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Electrochemical Performance of BFO–Br GO Composite for Advanced Sodium-Ion Battery Applications

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ABSTRACT

In the pursuit of efficient and sustainable energy storage systems, sodium-ion batteries (SIBs) have emerged as a promising alternative to lithium- ion batteries due to sodium's abundance and cost-effectiveness. This study focuses on the development and evaluation of a bismuth ferrite–boron-doped reduced graphene oxide (BFO–BrGO) composite as an advanced anode material for SIBs. The BFO–BrGO composite was synthesized using a hydrothermal method followed by thermal reduction, resulting in a nanostructured material with enhanced conductivity and electrochemical activity. Structural analysis confirmed the successful integration of BFO nanoparticles within the wrinkled BrGO sheets, promoting effective electron and ion transport pathways. Electrochemical testing revealed that the BFO–BrGO composite exhibits superior performance compared to pristine BFO and BrGO, delivering a high specific capacity, excellent cycling stability, and improved rate capability. These results demonstrate the composite's potential as a high-performance anode material, offering a viable route toward the development of next-generation sodium-ion batteries.

Keywords: Sodium-ion batteries (SIBs), Bismuth ferrite (BFO), Boron-doped reduced graphene oxide (BrGO) BFO–BrGO composite, Anode material

1. INTRODUCTION

A battery is a device that converts chemical energy contained within its active materials directly into electric energy by means of an electrochemical oxidation-reduction (redox) reaction. This type of reaction involves the transfer of electrons from one material to another via an electric circuit.

1.1 Aluminium-ion Battery

Aluminium-ion batteries (AIB) are a class of rechargeable battery in which aluminium ions serve as charge carriers. Aluminium can exchange three electrons per ion. This means that insertion of one Al^{3+} is equivalent to three Li^{+} ions. Thus, since the ionic radii of Al^{3+} (0.54 Å) and Li^{+} (0.76 Å) are similar, significantly higher numbers of electrons and Al^{3+} ions can be accepted by cathodes with little damage.

Al has 50 times (23.5 megawatt-hours m^{-3}) the energy density of Li-ion batteries **and is even higher than coal.** Rechargeable aluminium-based batteries offer low cost and low flammability, together with high capacity. The inertness and ease of handling of aluminium in an ambient environment offer safety improvements compared with Li-ion batteries. Al-ion batteries can be smaller and may also have more charge-discharge cycles. Thus, Al-ion batteries have the potential to replace Li-ion batteries.

1.2 Magnesium Battery

Magnesium batteries utilize magnesium cations as charge carriers. Both primary and secondary cell chemistries have been investigated. Magnesium has a theoretical energy density under half that of lithium (18.8 MJ/kg vs. 42.3 MJ/kg), but a volumetric energy density around 50% higher.

Magnesium anodes do not exhibit dendrite formation under certain conditions. These batteries are considered candidates for improving lithium-ion technologies in specific applications.

1.3 Sodium-ion battery

Sodium-ion batteries (NIBs, SIBs, or Na-ion batteries) are several types of rechargeable batteries, which use sodium ions (Na^{+}) as their charge carriers. In some cases, its working principle and cell construction are similar to those of lithium-ion battery (LIB) types, but it replaces lithium with sodium as the intercalating ion. Sodium belongs to the same group in the periodic table as lithium and thus has similar chemical properties. However, in some cases, such as aqueous batteries, SIBs can be quite different from LIBs.

Sodium-ion accumulators are operational for fixed electrical grid storage, but vehicles using sodium-ion battery packs are not yet commercially available. However, CATL, the world's biggest lithium-ion battery manufacturer, announced in 2022 the start of mass production of SIBs. In February 2023, the Chinese Hi Na Battery Technology Company, Ltd. placed a 140 W h/kg sodium-ion battery in an electric test car for the first time, and energy storage.

1.4 Electrochemical Performance of BFO–Brgo Composite for Advanced Sodium-Ion Battery Applications

The electrochemical performance study of BFO-BrGO (Bismuth Ferrite–Brominated Reduced Graphene Oxide) as an anode material in sodium-ion batteries reveals promising results in terms of capacity, stability, and efficiency. BFO, known for its high theoretical capacity, combined with BrGO, which offers excellent conductivity and structural support, forms a composite that enhances sodium storage capabilities.

During charge-discharge tests, the BFO-BrGO electrode exhibits high initial specific capacity with good voltage profiles, indicating efficient Na^+ ion intercalation and deintercalation processes. The composite shows stable cycling performance, retaining a significant portion of its capacity over extended cycles, and maintains a coulombic efficiency close to 100%, demonstrating reversible electrochemical reactions.

The BrGO component plays a crucial role in buffering volume changes and maintaining electrode integrity, which helps improve the cyclability. Moreover, electrochemical impedance spectroscopy (EIS) typically indicates reduced charge transfer resistance in the composite, further confirming improved ion transport and electrical conductivity. These results suggest that BFO-BrGO is a strong candidate for advanced sodium-ion battery applications, offering a balance of high capacity, long-term stability, and efficient charge transport Zhang, X., et al. (2020).

1.The synthesis diagram for the fabrication of electrodes for the NIB.

2. EXPERIMENTAL SECTION

2.1 Introduction of BFO

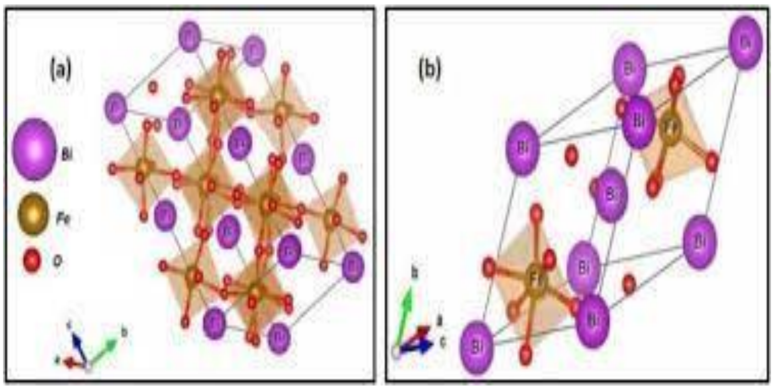
Bismuth Ferrite (BFO), with the chemical formula $BiFeO_3$, is a prominent multiferroic material that has attracted significant interest in recent years due to its unique combination of ferroelectric and magnetic properties at room temperature. As one of the few single-phase multiferroics, BFO exhibits both ferroelectricity and antiferromagnetism simultaneously, making it a prime candidate for applications in spintronics, memory devices, sensors, and photovoltaics.

BFO crystallizes in a distorted perovskite structure with a rhombohedral unit cell (space group R3c), which is responsible for its intrinsic ferroelectric behaviour. The ferroelectric Curie temperature of BFO is around 1100 K, while the Néel temperature (the temperature above which it loses its antiferromagnetic order) is about 643 K. These high transition temperatures enable its functionality well above room temperature, which is a significant advantage over other multiferroic materials.

The multiferroic nature of BFO arises from the stereochemically active $6s^2$ lone pair of Bi^{3+} ions, which contributes to the off-centre displacement and spontaneous polarization, while the Fe^{3+} ions are responsible for the magnetic ordering. Moreover, BFO is known to exhibit strong magnetoelectric coupling, which means that its magnetic properties can be tuned by applying an electric field and vice versa. Liu, K., Fan, H., Ren, P. and Yang, C., 2011.

Despite its promising characteristics, BFO faces several challenges, such as leakage current, phase instability, and difficulty in synthesizing phase-pure materials. Various synthesis techniques, including sol-gel, hydrothermal, solid-state reactions, and thin film deposition methods, have been explored to improve its structural, electrical, and magnetic properties.

In summary, Bismuth Ferrite is a multifunctional material with remarkable physical properties, making it an exciting subject of study in the field of materials science and condensed matter physics. Its continued research holds promise for next-generation multifunctional devices and energy applications. 3.Man, X., Min, X., Yan, Y., Gong, H., Dai, Y., Li, T., Xiao, P., Sun, Y., Yin, L. and Wang, R., 2025.



1 BFO Structure

2.2 Fabrication of BFO-BrGO Electrode

Step 1: Weigh components

Measure the materials in a weigh ratio of 80:10:10 for BFO-BrGO.

Fig 1Bfo-BrGo

Fig 2 pvdf

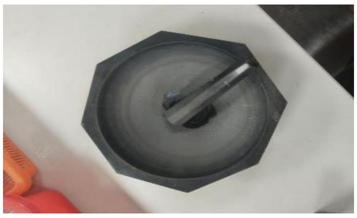
Fig 3 carbonblack

Step 1: Weighing Components

To take measure the components, the materials in a weigh ratio of 80:10:10 BFO-BrGO.

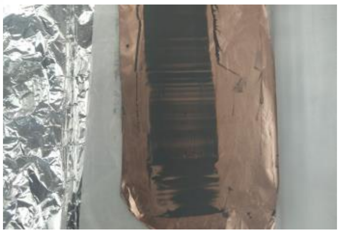
Step 2: Mixing

Combine the materials in an agate mortar to ensure the uniform distribution.
Add the NMP solution to this mixture, continuously 30–60 mins slurry is obtained.



Step 3: Coating

Clean the copper foil using ethanol and dry it removes any contaminates.
Using the doctor blade uniformly spread the slurry onto foil archive the desired thickness.



Step 4: Drying
Place the coated foil in vacuum oven and dry at 60–80°C for 12–24 hrs to remove the solvent completely.

Step 5: Cutting electrode
Cut the electrode into size and shape suitable for electrochemical cell configuration.

3. COIN CELL ASSEMBLY

3.1 Introduction

Coin cell assembly is a crucial step in the development and evaluation of electrochemical energy storage devices, such as lithium-ion batteries and supercapacitors. Coin cells—also known as button cells—are small, compact electrochemical cells used widely in research laboratories for testing electrode materials and electrolyte systems. Their design mimics commercial battery configurations but on a smaller scale, making them ideal for material screening and fundamental electrochemical studies.

A standard coin cell comprises two electrodes (anode and cathode), a separator, and an electrolyte, all enclosed in a metal casing. The coin cell design allows for precise control over component arrangement, uniform pressure application, and minimized contamination—factors essential for obtaining reproducible and reliable electrochemical data.

Coin cell assembly typically takes place in a dry environment, such as an argon-filled glove box, to prevent moisture and oxygen from interfering with sensitive battery materials. The process involves preparing the electrodes (coating, drying, punching), assembling the cell with correct component alignment, and crimping it into a sealed unit.

Researchers use coin cells to perform electrochemical tests like cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS). The data from these tests help assess parameters such as specific capacity, cycling stability, energy density, and internal resistance, thereby guiding the optimization of new battery materials and configurations.

In summary, coin cell assembly provides a standardized and practical method to evaluate the performance of novel battery materials in a controlled and reproducible manner, serving as a bridge between material discovery and commercial battery development.

3.2 Assembly the Electrode

Electrode assembly in coin cells is a delicate and systematic process that directly affects the accuracy and reliability of electrochemical measurements. Proper preparation and handling of electrodes, strict control of environmental conditions, and precise stacking of components are essential to ensure high-performance battery research and reproducibility of results.

This image illustrates the structure and working principle of a sodium-ion (Na-ion) coin cell during charge and discharge cycles. It shows the exploded view of the cell components and highlights the movement of sodium ions (Na^+) and electrons (e^-) during operation. Here is a breakdown of the components and processes:

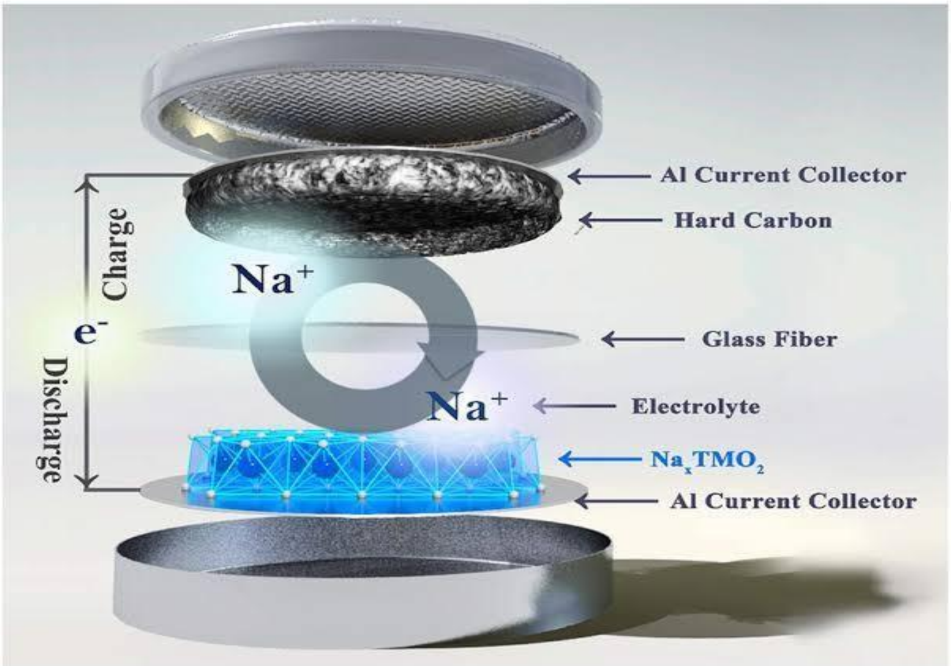


Fig Internal design of the anode coin cell

3.3 Component Breakdown (From Top to Bottom):

1. **Aluminium (Al) Current Collector (Top)**
   o Conductive metal disk that collects electrons from the hard carbon (anode) and connects to the external circuit.

2. **Hard Carbon (Anode)**
   o Serves as the negative electrode where sodium ions are stored (intercalated) during the charging process.
   o During discharge, Na^+ ions are released from this layer and travel to the cathode.

3. **Glass Fiber Separator**
   o A porous, insulating layer that physically separates the anode and cathode.
   o Prevents short circuits while allowing ionic movement of Na^+ through the electrolyte soaked in the separator.

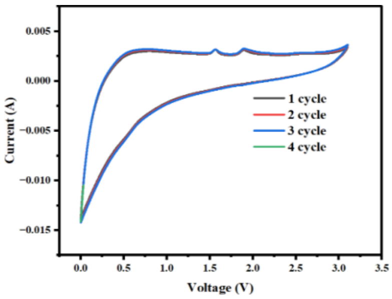
4. **Electrolyte**
   o The medium (typically a sodium salt in an organic solvent) that allows Na^+ ion transport between electrodes.
   o Ensures high ionic conductivity and electrochemical stability.

5. **Aluminium Current Collector (Bottom)**
   o Collects electrons from the cathode and connects to the external circuit during cell operation.

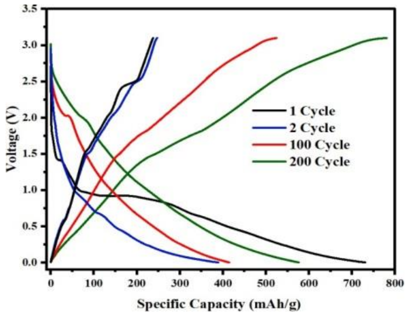
3.4 Working Mechanism: Charge/Discharge

1 **Discharge (Powering a Device):**
o Sodium ions (Na^+) move from the anode (hard carbon) to the cathode (Na_xTMO_2) through the electrolyte.
o Electrons flow through the external circuit, providing electrical energy.

2 **• Charge (Storing Energy):**
o Sodium ions migrate back from the cathode to the anode, where they are stored in the hard carbon.
o Electrons return through the external circuit to balance the charge.



(a) Cyclic Voltammetry of BFO-B-rGO,



(b) Galvanostatic Charge Discharge BFO-B-rGO

3.5 Electrochemical Performance

The BFO-BrGO electrode, a composite of bismuth ferrite (BFO) and brominated reduced graphene oxide (BrGO), exhibits excellent electrochemical performance, making it a promising material for energy storage applications. BFO contributes to high pseudo capacitance through redox reactions involving Bi^{3+} and Fe^{3+} ions, while BrGO enhances electrical conductivity and provides a large surface area for effective ion diffusion.

The synergy between BFO and BrGO improves charge storage capacity and rate capability, allowing the electrode to deliver high specific capacitance and fast charge-discharge responses. Additionally, the composite structure maintains stability during repeated cycles, offering long cycle life and consistent performance.

Electrochemical tests such as cyclic voltammetry (CV) typically reveal clear redox peaks, indicating good reversibility, while galvanostatic charge-discharge (GCD) curves show symmetrical shapes, confirming efficient energy storage behaviour. Electrochemical impedance spectroscopy (EIS) further demonstrates low charge-transfer resistance, thanks to the conductive BrGO network.

Overall, the BFO-BrGO electrode combines the benefits of both components to achieve enhanced electrochemical performance, making it suitable for use in advanced supercapacitors and hybrid energy storage devices.

The electrochemical performance of the BFO–B–rGO composite was systematically evaluated using cyclic voltammetry (CV) shown in Fig 15 (a) and galvanostatic charge–discharge (GCD) techniques shown in Fig 15 (b). The CV profiles recorded at a scan rate of 100 mV/s reveal quasi-rectangular shapes with broad redox peaks, indicative of a synergistic combination of electric double-layer capacitance and pseudocapacitive behaviour.

The presence of these redox features confirms the contribution of faradaic reactions, likely associated with the Bi^{3+}/Bi^{0} and Fe^{3+}/Fe^{2+} redox couples within the bismuth ferrite framework. Additionally, boron doping and the reduced graphene oxide (rGO) network introduce additional electrochemically active sites and enhance electronic conductivity, leading to an overall increase in redox activity. The CV curves across multiple cycles are nearly overlapping, suggesting excellent reversibility and electrochemical stability of the composite Soam, A., Kumar, R., Singh, M., Thatoi, D. and Dusane, R.O., 2020.

Complementary to the CV results, the GCD measurements further validate the composite's robust sodium-ion storage behaviour. The charge–discharge curves for the 1st, 2nd, 100th, and 200th cycles show distinct voltage plateaus, which are characteristic of redox reactions occurring during the sodiation and desodiation processes.

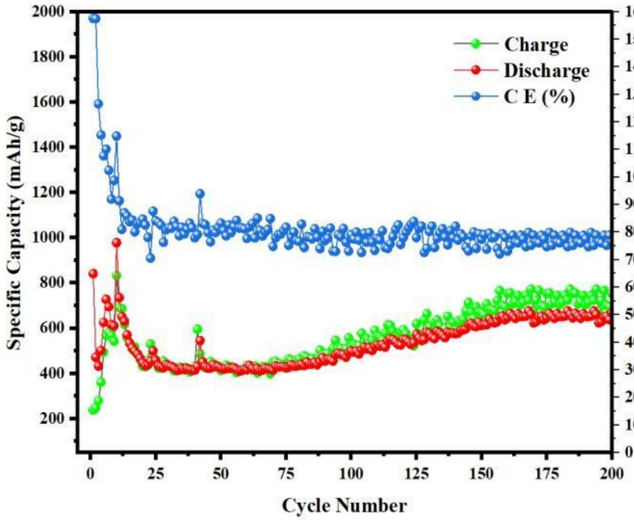
The initial discharge cycle shows a higher capacity due to the formation of the solid electrolyte interphase (SEI) and other irreversible reactions, but subsequent cycles exhibit improved coulombic efficiency and stable voltage profiles. Notably, the GCD curves remain consistent over 200 cycles, highlighting the material's excellent cyclic stability and ability to retain capacity during prolonged operation. The specific capacity remains high, which can be attributed to the synergistic effect of the BFO matrix and the conductive boron-doped rGO network 6. Akbar, S., Irshad, A., Zulfiqar, S., AlOthman, Z.A., Shakir, I., Warsi, M.F. and Cochran, E.W., 2024.

The correlation between the CV and GCD results is evident. The broad anodic and cathodic peaks observed in CV align with the voltage plateaus seen in GCD, indicating that the redox reactions identified through CV are directly contributing to the capacity observed during charge–discharge testing. Furthermore, the area under the CV curves corresponds to the specific capacity obtained from GCD, reaffirming the composite's efficient Na^{+} storage mechanism. The minor hysteresis in the GCD profiles and the stable CV loops across cycles further emphasize the high reversibility of the electrochemical reactions involved Zhang, Y., Qin, J., Batmunkh, M. and Zhong, Y.L., 2021.

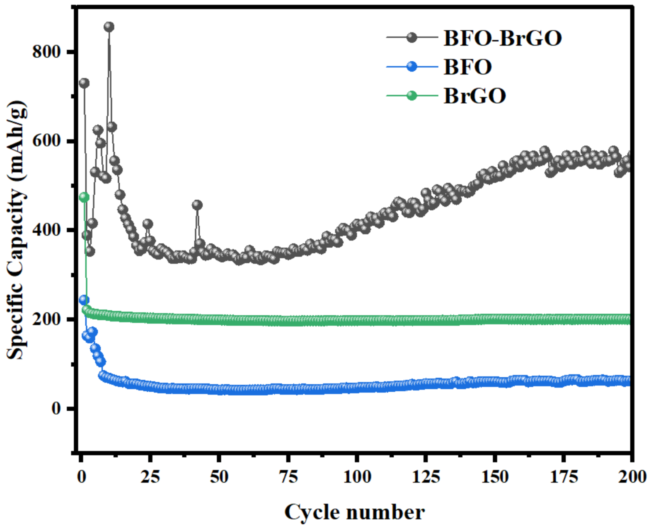
Overall, the BFO–B–rGO composite demonstrates a well-balanced combination of pseudocapacitive and faradaic charge storage mechanisms, enhanced by the conductive rGO network and boron-induced structural defects. These features collectively facilitate fast electron transport, provide abundant active sites, and support stable Na^{+} insertion/extraction processes. As a result, the composite exhibits promising potential as an anode material for high-performance sodium-ion batteries, capable of delivering both high capacity and excellent long-term stability Ding, X. and Liu, Y., 2020.

The cycling performance graphs demonstrate the electrochemical behaviour of electrode materials over 200 cycles. In the first graph Fig 16 (a), the specific capacity and coulombic efficiency (CE%) are plotted for charge and discharge processes. Initially, the electrode exhibits a very high discharge capacity of approximately 950 mAh/g at 200 mA/g current density, which rapidly declines due to irreversible capacity loss, likely caused by solid electrolyte interphase (SEI) formation and side reactions.

After about 50 cycles, both the charge and discharge capacities stabilize and begin to gradually increase, reaching around 550–600 mAh/g by the 200th cycle. This capacity recovery suggests structural activation and improved electrode kinetics over cycling. Meanwhile, the coulombic efficiency initially fluctuates, even exceeding 100%, which is often due to parasitic reactions or measurement artifacts, but eventually stabilizes at around 80%, indicating improved charge reversibility and cycle stability over time.



(a) Cyclability of BFO-B-rGO



(b) Comparative cyclability performance of BFO, BrGO and BFO-BrGO

The second graph shown in Fig 16 (b) compares the cycling performance of pure BFO, BrGO, and a composite of BFO–BrGO at same current density 200 mA/g. Among these, the BFO–BrGO composite displays the highest capacity and the most favourable cycling trend.

While BFO shows a relatively low capacity (~50–100 mAh/g) with minor improvement over time and BrGO maintains a stable but moderate capacity around 200 mAh/g, the BFO–BrGO composite starts with a higher capacity and demonstrates a continuous increase throughout the 200 cycles, reaching nearly 600 mAh/g. This enhanced performance is attributed to the synergistic effect between BFO and BrGO, where the conductive graphene matrix improves electron transport and structural integrity, thereby enhancing the electrochemical activity and stability of BFO.

Overall, the data highlights the superior long-term cycling behaviour of the BFO–BrGO composite compared to its individual components.

4. Conclusion

The electrochemical performance evaluation of the BFO–BrGO composite reveals its significant potential as an anode material for sodium-ion batteries. The cycling stability and specific capacity results clearly demonstrate that the BFO–BrGO composite exhibits superior electrochemical behaviour compared to pristine BFO and BrGO.

Notably, the BFO–BrGO electrode delivers a higher reversible capacity and shows a gradual capacity increase over extended cycling, indicating excellent activation and stability of the electrode material. In contrast, bare BFO and BrGO show limited capacity and poor stability.

The enhanced performance of the BFO–BrGO composite can be attributed to the synergistic effect between BFO and BrGO, which improves electronic conductivity, facilitates sodium-ion diffusion, and buffers volume expansion during cycling.

Overall, the BFO–BrGO nanocomposite is a promising candidate for high-performance sodium-ion battery systems.

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