ESTA JOURNAL
Energy Storage Technology and Applications
Article
jurnal.uns.ac.id/esta

Prussian Blue Pigment (Blue) Based on Iron(III) Chloride ($FeCl_3$)

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doi: https://dx.doi.org/10.20961/esta.v3i2.109544
Received: 03-10-2025; Revised: 19-03-2026; Accepted: 30-03-2026; Published: 01-04-2026

ABSTRACT: Prussian Blue (PB), or ferric ferrocyanide, is a multifunctional material with long-standing applications in the coating industry and emerging potential as a high-performance cathode material for energy storage systems. This study investigates the synthesis of PB pigment from iron(III) chloride ($FeCl_3$) and potassium ferrocyanide ($K_4[Fe(CN)_6]$) using the coprecipitation method, which is favored for its operational simplicity and low-temperature requirements. Beyond its conventional use as a colorant in paints and inks, the electrochemical properties of Prussian Blue Analogues (PBA) are discussed, particularly their open-framework crystal structure that facilitates reversible alkali-ion intercalation. To address the requirement for industrial scalability, this research evaluates strategies to optimize product yield through stoichiometric control and pH regulation. Furthermore, the potential utilization of sustainable iron precursors, such as iron sand and industrial metal waste, is explored to enhance the economic viability of the process. The results demonstrate that the $FeCl_3$-based synthesis route provides a robust pathway for producing both high-quality pigments and functional materials for next-generation battery applications.

Keywords: Adsorption, Energy Storage, Iron (III) Chloride, Prussian Blue, Yield Optimization.

1. INTRODUCTION

Pigments represent fundamental components within the industrial sector, serving as indispensable colorants and protective agents in paints, inks, and various coating systems [1]. Among the diverse array of synthetic pigments, Prussian Blue (PB)—chemically identified as ferric ferrocyanide ($Fe_4[Fe(CN)_6]_3$)—has sustained intense research interest due to its profound blue hue, exceptional opacity, and robust chemical stability. Traditionally, PB synthesis is achieved through the reaction between iron salts and cyanide complexes, with co-precipitation and hydrothermal routes being the most prevalent methodologies [2]. The co-precipitation method, in particular, offers distinct advantages, including operational simplicity, low energy requirements, and the ability to synthesize fine particles at ambient temperatures, making it highly feasible for

large-scale industrial manufacturing. Furthermore, the exploration of both synthetic and natural pigments continues to expand, enriching the functional diversity of colorants across multiple industrial domains [4].

However, the contemporary significance of Prussian Blue has transcended its conventional application as a pigment. In recent years, the global imperative for sustainable energy storage solutions has propelled Prussian Blue Analogues (PBAs) into the scientific spotlight as promising cathode materials for next-generation batteries, specifically Sodium-Ion Batteries (SIBs) and Potassium-Ion Batteries (KIBs) [5], [9]. The unique open-framework crystal structure of PB, characterized by a face-centered cubic (FCC) lattice with expansive interstitial sites, facilitates the rapid and reversible intercalation and extraction of alkali ions with minimal structural strain [10]. The utilization of PBAs in secondary battery technology is regarded as a strategic solution to mitigate the scarcity of lithium resources and the escalating costs of battery production [8]. Despite this immense potential, many studies remain narrowly focused on the pigmentary attributes of PB, often disregarding the critical nexus between synthesis parameters, product yield, and electrochemical performance.

A significant hurdle in the commercialization of PB-based materials lies in optimizing the production process to ensure high yield and purity while maintaining economic viability. The selection of iron precursors is a pivotal factor; while analytical-grade Iron(III) Chloride ($FeCl_3$) is standard in laboratory environments, there is an urgent need to investigate more sustainable and localized iron sources. In Indonesia, the abundance of iron sand along coastal regions offers a potent alternative precursor following necessary purification processes [3], [6]. Utilizing iron sand or industrial metal waste not only reduces raw material costs but also aligns with the principles of the circular economy and green manufacturing [7].

Beyond precursor selection, the optimization of physicochemical parameters during co-precipitation is decisive for the final product quality. Variables such as stoichiometric ratios, pH regulation, and aging time directly influence particle size distribution and the formation of a perfect crystalline phase. Low yields often present a primary obstacle in transitioning from laboratory-scale experiments to industrial implementation. Consequently, rigorous research into yield enhancement strategies is essential to ensure the feasibility of mass-producing PBAs.

This research aims to bridge these gaps by investigating the synthesis of Prussian Blue using $FeCl_3$ as the primary precursor through an optimized co-precipitation route. This study not only evaluates the physical characteristics of the synthesized pigment but also provides a comprehensive discussion on strategies to improve product yield and the strategic potential of the material as a PBA cathode for energy storage applications. By integrating technical optimization with an analysis of sustainable iron sources, this work contributes to a more versatile and eco-friendly framework for Prussian Blue production within the Indonesian industrial landscape.

2. MATERIALS AND METHODS

2.1 Materials and Equipments

The primary precursors utilized in this research were analytical-grade Iron (III) Chloride hexahydrate ($FeCl_3 \bullet 6H_2O$) as the source of iron cations and Potassium Ferrocyanide trihydrate ($K_4[Fe(CN)_6] \bullet 3H_2O$) as the cyanide

complexing agent. Distilled water was employed as the universal solvent for all synthesis and washing procedures. Additionally, 0.1 M Hydrochloric Acid (HCl) and 0.1 M Sodium Hydroxide (NaOH) solutions were prepared for precise pH regulation during the precipitation process.

The laboratory equipment included a digital magnetic stirrer with a heating element for homogeneous agitation, an analytical balance with a precision of 0.0001 g, Whatman No. 42 filter paper, a vacuum filtration system, a drying oven, and a mortar and pestle for pigment homogenization.

2.2 Methodology

Prussian Blue was synthesized via the co-precipitation method at ambient temperature. The procedure commenced by dissolving specific masses of $FeCl_3$ and $K_4[Fe(CN)_6]$ in distilled water to achieve the desired molar concentrations. To implement the yield optimization strategy, the stoichiometric ratio of Fe^{3+} to $[Fe(CN)_6]^{4-}$ was maintained at a precise molar ratio of 1:1:1 to ensure exhaustive complex formation.

The $FeCl_3$ solution was added dropwise into the $K_4[Fe(CN)_6]$ solution under constant stirring at 500 rpm. Throughout the mixing phase, the solution pH was strictly monitored and maintained within the acidic range (pH 2–3) using HCl to inhibit iron hydrolysis and the subsequent formation of hydroxide impurities. The mixture was then stirred for an additional 60 min to facilitate the aging phase, which is critical for optimal nucleation and crystal lattice development.

The resulting blue precipitate was isolated using vacuum filtration. The solid was washed repeatedly with distilled water and ethanol to remove residual chloride and potassium ions. This purification process continued until the filtrate reached a neutral pH. The wet precipitate was then dried in an oven at a constant temperature of 70 °C for 24 hours to eliminate interstitial water content while preserving the structural integrity of the crystal. The final dried product was ground into a fine powder.

The synthesized product was characterized through moisture content analysis and quantitative yield determination. The yield was calculated to evaluate the process efficiency using Equation (1):

$$Yield(\%) = \left(\frac{w_{actual}}{w_{theoretical}}\right) \times 100\% \quad (1)$$

Where w_{actual} represents the weight of the dried pigment obtained experimentally, and $w_{theoretical}$ is the theoretical weight calculated based on stoichiometric reaction laws. The pigment's optical quality was visually evaluated and compared against commercial Prussian Blue standards.

3. RESULTS AND DISCUSSION

The synthesis of Prussian Blue pigment was conducted through four experimental trials, yielding varying weights of blue precipitate: 6.08 g, 7.40 g, 9.60 g, and 11.38 g. The resulting conversions for these experiments ranged from 6.90% to 10.19%, with the highest conversion of 10.19% achieved in the fourth trial. While the co-precipitation method is favored for its simplicity and low energy requirements, these results indicate that further process optimization is necessary to achieve higher industrial efficiency. Table 1 presents a summary of the results from four Prussian Blue synthesis experiments showing variations in product weight and conversion percentage.

Table 1. The results from four Prussian Blue synthesis experiments

No.	Pigment Weight (grams)	Yield (gram pigment/gram $FeCl_3$)	Conversion (%)
1	6.08	0.225	7.50
2	7.40	0.273	7.62
3	9.06	0.858	6.90
4	11.38	0.855	10.19

Figure 1. The physical form of the blue pigment (Prussian Blue) that has been produced

To improve these yields for industrial applications, the following strategies are proposed:

1. Precise pH Regulation

While the current study notes that an acidic pH is optimal for pigment production, strict maintenance of the pH within the 2–3 range can further suppress the formation of competitive iron hydroxide species.

2. Stirring and Nucleation

Increasing the stirring time beyond the 30 minutes used in this study can facilitate more frequent molecular collisions, leading to larger crystal aggregates that are more easily recovered during filtration. Figure 2 illustrates the crucial steps in the co-precipitation method, namely stirring and heating the solution using a magnetic stirrer. This visually demonstrated process is the main determining factor for the yield figures in Table 1. Stirring serves to create collisions between the precursor molecules $FeCl_3$ and $K_4[Fe(CN)_6]$ to increase the chance of a chemical reaction occurring, while heating at a temperature of 60 °C is carried out to accelerate the reaction rate. If the stirring and temperature parameters in Figure 2 are not optimized, the resulting conversion values in Table 1 will tend to be low.

Figure 2. Stirring and heating the solution using a magnetic stirrer

3. Stoichiometric Ratio Control

Maintaining a precise molar ratio between the iron precursor and the cyanide complex is crucial to drive the reaction equilibrium toward the formation of the insoluble blue complex.

The physical properties of the produced pigment were evaluated by drying the precipitate in an oven at temperatures ranging from 80 °C to 120 °C until a constant weight was achieved. This process is vital for determining the moisture content, which directly impacts the pigment's stability and covering power in paint applications. In the context of energy storage, controlling this moisture is even more critical. Interstitial water trapped within the Prussian Blue framework can hinder ion diffusion and trigger unwanted side reactions within battery electrolytes.

The current study utilizes analytical-grade Iron(III) Chloride ($FeCl_3$) as the primary iron source. However, the high iron content found in localized resources, such as natural iron sand and industrial metal lathe waste, presents a significant opportunity for sustainable production. Utilizing these alternative precursors

aligns with green chemistry principles by reducing raw material costs and supporting a circular economy. Transitioning to these sustainable sources would enhance the economic viability of Prussian Blue production for both the coating industry and the energy sector.

The synthesized Prussian Blue possesses superior characteristics such as high chemical stability and non-toxicity, which are essential for its emerging role as a cathode material for energy storage systems. The open-framework crystal structure of Prussian Blue Analogues (PBAs) allows for the rapid and reversible intercalation of ions, such as Sodium (Na^+), making them ideal for next-generation battery technologies. Leveraging the co-precipitation method developed in this research provides a robust and low-energy pathway to produce functional materials that can meet the growing demand for sustainable battery components.

4. CONCLUSION

This study successfully demonstrated the synthesis of Prussian Blue pigment through a low-temperature co-precipitation method utilizing Iron(III) Chloride ($FeCl_3$) and Potassium Ferrocyanide ($K_4[Fe(CN)_6]$). The experimental data revealed that the process efficiency is highly sensitive to reaction conditions, with the highest conversion of 10.19% achieved in the fourth trial. While the synthesized material exhibits the characteristic deep blue hue required for industrial coating applications, its strategic value extends significantly into the field of electrochemical energy storage. The open-framework face-centered cubic (FCC) lattice of the synthesized Prussian Blue provides an ideal structural platform for the reversible intercalation of alkali ions, positioning it as a promising cathode material for next-generation sodium-ion batteries.

To enhance the industrial viability and scalability of this synthesis route, this research identifies that yield optimization can be effectively realized through precise pH regulation within the acidic range (pH 2–3), extended aging periods to facilitate complete nucleation, and stoichiometric adjustments. Furthermore, the transition toward utilizing sustainable iron precursors, such as localized iron sand and recycled industrial metal waste, offers a cost-effective and eco-friendly pathway that aligns with the principles of the circular economy. In summary, the optimized production of Prussian Blue serves as a versatile framework that bridges the gap between traditional pigment manufacturing and the advancing requirements of functional materials for sustainable energy systems.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the Chemical Engineering Department, Vocational School, Universitas Sebelas Maret, for providing the laboratory facilities and technical resources necessary to conduct this research. Special appreciation is extended to Mrs. Himmah Sekar Eka Ayu Gustiana, S.T., M.Eng., for her invaluable guidance, mentorship, and constructive feedback throughout the experimental and manuscript preparation stages. The authors also acknowledge the Centre of Excellence for Electrical Energy Storage Technology (PUI-PT Baterai Lithium UNS) for its academic support and for providing insights into the strategic application of Prussian Blue in battery technology. Finally, thanks are due to all colleagues and laboratory assistants who contributed to the successful completion of this study.

AUTHOR CONTRIBUTION

Conceptualization, D.A. and F.K.; methodology, R.D.; software, Y. and D.A.; validation, F.K. and R.D.; formal analysis, Y.; investigation, D.A.; resources, F.K.; data curation, D.A. and Y.; writing—original draft preparation, Y.; writing—review and editing, D.A. and F.K.; visualization, R.D.; supervision, H.S.E.A. All authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] F. A. Novial, J. B. W. R., and J. R. J. RPA, "Preliminary Design of Red Pigment Factory by Precipitation Method," J. Fundam. Appl. Chem. Eng., vol. 2, no. 1, 2021.

[2] A. K. Futhri, D. S. Asep, and S. Asep, "Synthesis and Characteristics of Iron (III) Oxide Red Pigment from Metal Lathe Waste Iron Powder," Chem. J., vol. 4, no. 1, 2019.

[3] M. Wahyuni and S. Aini, "Synthesis of Prussian Blue ($Fe_4[Fe(CN)_6]_3$) Dye Using Natural Iron Sand," Periodic, vol. 10, no. 1, pp. 73–76, 2021.

[4] M. Zulfikar, E. Kusdiantini, and S. Nurjannah, "Identification of Pigment Types and Antioxidant Potential Test of Rhodococcus sp Bacterial Pigment Extract Isolated from Gedong Songo Hot Spring Sediment," 2019.

[5] L. Wang, J. Song, R. Qiao, L. A. Wray, and M. A. Hossain, "Rhombic Prussian Blue as High-Capacity Cathode for Sodium-Ion Batteries," J. Am. Chem. Soc., vol. 137, no. 7, pp. 2548–2554, 2015.

[6] S. B. Abd Hamid, T. L. Tan, and C. W. Lai, "Green synthesis of iron oxide nanoparticles from iron sand: A review on its applications," Mater. Today Proc., vol. 31, pp. 182-189, 2020.

[7] X. Wu et al., "Highly crystallized Prussian blue with low defects as a super-long life cathode for sodium-ion batteries," Nano Energy, vol. 13, pp. 117-124, 2015.

[8] Y. Liu et al., "Prussian blue analogues for rechargeable batteries: Progress and prospects," Coord. Chem. Rev., vol. 427, p. 213567, 2021.

[9] J. B. Goodenough, "Sodium-ion batteries: A new energy storage system," Chem. Commun., vol. 50, no. 23, pp. 2968-2975, 2014.

[10] D. Asakura et al., "Fabrication of Prussian Blue Nanoparticles for Battery Applications," Nanoscale, vol. 4, no. 20, pp. 6485-6491, 2012.