* - **Andreas Heyn** (Karlsruhe Institute of Technology)

How Reliable are Potassium-Ion Half-Cell Measurements? – Hierarchically Structured Potassium-Titanium-Phosphates as Stable Polyanionic Reference and Counter-Reference Electrodes

- *Poster #12* - **Juan Andres Nieto** (Universidad Complutense de Madrid)

Hollandite-type $K_{1.6}V_{0.8}Ti_{7.2}O_{16}$ as Electrode Material for Rechargeable Potassium-Ion Batteries (KIBs)

- *Poster #13* - **Louiza Larbi** (Université de Haute-Alsace)

Impact of Graphite Properties and Electrode Formulation on Potassium-Ion Battery

- *Poster #14* - **Kaan Kizmaz** (University of Stavanger)

Understanding interphases in alkali metal batteries with focus on potassium

- *Poster #15* - **Ivan Madrazo Palou** (IQOG, CSIC)

Potassium salts of arene-amino acid hybrids: Synthesis, structural characterization and electrochemical properties

- *Poster #16* - **Tamara Donate-Rivas** (Karlsruhe Institute of Technology)

Comparative Aging Study of Graphite Anodes in Different Cells Set Up

- *Poster 17* - **Marta Santos Rodriguez** (Institute of Polymer Science and Technology)

Study of the composition-properties relationships of K-ion conducting solid polymer electrolytes

- *Poster #18* - **Charlie Nason** (University College London)

Optimization of a sustainable $K_2MnFe(CN)_6$||graphite potassium-ion full cell

Carboxylate-Derived Fluorenones as Electrode Materials in Potassium-Ion Batteries

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Organic materials are emerging as promising components for next-generation potassium-ion batteries (KIBs), offering advantages such as structural versatility, elemental abundance, and enhanced sustainability. Among them, small carbonyl-containing molecules stand out due to their well-defined redox-active sites and tunable electrochemical behaviour. [1]

In this work, we explore potassium 9-oxo-9*H*-fluorene-4-carboxylate, synthesized from 9-oxo-9*H*-fluorene-4-carboxylic acid, as a redox-active material for KIBs. Depending on the reaction conditions, two crystalline phases were obtained: a fully potassiated salt and a mixed form comprising the neutral acid and its potassium salt. These phases were characterized by single-crystal and powder X-ray diffraction, IR and Raman spectroscopy, NMR, DSC, and TGA.

Electrochemical performance was evaluated by galvanostatic charge–discharge in half-cells using 2.5 M KFSI in triethyl phosphate (TEP) as electrolyte within a voltage window of 0.5–2.5 V *vs.* K^+/K. Ex situ analyses were performed to monitor structural changes during cycling. While potassium 9-oxo-9H-fluorene-4-carboxylate demonstrates electrochemical activity in KIBs, challenges such as material solubility and capacity fading remain. Further research is needed to improve stability and fully assess the suitability of these organic compounds for practical potassium-ion battery applications.

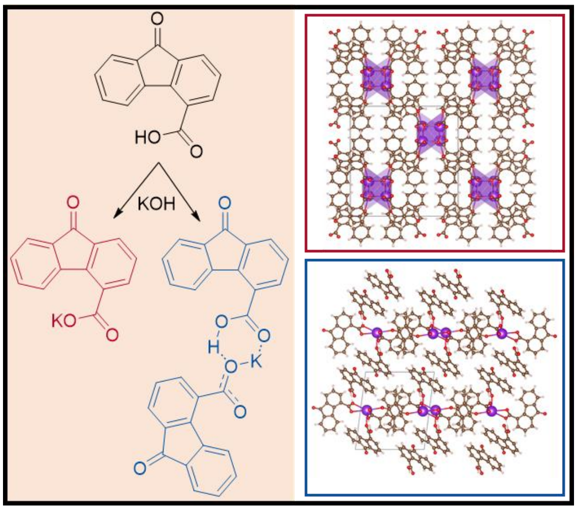

Figure 1. Synthesis, Crystal Structures, and Battery Scheme.

[1] Yuan, S.; Huang, X.; Kong, T.; Yan, L.; Wang, Y. Organic Electrode Materials for Energy Storage and Conversion: Mechanism, Characteristics, and Applications. *Acc. Chem. Res.* **2024**, *57* (10), 1550–1563. https://doi.org/10.1021/acs.accounts.4c00016

Designing Bio-waste Hard Carbon Anodes via Template Approaches for K-ion Batteries

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Potassium-ion batteries have emerged as a promising alternative to lithium-ion batteries due to the high abundance and low cost of this element. Graphite is a widely used anode in lithium-ion batteries; however, its performance in potassium-ion batteries is limited due to the large ionic radius of K^+ and the small interlayer distance, which leads to poorer intercalation kinetics and rapid capacity fading.[1]

As an alternative to graphite, hard carbon could be the best option, as it is abundant, low-cost, environmentally friendly, has high capacity, and a unique structure, which improves its electrochemical performance. Its relatively large interlayer distance, abundant pores, and high active defects make it an attractive anode material in energy storage devices, such as for K-ion batteries.[1] However, the choice of carbon precursor influences the properties of the resulting material, being a critical parameter for developing high-performing hard carbon anodes. Among several precursors, zinc gluconate plays a dual role in the development of hard carbon anode materials: it serves as a carbon precursor and provides ZnO, which acts as a sacrificial template to create controlled porosity, particularly closed pores.[2]

In this work, hard carbon based on hazelnut shells and zinc gluconate was synthesized using different pyrolysis temperatures and pre-treatment media. These hard carbon anode materials were physicochemically characterized using a wide range of techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and Raman spectroscopy. Additionally, they were electrochemically tested in half-cells using 2 M KFSI in TEP as electrolyte. The water-washed hazelnut-derived hard carbon delivered a specific capacity of 200 $mAh{\cdot}g^{-1}$ at 0.1C. However, its performance was improved by washing it with 2 M HCl to remove impurities more efficiently, significantly increasing the specific capacity to 240 $mAh{\cdot}g^{-1}$. Moreover, the template method, i.e., using zinc gluconate, yields hard carbon with superior electrochemical performance (320 $mAh{\cdot}g^{-1}$) at lower pyrolysis temperatures. These results confirmed that the use of templates to fabricate hard carbon anodes is an excellent strategy to reduce the energy consumption and enhance the performance of the battery.

[1] Liu et al., Adv. Func. Mater. 32, 2203117. "Advances in Carbon Materials for Sodium and Potassium Storage", https://doi.org/10.1002/adfm.202203117
[2] Igarashi et al., Adv. Energy Mater. 13, 2302647. "New Template Synthesis of Anomalously Large Capacity Hard Carbon for Na- and K-Ion Batteries", https://doi.org/10.1002/aenm.202302647

Effects of additive salts with voluminous cations on polymer electrolytes for fluorine free K ion batteries

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K-ion batteries are a sustainable alternative to Li-ion batteries, which are dependent on scarce materials like Li, Co and Mn. For an improved cycling stability and performance, substituting the organic liquid electrolytes by solid polymer electrolytes, with higher mechanical and fire resistance[1], but with enough flexibility to accommodate volume changes in the electrodes during cycling[2]. Polymer electrolytes still suffer from disadvantages such as low conductivity and high temperature of operation, as well as the use of salts based on fluorine, which are expensive, and can generate toxic and corrosive compounds when decomposing or in the event of a fire[1]. On this work, we have tested several polymer electrolytes, prepared by a solvent free method by hot-pressing, based on polyethylene oxide (PEO), a fluorine free salt (potassium tetraphenylborate, $KBPh_4$) and different voluminous imidazolium and pyrrolidinium based salts with BPh_4^- as the counterion, to improve the transport properties of the potassium ion in the polymer matrix by creating free volumes [2] and weakening the interaction between PEO and K ions[3]. The results obtained showed that steric effects and chemical compatibility of the substituent chains in pyrrolidinium and imidazolium-based cations allowed to tune the interaction between the polymer and the additive salts, permitting enhanced conductivities below the melting temperature of PEO crystals (Figure 1) by reducing the glass transition temperature and the crystallinity of the samples. These results may help for the future fine tuning of transport properties in polymer electrolytes.

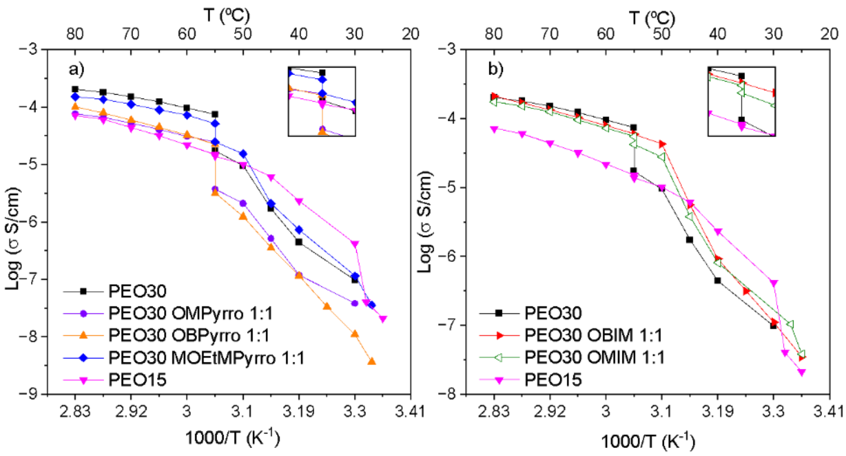

Figure 1. Conductivity of a) pyrrolidinium-based samples and b) imidazolium-based samples.

[1] Elmanzalawy, Mennatalla, et al. ACS Applied Energy Materials, 2022, vol. 5, no 7, p. 9009-9019 “High conductivity in a fluorine-free K-ion polymer electrolyte.”;

[2] KIM, Guk-Tae, et al. Journal of Power Sources, 2010, vol. 195, no 18, p. 6130-6137. “UV cross-linked, lithium-conducting ternary polymer electrolytes containing ionic liquids.”;

[3] ARYA, Anil; SHARMA, A. L. Journal of Physics D: Applied Physics, 2017, vol. 50, no 44, p. 443002. “Insights into the use of polyethylene oxide in energy storage/conversion devices: a critical review.”

Mechanistic Insights and Electrochemical Performance of Microwave-Synthesized SnS for K-Ion Batteries

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This study offers an in-depth analysis of the key parameters affecting the electrochemical behaviour of SnS-based composites as promising anode materials for potassium-ion batteries (KIBs), with a focus on the influence of synthesis methods and the proportion of conductive additives. Polycrystalline SnS was efficiently produced using a rapid "Fast Chemistry" strategy via microwave-assisted hydrothermal synthesis. Notably, just one minute of microwave exposure was sufficient to generate phase pure polycrystalline SnS, which outperformed samples synthesized with increased microwave durations. This improved performance is linked to the reduced particle size and nanogranular morphology achieved through ultrafast synthesis, which enhances the interface between active material and conductive agents, as evidenced by SEM/EDS analysis.

Incorporating 1 wt.% few-layer graphene led to a further increase in electrochemical efficiency. This enhancement is attributed to the dual protective effect of graphene and Super C65, mitigating volume expansion and promoting electrical conductivity, thereby improving rate capability. However, raising the graphene content to 2 wt.% had a detrimental impact on performance. Moreover, adjusting the ratio between active material and conductive additives proved critical. An optimized 75:25 ratio resulted in superior conductivity and capacity retention when compared to the 80:20 counterpart. Remarkably, reversible capacities of up to 285 mAh/g were recorded in the final cycles at a C/20 rate.

Mechanistic understanding was deepened through operando and ex situ XRD, along with ex situ Mössbauer spectroscopy, which together highlighted distinctions among the composite materials. The SnS-1min/24%C/1%FLG composite displayed improved reversibility during the conversion process. More precisely, ex situ and operando XRD suggested the appearance of a cubic structure, potentially *Im*-3*m* Sn, previously reported under high-pressure conditions, during battery cycling, along with amorphous metastable phases that revert to SnS and α-Sn once current is removed. These observations were corroborated by ex situ ^{119}Sn Mössbauer spectroscopy, reinforcing the proposed conversion mechanism.

Overall, these results not only deepen the understanding of SnS-based materials in KIB systems but also offer valuable guidelines for designing next-generation high-performance electrodes, contributing to the development of more sustainable energy storage solutions.[1]

[1] González-Barrios, M. M., García-Chamocho, E., Garitaonandia, J. S., Castillo-Martínez, E., Ávila-Brande, D., Prado-Gonjal, J., *Chem. Mater.* 2025, 37, 15, 5899–5912. Mechanistic Insights and Electrochemical Performance of Microwave-Synthesized SnS for K-Ion Batteries. https://doi.org/10.1021/acs.chemmater.5c01134

1st K IC-25
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25 and 26 September 2025, Madrid (Spain)

Transport and Thermodynamic Properties of Potassium-ion Electrolytes by Operando Raman Gradient Analysis

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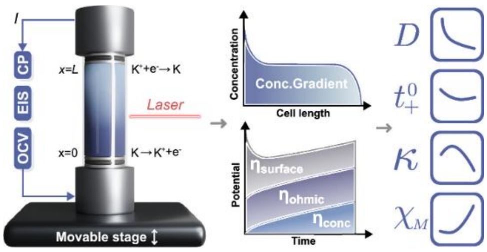
Potassium-ion batteries (KIBs) present a promising alternative to lithium-ion batteries (LIBs) due to the abundant availability of potassium resources, the compatibility with graphite anodes and critical-mineral-free cathodes.[1] However, currently available electrolytes for KIBs do not provide practical Coulombic efficiency (CE) with high-voltage cathodes, highlighting the need for further electrolyte development.

Current research in K-ion electrolytes predominantly addresses issues like aluminum current collector corrosion and stable solid-electrolyte-interphase (SEI) formation, with limited attention to electrolyte transport properties. Ionic transport, typically slower than electron transfer, impacts charge-discharge rates, low-temperature performance, and battery degradation due to concentration gradients promoting interfacial side reactions. Thus, comprehensive characterization of electrolyte transport and thermodynamic properties is critical for electrolyte optimization.

However, conventional approaches for full electrolyte characterization are often slow and labour-intensive. To address this, we employed Operando Raman Gradient Analysis (ORGA), a technique developed by our group, enabling efficient and precise electrolyte characterization.[2] ORGA applies chronopotentiometry (CP), electrochemical impedance spectroscopy (EIS) and open-circuit voltage (OCV) are applied during polarization to establish a concentration gradient, which is then tracked by Raman spectra at different positions of the cell. A model K-ion electrolyte system potassium bis(fluorosulfonyl)imide (KFSI) in triethyl phosphate (TEP) was characterized using ORGA. The technique delivered results consistent with conventional approaches while significantly reducing both the time and electrolyte volume, demonstrating ORGA's effectiveness and potential in accelerating K-ion battery electrolyte development.[3]



1 Dhir, S., Wheeler, S., Capone, I. et Al, *Chem* ***6****, page 2442-2460* "Outlook on K-Ion Batteries", https://doi.org/10.1016/j.chempr.2020.08.012.

2 Fawdon, J., Ihli, J., Mantia, F.L. et Al, *Nat. Commun.* ***12****, page 4053* "Characterising lithium-ion electrolytes via operando Raman microspectroscopy", https://doi.org/10.1038/s41467-021-24297-0

3 Zhao, J., Jagger, B., Olbrich, L. et Al, *ACS Energy Lett.* **9**, page *1537-1544* "Transport and Thermodynamic Properties of KFSI in TEP by Operando Raman Gradient Analysis" DOI: 10.1021/acsenergylett.4c00661

Polyimide-Powered PEO Electrolytes for Potassium Metal Batteries

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Lithium-ion batteries are the most widely used and abundant technology in energy storage systems, powering everything from portable electronics to electric vehicles. Transitioning from lithium metal batteries to potassium-based systems with polymer electrolytes offers the potential for improved resource availability and cost-effectiveness, while maintaining high energy density and stability in solid-state battery applications. Solid polymer electrolytes (SPE), consisting of salts dissolved in a polymer matrix, are widely recognized as attractive materials for next-generation solid-state energy storage devices. They offer several advantages over traditional liquid electrolytes, including flexibility, enhanced safety, ease of membrane formation, and excellent electrochemical stability. Over the past five decades, poly(ethylene oxide) (PEO) has become a preferred option for PE applications due to its low glass transition temperature, chain flexibility, remarkable electrochemical stability against lithium metal, and excellent solubility for conductive lithium salts. Polyimides (PI) are high-performance polymers commonly used in areas such as membrane separation, adhesives, electrical insulation, gas transport, oil storage, and composite matrices, due to their excellent thermal and chemical resistance combined with good mechanical properties.

Previously, we synthesized PI-PEO copolymers with different ratios for use in lithium metal batteries[1]. It was shown that a copolymer with 95 mol% PI exhibited the best mechanical properties as well as high room-temperature ionic conductivity, surpassing that of PEO. By incorporating this copolymer into PEO, we aim to improve the mechanical properties of PEO based SPE, enhance ionic conductivity at low temperatures, and improve interfacial compatibility.

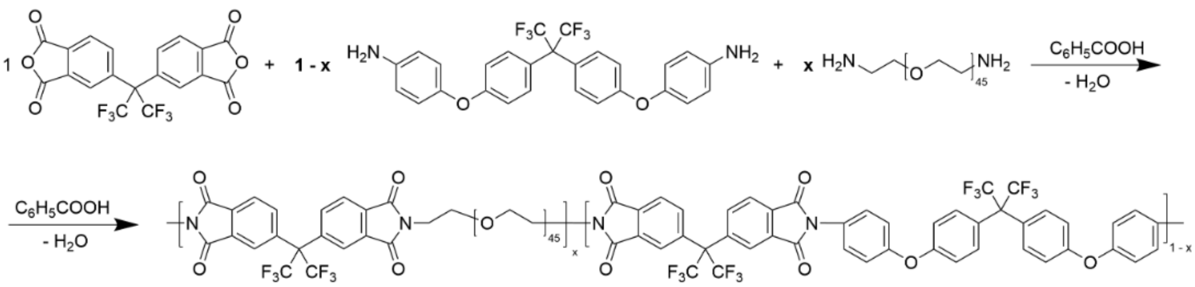

Figure 1. General synthesis route of copolymers (simplified structure of Jeffamine ED-2003)

[1] T.I. Kolesnikov, D. Voll, F. Jeschull, P. Theato, *Eur. Pol. Journ.* **217** (2024) 113315 “Synthesis of Polyimide-PEO Copolymers: Toward thermally stable solid polymer electrolytes for Lithium-Metal batteries” 10.1016/j.eurpolymj.2024.113315

Supramolecular and Honeycomb Iron-Chloranilate MOFs: Low-Cost Cathodes for Alkali-Ion Batteries

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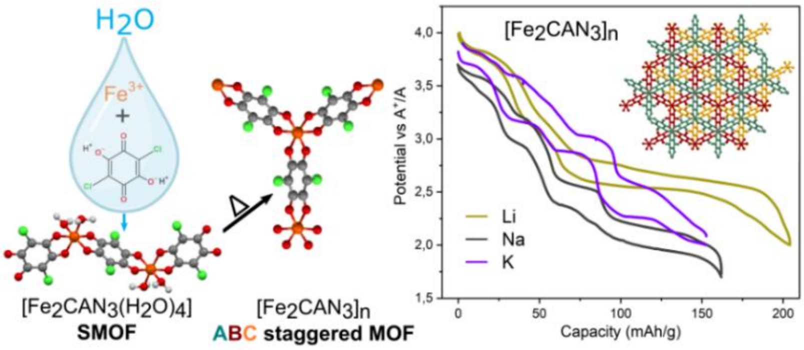

Reaching high battery performance from low-cost, easily synthesisable electrode materials is crucial for advancing energy storage technologies.[1] Metal organic frameworks (MOFs) combining inexpensive transition metals and organic ligands are promising candidates for high-capacity cathodes.[2] Iron-chloranilate frameworks were synthesised in water under mild conditions. Removal of reticular water from known $[Fe_2(CAN)_3(H_2O)_4]\cdot 4H_2O$ yields a new supramolecular metal-organic framework (SMOF), $[Fe_2(CAN)_3(H_2O)_4]$. Removing coordination water, a new 2D honeycomb-like MOF forms, $Fe_2(CAN)_3$, stable without counterions and solvent.[3] This MOF adopts the unusual ABC layer-stacking, as determined combining *ab initio* random structure searching, electron diffraction, and Rietveld refinement of PXRD data. Magnetometry, Mössbauer and Raman spectroscopy confirm that all three $[Fe_2(CAN)_3(H_2O)_x]\cdot yH_2O$ phases contain HS-Fe^{3+} and CAN^{2-}. The SMOF and MOF show reversible (de)insertion of >4Li^+/f.u. at average 2.6 V and 2.8 V vs Li^+/Li, respectively. $[Fe_2(CAN)_3]$ achieves 146 mAh/g at 1C, thus specific energy (563 Wh/kg) and power (446 W/kg) in Li half-cells competitive with conventional $LiFePO_4$ (~580 Wh/kg and ~450 W/kg). Beyond Li, $[Fe_2(CAN)_3]$ delivers 421 Wh/kg in K half-cells accounting for 2.8 V average redox potential (as high as in a Li half-cell), thus making it a competitive cathode for sustainable batteries.

1 Abakumov, A. M.; Fedotov, S. S.; Antipov, E. V.; Tarascon, J. M. *Nat Commun* **2020**, 11, 4976.
2 J. Wang, X. Liu, H. Jia, P. Apostol, X. Guo, F. Lucaccioni, X. Zhang, Q. Zhu, C. Morari, J. F. Gohy, A. Vlad, *ACS Energy Lett* **2022**, *7*, 668–674.
3 V. Durán-Egido, J. P. Darby, M. J. Cliffe, J. S. Garitaonandia, P. Grande-Fernández, A. J. Morris, J. Carretero-González, E. Castillo-Martínez. *Angew. Chem. Int. Ed.* **2025**, e202424416.

Synergistic Effects of Electrolyte Additives in High-Voltage Potassium-Ion Full Cells

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Lower specific capacities due to the heavier K-ions are a bottleneck of the potassium battery technology. However, it could be offset by higher cell voltages, for example by using high-voltage materials such as potassium vanadium phosphates ($K_3V_2(PO_4)_3$, KVP).[1] To achieve long cycle life as well as high capacity retention in materials operating at high potentials, the electrolytes must exhibit either distinguished electrochemical stability or resilient passivating properties. Currently, a wide range of electrolytes are being primarily evaluated in half-cell configurations which exposes them to inherent reactivity, aging and dendritic growth associated with K-metal, often inducing detrimental side reactions and cross-talk. Therefore, the transition to a metal free full cell setup is a crucial step towards more reliable cell testing.

We hereby present a comprehensive study of graphite/KVP full cell setups which critically evaluates various electrolyte mixtures with additives towards their feasibility to enhance electrochemical performance in comparison to a classical carbonate-based reference electrolyte. The cells were tested in a standardized operating procedure with constant cycling parameters. Analytic techniques such as X-ray photoelectron spectroscopy (XPS), gas chromatography-mass spectrometry (GC-MS) and scanning electron microscopy (SEM) were applied to correlate cycling behaviour with the specific interphase chemistries and dissolved active species (such as additive decomposition products) and thus to gain deeper insights into the working principles of the different electrolyte additives.

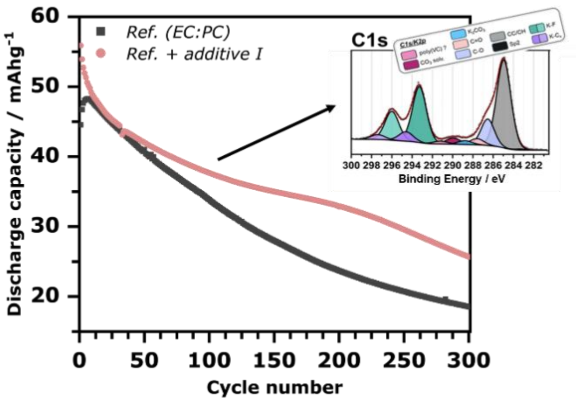

Figure 1. Discharge capacity profile of graphite/KVP full cells with different electrolytes. The inlet shows an exemplary C1s spectrum of a graphite anode after cycling in the additive containing electrolyte.

[1] Komaba et al., *Chem. Rev.* **2020**, *120*, 6358; "Research Development on K-Ion Batteries", DOI: 10.1021/acs.chemrev.9b00463

Operando HAXPES Investigation of the Anode Interphase in Solid-State Potassium Cells Comprising Block-Copolymer Electrolytes

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X-ray photoelectron spectroscopy (XPS) is a common technique for elucidating surface chemistry at electrode-electrolyte interfaces. Conventionally, XPS is applied as an *ex-situ*/ *post-mortem* method, requiring the disassembly of the cell. For solid polymer electrolytes (SPEs), this approach is challenging as separating the electrolyte from the electrodes often damages the interphases, which can be avoided by conducting operando experiments. Thereby an 'anode-free' cell configuration is used, where a metal film (such as Ni or Cu), thin enough for photoelectrons to pass through, is deposited on the polymer electrolyte surface. The solid electrolyte interphase (SEI) formation can then be followed throughout cycling by looking from the backside of the current collector. The use of hard X-ray photoelectrons further allows for a variation of excitation energies to scan different probing depths.

Here we present the results of our operando hard X-ray photoelectron spectroscopy (HAXPES) study on a potassium-ion conductive polystyrene-polyethylene block copolymer (PEO as ionically conductive phase) [1] cycled in an 'anode-free' cell setup with a Prussian White cathode ($K_{1.90}Fe[Fe(CN)_6]$). A series of in-situ and ex-situ measurements were performed to examine the formation of degradation products in relation to the cell potential and their chemical environment at greater analysis depths. In-house scanning electron microscopy (SEM) was also conducted before and after cycling the SPE to develop an optical methodology that offers deeper insights into the electrochemical degradation processes at the anode interphase.

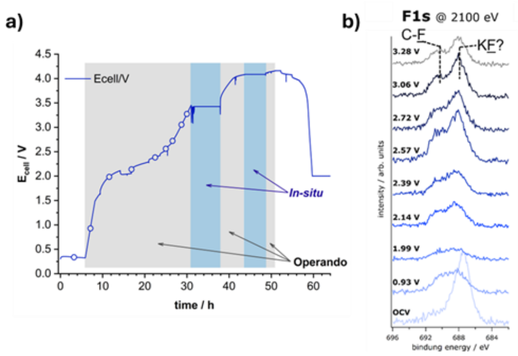

Fig. 1. a) Potential curve of the HAXPES cell and b) HAXPES spectra of the F1s regions during the first operando phase.

[1] Khudyshkina e*t al.*, *Electrochim. Acta.* **2023,** *454, 142421; "From lithium to potassium: Comparison of cations in poly(ethylene oxide)-based block copolymer electrolytes for solid-state alkali metal batteries*", DOI: 10.1016/j.electacta.2023.142421

Facile synthesis of composite Cu_3P-ppy nanofibers as anode for Potassium-ion batteries

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[a] University of Limerick, Department of Chemical Sciences, Bernal Institute

Rechargeable potassium-ion batteries (KIBs) are promising candidates for low-cost and sustainable energy storage, owing to the natural abundance and favourable electrochemical properties of potassium. In this study, we report a facile synthesis of copper phosphide-functionalized carbon nanofibers (Cu_3P@CNFs) as a high-performance anode material for KIBs. The Cu_3P nanoparticles were synthesized using phytic acid as the P-source and uniformly integrated into a polypyrrole-derived CNF matrix. When evaluated as a KIB anode, the Cu_3P@CNFs composite delivers a specific capacity of ~260 mAh g^{-1} at 100 mA g^{-1} and demonstrated excellent cycling stability over 100 cycles. Additionally, the anode exhibits robust rate capability, retaining performance even at high current densities up to 2000 mA g^{-1}. Mechanistic investigations suggest that the synergistic interaction between the uniformly dispersed Cu_3P nanoparticles and the conductive CNF framework enhances charge storage and cycling durability. This work offers valuable insights into the rational design of metal phosphide/carbon composites as advanced anode materials for potassium-ion batteries.

How Reliable are Potassium-Ion Half-Cell Measurements? – Hierarchically Structured Potassium-Titanium-Phosphates as Stable Polyanionic Reference and Counter-Reference Electrodes

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Potassium-ion-batteries (PIBs) are the latest addition to the monovalent ion portfolio and could complement LIBs and SIBs.[1] As PIBs are potentially cheaper as LIBs, they have one main benefit compared to SIBs: Potassium ions could reversibly intercalate into graphite, what means anode production on a large scale is already possible for PIBs.[2,3] Based on these fact the main critical research fronts for practical PIBs arise: development of high-voltage cathode materials and electrolytes compatible with graphite.[2,4] Usually, half-cell setups with metallic potassium anodes are used for the characterization of cathodic materials like for SIBs and LIBs as well. But several recent studies revealed different serious issues due to the highly reactive metal anode, like electrode cross-talk, unstable alkali metal potential and formation of an unstable SEI.[1,4,5] This leads to the question: How reliable are characterizations of different electrode materials in a PIB half-cell setup in reality?

In our work we investigated the influence of the metallic potassium anode onto the electrochemical performance of polyanionic cathodic materials in 3-electrode-setups. For this purpose, two different potassium-titanium-phosphates $KTi_2(PO_4)_3$ (KTP) and $KTiOPO_4$ (KTPO) were characterized as Reference (RE) and Diagnostic/Counter-Reference (CRE) electrodes for PIBs. For the material synthesis we coupled well-known solid-state synthesis with a spray-drying process to create hierarchical structured KTP/C and KTPO/C as electrode materials for PIBs. The polyanionic carbon-composites were thoroughly characterized in terms of morphology and crystal structure by SEM, XRD, BET, particle size distribution and porosity measurements. Both composites were electrochemically characterized in half-cell and 3-electrode-setups regarding their use as a RE or QRE in PIBs.

With KTP/C a stable RE for PIB was explored, which allows detailed and precise characterisation of insertion properties of different cathode materials and underlines the severe issues caused by the reactive potassium metal anode. Based on the results from the 3-electrode-measurments a stable PIB full cell setup with KTPO/C as a CRE anodic material was developed. This allows the easy and precise electrochemical characterization of several polyanionic cathode materials (KVP, KVPO, etc.), which were synthesized in a similar way as the KTP/C or KTPO/C composites, without any serious influences caused by the reactive potassium metal anode.

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Hollandite-type $K_{1.6}V_{0.8}Ti_{7.2}O_{16}$ as Electrode Material for Rechargeable Potassium-Ion Batteries (KIBs)

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The search for alternative electrochemical energy storage systems to lithium-ion batteries (LIBs) has driven interest in potassium-ion batteries (KIBs) due to potassium's higher natural abundance and lower cost. However, identifying electrode materials capable of reversibly accommodating potassium ions without excessive volumetric expansion remains a challenge.[1] Hollandite-type materials ($A_yB_xTi_{8-x}O_{16}$, A = alkali metal, B = transition metal) are promising candidates due to their (2×2) tunnel structures, formed by double chains of TiO_6 octahedra connected at the vertices (Fig 1). These features allow stable insertion and extraction of potassium ions, reducing the risk of volume expansion and degradation during cycling.[2]

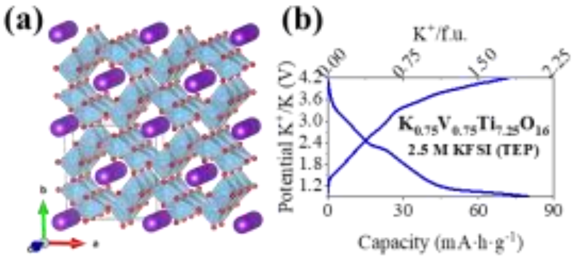

Figure 1. (a) Crystal structure of nominal composition $K_2V_2Ti_6O_{16}$[3], where TiO_6 coordination octahedra are depicted in blue. The (2 x 2) tunnels accommodate K^+ (purple spheres) along the c-axis. (b) Galvanostatic charge-discharge of nominal composition $K_{1.5}V_{0.75}Ti_{7.25}O_{16}$[3].

In this study[3], hollandite-type oxides with the formula $K_yV_xTi_{8-x}O_{16}$ (x = 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2) were synthesized via the citrate route and tested as electrode materials for KIBs. NPD confirmed a stable, undistorted I4/m crystalline structure with a consistent potassium content ($1.4 \le y \le 1.6$). TEM techniques, including SAED, ABF, and HAADF-STEM, identified potassium/vacancy short-range ordering along the c-axis with disorder between tunnels. Magnetic characterization revealed paramagnetic behavior down to 2 K, with antiferromagnetic interactions at low temperatures, except for x = 0.25, which exhibited ferromagnetic interactions. The experimentally determined magnetic moment suggested a low Ti^{3+} concentration, with deviations at x = 1.25. Electrochemical properties were evaluated via galvanostatic cycling using 2.5 M KFSI (TEP) as electrolyte. At C/10, the material exhibited reversible insertion/extraction of 2 K^+ per formula unit (Fig 1). At C/5, x = 0.75 demonstrated stable insertion of 1 K^+ per formula unit, highlighting its viability as an electrode material for rechargeable KIBs.

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Impact of Graphite Properties and Electrode Formulation on Potassium-Ion Battery Performance and Storage Mechanisms

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Graphite is a promising negative electrode material for K-ion batteries thanks to its high reversibility, stability, and low potential plateau[1,2]. This study examines four commercial graphite samples with different particle sizes and properties, along with three electrode formulations. Smaller particle sizes (Gr-SLP6 and Gr-SLP10) lead to lower performance due to higher specific surface area (SSA), active surface area, and oxygen functional groups. Gr-SLP30 and Gr-SLP50 present similar properties, but the large particle size of Gr-SLP50 hinders the benefits of its properties, leading to lower performance. Additionally, an electrode formulation using both carboxymethyl cellulose and Styrene-Butadiene Rubber as a binder was found to be the most promising electrochemical performance. Optimal particle size, low SSA, low defect content, and enhanced electrode structure ensured such good performance.
The X-ray photoelectron spectroscopy analysis was performed to explain the initial coloumbic efficiency using PVDF binder and revealed an evolution of the electrode-electrolyte interface over multiple cycles, characterized by a slight decrease in organic by-products and an increase in inorganic potassium species, while maintaining a relatively stable organic-to-inorganic ratio. Ex situ and in situ X-ray diffraction identified a four-stage K^+ intercalation mechanism and structural modifications after extraction. Self-depotassiation studies showed that the KC_8 phase was not formed during potassiation, while depotassiation occurred with slower kinetics in self-discharge compared to electrochemical discharge.

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Understanding interphases in alkali metal batteries with focus on potassium

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Next generation batteries with alkali metal electrodes promise higher energy density compared to contemporary cell technology based on intercalation-anodes and are hence attracting academic and industrial attention. Despite their potential, the implementation of metal electrodes faces significant challenges including substantial electrode volume expansion or contraction upon cell cycling, the emergence of non-passivating or ion-blocking interphases and undesired instances of electrodeposition.[1,2] Alkali metal electrodes react vigorously with battery electrolytes to form the solid electrolyte interphase (SEI), which plays a dominant role in the complex interplay of the abovementioned processes. Thus, understanding of the ion transport in and evolution of the SEI is crucial as it may enable a rational design of alkali metal cells, as well as electrochemical responses in half-cells.

Electrochemical impedance spectroscopy (EIS) is a powerful method giving access to individual impedance responses of physical processes in-situ, circumventing common experimental difficulties such as handling or perturbation of air-sensitive materials. In addition, EIS gives insight into meaningful performance parameters such as resistances, and their evolution upon battery degradation. In context of planar electrodes (Li, Na, Mg, Al, Si), EIS can be employed to gain information on ion transport mechanism[3,4] and the morphological evolution of the SEI[5].

In this work we will demonstrate the capability of EIS towards a thorough understanding of interphase stability of potassium metals with solid-state (for example K_3SbS_4[6]), liquid-solid (AAO infiltrated with liquid electrolyte)[7] and liquid-state (for example KTFSI and potassium triflate in triglyme) battery electrolytes.

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Potassium salts of arene-amino acid hybrids: Synthesis, structural characterization and electrochemical properties

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Potassium-ion batteries (KIBs) are a promising alternative to lithium-ion batteries (LIBs). Potassium presents several advantages, such as more abundancy in earth's crust, lower cost and reduced environmental impact, while having similar electrochemical properties to lithium. Current day LIBs components contain toxic and highly polluting elements such as cobalt and nickel. The substitution of these inorganic electrodes for organic molecules, ideally made from abundant compounds with low price, low toxicity and zero environmental impact is highly important for the future development of sustainable energy storage devices[1]. Arene-amino acids hybrids are compounds made of an aromatic fragment linked to an amino acid through an amide bond[2]. The arene works as a mold, giving rigidity to the molecule and favoring intramolecular and intermolecular interactions. If the arene presents electrochemical active groups (quinone derivatives, carboxylates, imides, etc)[3] they pose a promising future as electrode materials due to their ability to complex metal cations, structural diversity and environmental sustainability.

In this poster we will present the synthesis, structural and compositional characterization, as well as the electrochemical performance for potassium insertion of a series of novel potassium salts of arene-amino acid hybrids. Electrochemical properties were obtained via the measurement of charge and discharge capacities in galvanostatic mode in various electrolytes. With the data obtained we discussed the viability of these compounds as electrodes for KIBs.

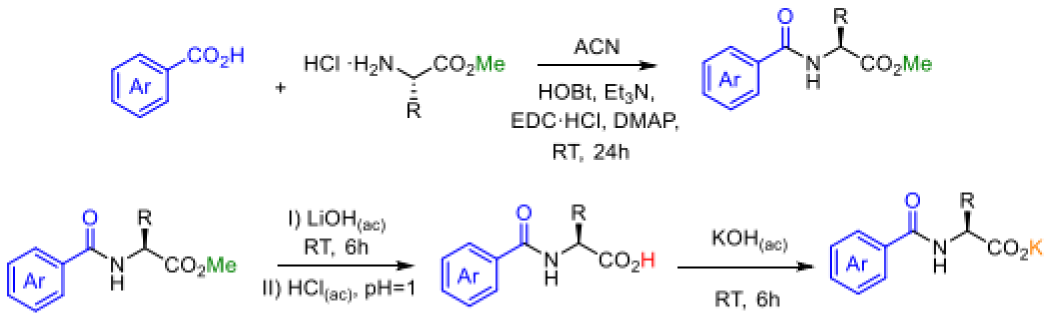

Figure 1: Synthetical procedure of arene-amino acid hybrids studied in this work.

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Comparative Aging Study of Graphite Anodes in Different Cells Set Up

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Between success in LIBs and struggle in KIBs, graphite reveals how small differences can lead to big challenges. Potassium-ion batteries (KIBs) are attracting increasing interest as a sustainable and cost-effective alternative to lithium-ion systems, due to the abundance of potassium and its favourable redox potential.[1] However, the intercalation of K^+ into graphite poses significant challenges due to the larger ionic radius and associated volume expansion.[2] Understanding the intercalation dynamics and reversibility is critical for developing stable and efficient carbon-based anodes.

In this work, we compare the electrochemical behaviour of different types of graphite in half-cell configurations versus potassium counter electrodes. Galvanostatic cycling Galvanostatic cycling test is used as a means to activate and evolve the electrode–electrolyte interface under controlled conditions. This setup enables the comparation of graphite materials cycled against metallic potassium and transition metal phosphate counter electrode, with the aim of assessing their structural and interfacial stability under different electrochemical environments. Complementing the cycling results, the study is designed to identify early signs of degradation through complementary post-mortem techniques such as SEM and GC-MS which are planned for ongoing analysis.

This study represents an initial step establishing a baseline for the suitability of commercial graphite in potassium-ion systems and to identify promising candidates for further development. The findings provide insights into the fundamental behaviour of K-ion intercalation and lay the foundation for future surface and structural investigations.

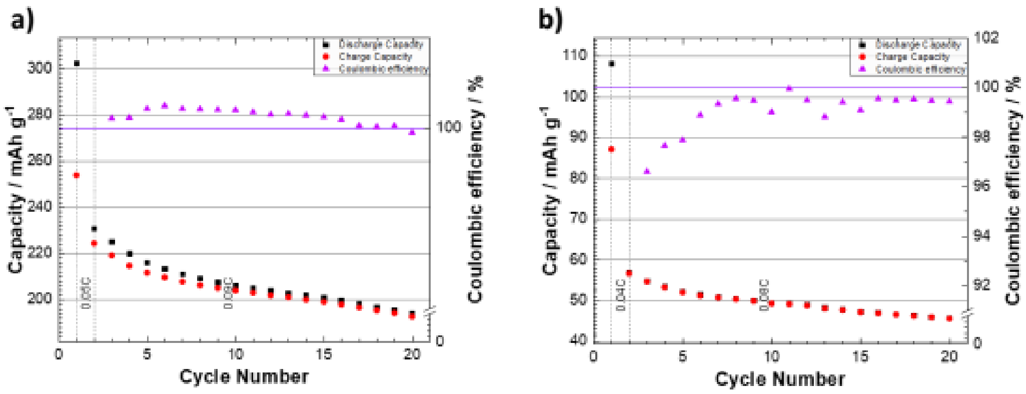

Figure 1. a-b): Comparison of cycling behaviour and coulombic efficiency of two graphite electrodes.

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Study of the composition-properties relationships of K-ion conducting solid polymer electrolytes

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Solid Polymer Electrolytes (SPE) play a crucial role in high-energy density solid state batteries. The development of this new kind of electrolytes has emerged as a promising alternative to conventional liquid electrolytes in solid state batteries, thanks to their improved safety, mechanical flexibility and thermal stability. These materials are usually composed of a polymeric matrix, such as poly (ethylene oxide) (PEO), which acts as solvent of an alkali (e.g. Li) metal salt allowing the ionic transportation and the mechanical stability. Solid-state potassium batteries, offer a potential solution to the challenges associated with instability and formation of potassium metal dendrites during the cycling. Moreover, their capacity to establish stable interfaces with solid electrodes signifies their importance in the development of solid-state batteries. However, their low ionic conductivity remains a critical challenge. Consequently, current research focuses on optimising their composition and structure to enhance ionic transport without compromising their electrochemical stability. In this work, we evaluate the conductivity of different solid polymer electrolytes for potassium ion batteries varying the potassium salt and their concentration and then establishing the correlation between the composition and the electrochemical stability and cyclability in potassium ion batteries. The polymer electrolytes were prepared from PEO and KFSI and KBOB salts following the procedure previously described by our research group **(1)**. Conductivity measurements were assessed through electrochemical impedance spectroscopy (EIS). Linear Sweep Voltammetry and Platting and stripping tests were also performed.

Acknowledgments
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Optimization of a sustainable $K_2MnFe(CN)_6$||graphite potassium-ion full cell

Charlie A.F. Nason, Yingkengzi Mei, Yang Xu

University College London

Many positive-negative electrode configurations have been demonstrated for potassium-ion battery full cells, but the pairing of the Prussian Blue analogue $K_2Mn[Fe(CN)_6$ and graphite has the most promise for future development. However, the research on this full cell remains highly fundamental, with low areal loadings, large amounts of conductive carbon and small particle sizes. Therefore, to address this research deficiency, we report the optimization of a sustainable $K_2MnFe(CN)_6$||graphite full cell, using only water-based binders. The positive electrode composition, particle size, areal loading and porosity are optimized, yielding an electrode with 93 wt% active material and areal loadings of 20 mg cm^{-2} with capacities of 3 mAh cm^{-2}. The effect of calendaring was evaluated, with a maximum energy density of 528 Wh L^{-1} at 47% porosity. The resulting full cell was then optimized in terms of N/P ratio and cycling voltage, demonstrating the viability of the $K_2Mn[Fe(CN)_6]$||graphite configuration.

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