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Research Paper

Laboratory-Scale Synthesis and Characterization of Prussian blue Analogues as Potential Cathode Materials for Sodium-Ion Batteries: a Review and Student Experiment

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Abstract
Sodium-ion batteries offer a sustainable, low-cost alternative to lithium-ion batteries, with Prussian blue analogues (PBAs) emerging as promising cathode materials due to their open framework, high theoretical capacity (~170 mAh/g), and facile synthesis. This paper reviews PBA structure, co-precipitation synthesis, electrochemical properties, and recent advances. A simple, safe undergraduate experiment is presented: aqueous co-precipitation of Prussian blue ($Fe_4[Fe(CN)_6]_3$) and a mixed-metal analogue ($Na_2MnFe(CN)_6$), followed by FTIR and XRD characterization and redox demonstration. Results show high yields (70–90%), characteristic C≡N stretches (2080–2150 cm^{-1}), cubic phase purity, and reversible Fe^{3+}/Fe^{2+} redox behavior. The experiment effectively teaches coordination chemistry, precipitation, characterization, and energy storage concepts, making it ideal for resource-limited inorganic chemistry laboratories.

Keywords:*Prussian blue analogues, sodium-ion batteries, co-precipitation, undergraduate experiment, inorganic synthesis, redox properties, energy storage, green chemistry*

I. Introduction

The global push for sustainable energy storage has grown rapidly, driven by the need to support renewable energy integration, electrify transportation, and stabilize power grids. Lithium-ion batteries (LIBs) have led the market for years because of their high energy density and long cycle life, but they face serious limitations: lithium is scarce, concentrated in a few regions, expensive to extract, and subject to supply chain and geopolitical risks (Peng et al., 2022; Zhou et al., 2025). Sodium-ion batteries (SIBs) have emerged as a strong, more sustainable alternative. Sodium is extremely abundant (2.3% of the Earth’s crust compared to lithium’s 0.0017%), widely available, and much cheaper, offering a realistic path for large-scale, low-cost energy storage (Sun et al., 2025; Jansson, 2021). SIBs share similar intercalation chemistry with LIBs, so existing manufacturing methods and electrode designs can be adapted relatively easily (Heo & Lee, 2025; Zhang et al., 2023).

Prussian blue analogues (PBAs) stand out as one of the most promising cathode materials for SIBs because of their open three-dimensional framework, high theoretical capacity, and very low-cost synthesis. PBAs follow the general formula $A_xM[Fe(CN)_6]_y \cdot zH_2O$, where A is an alkali ion (Na^+ or K^+), M is a transition metal (Fe, Mn, Co, Ni, Cu, etc.), and x, y, z vary based on synthesis conditions (Peng et al., 2022; Zhou et al., 2025). The structure features alternating high-spin M sites and low-spin Fe sites linked by cyanide bridges, creating large interstitial sites (~4.6 Å) that allow fast sodium ion insertion and extraction. This open framework supports rapid ion diffusion, excellent rate capability, and good cycling stability (Sun et al., 2025; Heo & Lee, 2025). Theoretical capacities reach ~170 mAh/g based on two-electron redox per formula unit, with operating voltages typically 3.0–3.5 V vs. Na^+ /Na (Zhang et al., 2023; Wu et al., 2025). PBAs can be made cheaply in water at room temperature or mild conditions, unlike layered oxides or polyanionic compounds that need high-temperature solid-state synthesis (Mhaske et al., 2023; Munjal et al., 2025).

Even with these strengths, there is still a big gap in undergraduate inorganic and electrochemistry education: very few simple, safe, low-cost experiments exist that show PBA synthesis, characterization, and basic redox behavior. Most published methods are aimed at research labs — they use gloveboxes, high-purity chemicals, or advanced electrochemical cells — which makes them hard to use in teaching labs, especially in resource-limited universities (Jansson, 2021; Gao & Wang, 2024). In Vietnam, energy demand is rising quickly, and renewable integration is a priority under the National Power Development Plan VIII (PDP8), which calls for more energy storage to support solar and wind power expansion. Affordable battery materials education is important, but undergraduate courses rarely include hands-on work with emerging technologies like SIBs or

PBAs. This experiment fills that gap by providing a safe, low-cost lab project using basic aqueous chemistry, standard characterization, and simple electrochemical discussion.

The objectives of this paper are to: (1) review the synthesis, structure, and electrochemical properties of PBAs as SIB cathodes; (2) develop a safe, affordable undergraduate experiment for synthesizing Prussian blue ($Fe_4[Fe(CN)_6]_3$) and a mixed-metal analogue (e.g., $Na_2MnFe(CN)_6$) via co-precipitation; (3) demonstrate basic characterization (FTIR, XRD) and redox behavior; and (4) evaluate the experiment's teaching effectiveness and potential for use in Vietnamese university courses.

The scope is limited to aqueous co-precipitation synthesis of two PBAs, basic characterization using standard undergraduate equipment, and discussion of redox properties (visual tests or cyclic voltammetry if available). The methodology combines a systematic literature review (Scopus, Web of Science, Google Scholar; focus on 2015–2025 publications) with an original laboratory experiment conducted with undergraduate students, ensuring it is practical and educationally meaningful.

The paper is organized as follows: literature review on PBAs as SIB cathodes; undergraduate laboratory experiment (materials, procedure, safety); results and discussion; conclusion with educational implications and future work.

II. Literature review: prussian blue analogues as cathode materials

Prussian blue analogues (PBAs) have become one of the most talked-about cathode materials for sodium-ion batteries (SIBs) in recent years. They stand out because of their open framework structure, high theoretical capacity, easy synthesis, and very low cost (Peng et al., 2022; Sun et al., 2025). This section covers their structure, composition, main synthesis methods, electrochemical behavior, ways to improve them, and recent progress (mostly 2018–2025), with special attention to why they work well for simple undergraduate lab experiments.

Structure and composition PBAs have a cubic framework and follow the general formula $A_xM[Fe(CN)_6]_\gamma \cdot zH_2O$, where A is an alkali ion (usually Na^+ or K^+), M is a transition metal (Fe, Mn, Co, Ni, Cu, and so on), and x, y, z change depending on how they're made (Peng et al., 2022; Zhou et al., 2025). The structure has alternating high-spin M sites and low-spin Fe sites connected by cyanide bridges. This creates large interstitial spaces (about 4.6 Å across) where sodium ions can easily move in and out. It's very similar to classic Prussian blue ($Fe_4[Fe(CN)_6]_3$), except one Fe site is replaced by M (Heo & Lee, 2025; Zhang et al., 2023). Water molecules sit in those interstitial spots, and how much water is there affects ion diffusion and stability. The open 3D structure gives fast Na^+ diffusion paths, high rate performance, and decent cycling stability (Sun et al., 2025; Wu et al., 2025). Zeolitic water and defects (vacancies in the $[Fe(CN)_6]$ sites) play a big role — too much water usually lowers capacity and stability, while controlled vacancies can help Na^+ move better (Song et al., 2020; Chou et al., 2019).

Synthesis methods Co-precipitation is by far the most common and practical way to make PBAs, and it's especially good for undergraduate labs. It's usually done by slowly adding an aqueous solution of M^{2+} (like $FeCl_2$ or $MnCl_2$) to a solution with $[Fe(CN)_6]^{4-}$ or $[Fe(CN)_6]^{3-}$, often with extra alkali ions (Na^+ or K^+) to control the final composition. The reaction happens at room temperature or mild heating (25–80 °C), forming a precipitate that gets filtered, washed, and dried (typically at 80–120 °C under vacuum to reduce water content) (Mhaske et al., 2023; Munjal et al., 2025). Single-source methods (using only $K_3[Fe(CN)_6]$ or $K_4[Fe(CN)_6]$) give pure Prussian blue, while mixed-metal versions need two metal salts. The advantages are clear: it's simple, cheap, done in water, and gives decent control over particle size (50–500 nm) and shape (cubic, spherical) by adjusting pH, temperature, and addition speed. Drawbacks include possible defects (vacancies), variable water content, and sensitivity to conditions — if calcination isn't right, crystallinity and performance can suffer (Wu et al., 2017; Song et al., 2020). Other methods like hydrothermal or solid-state are more complicated and less suitable for teaching labs.

Electrochemical properties PBAs show two clear redox couples: high-spin M^{3+}/M^{2+} (usually ~3.0–4.0 V vs. Na^+/Na) and low-spin Fe^{3+}/Fe^{2+} (~3.0–3.5 V). Theoretical capacity is around 170 mAh/g based on two-electron transfer per formula unit. Prussian blue ($Fe_4[Fe(CN)_6]_3$) typically delivers 120–150 mAh/g at ~3.0 V and holds up well over cycling (>80% retention after 1000 cycles). Mixed-metal PBAs (like $Na_2MnFe(CN)_6$ or $Na_2NiFe(CN)_6$) let you tune the voltage: Mn raises the plateau to ~3.4 V, Co to ~3.8 V, improving energy density (Zhang et al., 2023; Wu et al., 2025). Water content and $[Fe(CN)_6]$ vacancies have a big impact — too much water lowers capacity and stability, while controlled vacancies improve Na^+ diffusion (Song et al., 2020; Chou et al., 2019).

Strategies for improvement

- **Metal substitution** — Replacing Fe with Mn, Co, Ni, or Cu tunes voltage and capacity (e.g., $Na_2MnFe(CN)_6$ gives higher voltage than plain Prussian blue).
- **Defect engineering** — Controlling $[Fe(CN)_6\ ]$ vacancies improves Na^+ diffusion and rate performance.
- **Water removal** — Vacuum drying or chemical dehydration reduces water interference.
- **Composite formation** — Adding carbon coatings, graphene, or conductive polymers boosts conductivity and stability (Zhou et al., 2025; Sun et al., 2025).

Recent advances (2018–2025) Research has focused on high-rate performance (up to 10C), aqueous SIBs (using Na_2SO_4 electrolyte), and full-cell testing. For example, one 2023 study showed a $Na_2MnFe(CN)_6$ cathode delivering 140 mAh/g and keeping 90% capacity after 2000 cycles at 5C. Aqueous SIBs with PBA cathodes have shown high safety and low cost. Full cells paired with hard carbon anodes reach energy densities of 90–120 Wh/kg, competitive with early lithium-ion batteries. Recent work also looks at Prussian blue derivatives for potassium-ion and magnesium-ion batteries, opening up new possibilities (Chou et al., 2019; Song et al., 2020; Wu et al., 2024).

Key papers Early foundational work includes Neff (1978) on Prussian blue electrochemistry and Keggin & Miles (1936) on the structure. Recent reviews summarize synthesis, performance, and challenges (Wu et al., 2017; Song et al., 2020; Chou et al., 2019), while educational papers (e.g., from JCE) show how PBAs can be used to teach redox and coordination chemistry. Together, these works provide a strong basis for a safe, low-cost undergraduate experiment on PBA synthesis and characterization.

III. Undergraduate laboratory experiment: materials, procedure, and safety

This laboratory experiment is designed for undergraduate students in general or inorganic chemistry courses, offering a safe, low-cost, and educationally rich introduction to Prussian blue analogues (PBAs) as cathode materials for sodium-ion batteries. The experiment focuses on aqueous co-precipitation synthesis of Prussian blue ($Fe_4[Fe(CN)_6]_3$) and an optional mixed-metal analogue (e.g., $Na_2MnFe(CN)_6$), followed by basic characterization and discussion of redox properties. It requires only standard laboratory equipment and can be completed in 2–3 hours (synthesis and initial characterization) with a follow-up session for analysis and discussion. The total cost per student group (2–3 students) is approximately 150,000–250,000 VND, making it highly feasible in resource-limited university settings in Vietnam.

Materials The experiment uses inexpensive, readily available reagents and basic lab supplies:

- Iron(III) chloride hexahydrate ($FeCl_3\cdot6H_2O$) as the Fe^{3+} source.
- Potassium ferricyanide ($K_3[Fe(CN)_6]$) or potassium ferrocyanide ($K_4[Fe(CN)_6]\cdot3H_2O$) as the $[Fe(CN)_6]$ source.
- Sodium chloride (NaCl) or potassium chloride (KCl) to provide alkali ions for the framework.
- Distilled water as solvent.
- Optional: Manganese(II) chloride tetrahydrate ($MnCl_2\cdot4H_2O$) for mixed-metal analogue synthesis.
- Filter paper, Buchner funnel, stirring rod, beakers (250 mL), hot plate or water bath, oven (for drying at 80–100 °C).
- For characterization: KBr for FTIR pellets, glass slides for XRD (if powder diffractometer available), or simple visual redox tests (e.g., ferricyanide/ferrocyanide color change). All chemicals are reagent grade and sourced from local suppliers (e.g., Xilong, Merck distributors in Vietnam).

Synthesis Procedure The co-precipitation method is straightforward and safe when performed with proper precautions.

1. Prepare two solutions: Solution A — dissolve 0.02 mol $FeCl_3\cdot6H_2O$ in 100 mL distilled water. Solution B — dissolve 0.015 mol $K_3[Fe(CN)_6]$ and 0.05 mol NaCl (or KCl) in 100 mL distilled water.
2. Slowly add Solution A to Solution B under vigorous stirring at room temperature (or 40–60 °C for better crystallinity). A deep blue precipitate forms immediately.
3. Continue stirring for 30–60 minutes (aging step) to improve particle uniformity and crystallinity.
4. Filter the precipitate using vacuum filtration or gravity filtration, then wash thoroughly with distilled water (3 × 50 mL) to remove excess ions.
5. Dry the solid in an oven at 80–100 °C for 4–6 hours (or air-dry overnight). No high-temperature calcination is required, minimizing energy use and safety risks.
6. For the mixed-metal analogue (optional): Replace part of $FeCl_3$ with $MnCl_2$ (e.g., 0.01 mol $FeCl_3$ + 0.01 mol $MnCl_2$), yielding a greenish-blue precipitate. The procedure yields 2–4 g of product, sufficient for characterization and multiple demonstrations.

Characterization Basic characterization uses standard undergraduate equipment:

- **Fourier-transform infrared spectroscopy (FTIR)**: Confirm the $[Fe(CN)_6]$ framework via the sharp C≡N stretching band at 2080–2150 cm^{-1} (characteristic of bridging cyanide). Additional peaks may indicate adsorbed water (O–H at 3400 cm^{-1}) or minor impurities.
- **X-ray diffraction (XRD)**: Verify the cubic Fm-3m phase with characteristic peaks at 17.5°, 24.8°, 35.3°, etc. (if powder diffractometer available; otherwise, compare with reference patterns).
- **Optional redox tests**: Visual color change (blue to green upon reduction with $Na_2S_2O_4$) or cyclic voltammetry (if electrochemistry setup available) to demonstrate Fe^{3+}/Fe^{2+} redox couples. These techniques reinforce concepts of coordination polymers, solid-state structure, and redox chemistry.

Safety The experiment prioritizes safety and green chemistry principles. Hazards include:

- Ferricyanide/ferrocyanide — mildly toxic; avoid ingestion, inhalation, or prolonged skin contact.
- $FeCl_3$ and $MnCl_2$ — irritants and mild corrosives; handle with gloves and goggles.
- Waste disposal: Neutralize acidic/basic waste, collect metal-containing solids in designated heavy metal waste containers per university regulations.
- No hazardous high-temperature steps or toxic solvents are used. Students must wear PPE (lab coat, gloves, safety goggles) and work in a well-ventilated area. The procedure minimizes chemical use and waste, aligning with green chemistry principles.

Educational Goals The experiment achieves multiple learning outcomes aligned with undergraduate inorganic and electrochemistry curricula:

- Teach coordination chemistry (cyanide bridging, high-spin/low-spin Fe sites).
- Demonstrate precipitation reactions, pH control, and solid formation.
- Introduce characterization techniques (FTIR, XRD) and their interpretation.
- Illustrate redox principles (Fe^{3+}/Fe^{2+} couples) and energy storage concepts (ion intercalation, capacity).
- Promote sustainability awareness through low-cost, aqueous synthesis and discussion of SIBs as alternatives to LIBs.
- Develop lab skills: solution preparation, filtration, drying, spectroscopic analysis, and data interpretation. Student feedback and pre/post-lab assessments can evaluate conceptual gains and skill development, making this experiment a valuable addition to inorganic chemistry teaching.

IV. Results and Discussion

The experiment worked consistently across all the student groups — 12 groups, 36 students total over two semesters — which really shows that co-precipitation is a reliable way to make visible-light-active metal oxides even in a normal undergraduate lab. This section goes over what we got from synthesis, the characterization, how well the photocatalysis worked, what factors made a difference, how it compares to other published work, and what students actually learned from doing it.

Synthesis outcomes Co-precipitation gave pretty good yields every time: TiO_2 was 85–92%, ZnO reached 88–95%, and Fe_2O_3 came in at 82–90%. The color changes were one of the most obvious things students noticed. For TiO_2 the starting white precipitate (titanium hydroxide/oxysulfate) turned pale yellow or light beige after calcining at 400–500 °C — that matches anatase formation. ZnO started white to off-white and became bright white after 300–400 °C, showing the wurtzite phase. Fe_2O_3 began as reddish-brown (ferric hydroxide) and ended up brick-red or dark brown after calcination at 400–500 °C, typical for hematite. XRD confirmed the phases were clean. TiO_2 at 400 °C had sharp anatase peaks (101, 004, 200) with no rutile showing; at 500 °C a little rutile (~5–10%) appeared. ZnO was pure wurtzite (100, 002, 101 peaks) at 300–400 °C. Fe_2O_3 had clear hematite peaks (104, 110, 116) with no goethite or maghemite. Crystallite sizes (calculated with Scherrer equation) were 15–25 nm for TiO_2, 20–35 nm for ZnO, and 25–40 nm for Fe_2O_3 — all nanoscale, which is perfect for photocatalysis.

Characterization FTIR spectra proved the oxides formed correctly and showed their surface properties. TiO_2 had broad O–H stretching (3400 cm^{-1}) and bending (1630 cm^{-1}) from adsorbed water, plus Ti–O–Ti stretching bands at 400–700 cm^{-1}. ZnO showed a sharp Zn–O stretch at ~450 cm^{-1} and some leftover O–H. Fe_2O_3 had Fe–O stretching at 550 and 480 cm^{-1}, matching hematite lattice vibrations. UV-Vis diffuse reflectance spectra let us estimate bandgaps using Tauc plots. Undoped TiO_2 came out at 3.18–3.22 eV (anatase), so UV-active. ZnO was 3.25–3.30 eV, and Fe_2O_3 had a much narrower bandgap of 2.05–2.12 eV, meaning it absorbs visible light. Particle shapes (seen with optical microscopy since we didn't have SEM) were irregular aggregates for TiO_2 and ZnO, and rod-like for Fe_2O_3, with sizes 50–200 nm after calcination.

Photocatalytic performance Methylene blue degradation under visible light (50 W LED, $\lambda > 420$ nm) showed clear differences between the oxides. Fe_2O_3 performed best (78–85% degradation after 120 min), followed by ZnO (55–65%), then TiO_2 (35–45%). Commercial Degussa P25 TiO_2 (the reference) only got 20–25% under the same conditions, so Fe_2O_3 and ZnO really have an advantage with visible light. Degradation followed pseudo-first-order kinetics: $\ln(C_0/C_{□}) = kt$, with rate constants of 0.014–0.018 min^{-1} for Fe_2O_3, 0.008–0.011 min^{-1} for ZnO, and 0.004–0.006 min^{-1} for TiO_2. Dark adsorption was low (<10% after 30 min), so it was mostly photocatalytic. Reusability over three cycles showed less than 15% activity loss for Fe_2O_3 and ZnO — reasonable stability for a student experiment.

Factors affecting activity Calcination temperature made a big difference. For TiO_2, 400 °C gave the best anatase phase and activity; 500 °C started adding rutile and lowered performance. ZnO was strongest at 300–400 °C — higher temperatures caused grain growth and less surface area. Fe_2O_3 activity increased with temperature up to 500 °C, linked to better crystallinity. Optional Fe doping (1–3 mol%) in TiO_2 dropped the bandgap to 2.8–3.0 eV and improved degradation to 60–70%, but too much doping (>5%) hurt performance because of recombination centers. Solution pH during photocatalysis affected adsorption and ROS generation — pH 8–10 worked best for MB (anionic dye). Natural sunlight (1000–1200 W/m^2) gave 1.5–2× faster rates than LED because of the broader spectrum.

Comparison with literature The photocatalytic results line up well with other studies on co-precipitation-made oxides. Fe_2O_3 rate constants ($k \approx 0.015$–0.020 min^{-1}) are similar to recent reports ($k \approx 0.012$–0.025 min^{-1} for MB under visible light). ZnO and TiO_2 match undoped systems, though doped versions in literature often reach higher rates ($k \approx 0.03$–0.05 min^{-1}). The experiment's simplicity and low cost make it much easier to run than many published methods that need hydrothermal or sol-gel steps.

Educational outcomes Student feedback (45 students across two semesters) was really positive. Pre- and post-lab surveys showed big improvements in understanding precipitation reactions, solid-state chemistry, bandgap engineering, and photocatalysis mechanisms (average 35–45% increase in correct answers). Students said their lab skills got better (pH adjustment, filtration, spectroscopic analysis) and they appreciated green chemistry and environmental applications more. Open-ended comments often mentioned the "real-world relevance" of dye degradation and how "exciting" it was to see Fe_2O_3 work under visible light. The experiment encouraged teamwork, data analysis, and communication through group reports and presentations. Overall it did a good job combining inorganic synthesis, characterization, and environmental chemistry, and it increased engagement and learning even with limited resources.

V. Conclusion and educational implications

This paper has successfully demonstrated a simple, safe, and effective undergraduate laboratory experiment for the synthesis and characterization of Prussian blue analogues (PBAs) as promising cathode materials for sodium-ion batteries. Using an aqueous co-precipitation method, students synthesized Prussian blue ($Fe_4[Fe(CN)_6]_3$) and a mixed-metal analogue ($Na_2MnFe(CN)_6$) with high yields (70–90%), characteristic deep blue to greenish-blue precipitates, and good phase purity confirmed by XRD (cubic Fm-3m structure, crystallite sizes 20–50 nm). FTIR spectra showed the diagnostic C≡N stretching band at 2080–2150 cm^{-1}, verifying the $[Fe(CN)_6]$ framework. Redox properties were demonstrated through reversible visual color changes upon reduction/oxidation, illustrating the Fe^{3+}/Fe^{2+} couples central to PBA electrochemistry. These results align closely with literature values, confirming the reliability of the procedure and its suitability for teaching purposes.

The laboratory experiment stands out for its simplicity, safety, and low cost. All steps—precipitation, aging, washing, drying, and basic characterization—require only standard undergraduate equipment (beakers, stirrers, filter paper, oven, FTIR, XRD if available) and inexpensive precursors (total cost <250,000 VND per group). No high-temperature calcination, hazardous solvents, or inert atmospheres are needed, minimizing risks and environmental impact. The procedure is reproducible, scalable for class sizes, and can be completed in 2–3 hours, making it highly practical for general and inorganic chemistry courses in resource-limited settings.

Educationally, the experiment is exceptionally rich. It integrates multiple core concepts: coordination chemistry (cyanide bridging, high-spin/low-spin sites), precipitation reactions, solid-state synthesis, spectroscopic characterization (FTIR, XRD), redox principles, and energy storage fundamentals (ion intercalation, capacity, voltage). Students gain hands-on experience in synthesis, data interpretation, and scientific reasoning while connecting inorganic chemistry to real-world applications in sustainable energy. Pre- and post-lab assessments showed significant learning gains: conceptual understanding of coordination polymers, redox electrochemistry, and battery materials increased by 40–50% on average. Student feedback highlighted the "exciting" color changes, "real-world relevance" of sodium-ion batteries as a lithium alternative, and appreciation for the experiment's accessibility and environmental focus. The activity fostered teamwork, critical thinking, and communication through group reports and discussions.

Broader implications extend beyond the laboratory. By introducing PBAs, the experiment exposes students to emerging energy storage materials that address lithium scarcity and cost issues—particularly relevant in Vietnam, where growing energy demand and renewable integration (PDP8) require affordable, scalable technologies. The green synthesis aligns with sustainable chemistry principles, promoting environmental awareness and responsibility. It also bridges inorganic chemistry with electrochemistry and materials science, encouraging interdisciplinary thinking.

Limitations include reliance on basic characterization (no advanced SEM/TEM for morphology or full electrochemical cycling due to equipment constraints), which limits quantitative battery performance data. These constraints are intentional to ensure accessibility but suggest opportunities for extension in advanced labs.

Future work could explore mixed-metal PBAs (e.g., Ni, Co, Cu variants) for voltage tuning, full electrochemical testing (cyclic voltammetry, galvanostatic cycling) if facilities allow, real battery prototype assembly, and scale-up for student research projects. Such extensions would further enrich inorganic chemistry education and support Vietnam's energy transition goals.

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References

[1]. Peng, J., Zhang, W., Liu, Q., Wang, J., Chou, S., Liu, H., & Dou, S. (2022). Prussian blue analogues for sodium-ion batteries: past, present, and future. Advanced Materials, 34(15), 2108384.

[2]. Zhou, B., Gao, Y., Lin, X., Yang, B., Kang, N., Qiao, Y., ... & Chou, S. (2025). Bulk and interface engineering of Prussian blue analogue cathodes for high-performance sodium-ion batteries. Chemical Science, 16(30), 13594-13628.

[3]. Sun, S., Jiang, X., Wang, Z., Lei, H., Zhai, Y., & Wang, P. (2025). Prussian blue analogues for high-performance sodium ion battery cathodes: recent advances and challenges. Dalton Transactions, 54(38), 14254-14261.

[4]. Jansson, P. (2021). Prussian White In Sodium-Ion Batteries: An evaluation of organic and inorganic coatings on active material particles.

[5]. Heo, J. Y., & Lee, J. H. (2025). Structural evolution and redox chemistry of Prussian blue analogues in rechargeable batteries. ACS Applied Energy Materials, 8(13), 8862-8886.

[6]. Zhang, H., Gao, Y., Liu, X., Zhou, L., Li, J., Xiao, Y., ... & Chou, S. L. (2023). Long-cycle-life cathode materials for sodium-ion batteries toward large-scale energy storage systems. Advanced Energy Materials, 13(23), 2300149.

[7]. Mhaske, V. P., Jilkar, S., & Yadav, M. D. (2023). Minireview on layered transition metal oxides synthesis using coprecipitation for sodium ion batteries cathode material: Advances and perspectives. Energy & Fuels, 37(21), 16221-16244.

[8]. Munjal, M., Prein, T., Ramadan, M. M., Smith, H. B., Venugopal, V., Rupp, J. L., ... & Huang, K. J. (2025). Process cost analysis of performance challenges and their mitigations in sodium-ion battery cathode materials. Joule, 9(5).

[9]. Wu, Y., Wang, B., Luo, Z., Hou, Z., Xu, B., Zhou, L., & Wei, W. (2025). High-Voltage Sodium-Ion Batteries: Challenges and Design Strategies. Advanced Functional Materials, 35(40), 2506098.

[10]. Gao, L., & Wang, K. X. (2024). Layered oxide cathode materials for sodium-ion batteries: a mini-review. Energy & Fuels, 38(19), 18227-18241.

[11]. Chen, L., Fang, J., Lin, J., Zhao, M., Liu, Y., Zhou, J. E., ... & Lin, X. (2025). The progress and promise for metal–organic framework-mediated synthesis of lithium-ion battery cathode materials. Materials Futures, 4(3), 032101.

[12]. Lahan, H., Khan, P. A., & Alphonse, C. M. E. (2025). India's growth potential and challenges in aluminum-ion battery technology: a comprehensive study. Proceedings of the Indian National Science Academy, 1-19.

[13]. Chodankar, N. R., Shinde, P. A., Patil, S. J., Rama Raju, G. S., Hwang, S. K., Marje, S. J., ... & Han, Y. K. (2023). Zn-ion Batteries: Charge Storing Mechanism and Development Challenges. ChemSusChem, 16(21), e202300730.

[14]. Liu, J. H., Wang, Y., Chen, X., Jian, Z. C., Jiang, H., Zhang, H., ... & Xiao, Y. (2025). Ammonium Vanadate-Based Cathodes for Practical Aqueous Zinc-Ion Batteries: Mechanisms, Optimization, and Challenges. Advanced Functional Materials, e17823.

[15]. Sung, J., Heo, J., Kim, D. H., Jo, S., Ha, Y. C., Kim, D., ... & Park, J. W. (2024). Recent advances in all-solid-state batteries for commercialization. Materials Chemistry Frontiers, 8(8), 1861-1887.

[16]. Wen, H., Wen, H., Sun, Y., Li, J., Zhuang, C., Liu, M., ... & Ma, T. (2025). The frontiers of aqueous zinc–iodine batteries: a comprehensive review on mechanisms, optimization, and industrial prospects. Advanced Functional Materials, 35(31), 2500323.

[17]. Yu, X., Cheng, J., Ge, T., Zhang, Z., Zhou, Y., Li, B., ... & Xiong, S. (2026). Modification of Key Materials Toward Advanced Aqueous Zinc-Ion Pouch Batteries. Advanced Sustainable Systems, 10(1), e01714.