

# Bridging the Gap: A Short Review of BSCF Composite Materials for Intermediate Temperature SOFC

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## Abstract

Barium Strontium Cobalt Ferrite (BSCF) is highly regarded as the top choice for solid oxide fuel cell (SOFC) cathodes because of its exceptional catalytic activity in oxygen reduction and superior mixed electrical and ionic conductivity. This abstract provides an overview of recent research efforts focused on the synthesis, characterization, and performance evaluation of BSCF composite materials operating at intermediate temperatures. Various synthesis methods, including solid-state reaction, sol-gel and mechanical milling are discussed, along with characterization techniques such as X-ray diffraction (XRD) and scanning electron microscopy (SEM). Issues related to BSCF composites, such as chemical stability and long-term performance, are discussed, along with recommendations for future research to overcome these obstacles and enhance the commercialization of IT-SOFCs using BSCF composite materials.

## 1. Introduction

Intermediate temperature solid oxide fuel cells (IT-SOFCs) have emerged as promising energy conversion devices due to their high efficiency, reduced operating costs, and compatibility with a variety of fuels [1]. Electrolytes and cathodes are two of the most important parts of an IT-SOFC because of the significant impacts these components have on overall performance and stability of the system. In recent years, significant research efforts have been directed towards the development of advanced materials for IT-SOFCs, with barium strontium cobalt ferrite (BSCF) composites emerging as particularly attractive candidates. BSCF exhibits a unique combination of properties, including high ionic and electronic conductivity, mixed ionic-electronic conduction, and excellent catalytic activity for oxygen reduction reaction (ORR) [2-3]. These characteristics make BSCF an ideal material for both electrolyte and cathode applications in IT-SOFCs, especially at intermediate temperatures ranging from 500°C to 800°C. Additionally, BSCF demonstrates remarkable thermal stability and resistance to chemical degradation under operating conditions, further enhancing its suitability for SOFC applications.

Extensive research has been conducted on synthesizing BSCF composite materials using methods like solid-state reaction, sol-gel, and mechanical milling to customize the composition, structure, and characteristics of the composites [3-5]. Advanced characterisation techniques such as X-ray diffraction (XRD) and scanning electron microscopy (SEM) have been used to analyse the structural, morphological, and electrochemical properties of BSCF composites simultaneously. In spite of the fact that BSCF composites have a number of intriguing properties, there are still a number of obstacles to overcome. These obstacles include issues related to chemical stability, long-

term performance, and the scalability of synthesis processes [2,6]. The successful resolution of these problems is crucial for achieving widespread commercialization and practical implementation of IT-SOFCs based on BSCF composite materials. In light of these considerations, this review aims to provide a comprehensive overview of the recent advancements in BSCF composite materials for IT-SOFCs operating at intermediate temperatures. This review will discuss the synthesis methods, characterization techniques, electrochemical performance, durability, and challenges associated with BSCF composites, and propose future research directions to address these challenges and realize the full potential of BSCF-based IT-SOFCs.

## 2. Synthesis Of BSCF Composite

Synthesizing of BSCF composite materials is crucial for determining their structural, morphological, and electrochemical properties, which directly impact their performance in intermediate temperature solid oxide fuel cells. Varying synthesis techniques can greatly impact the microstructure, phase purity, and ionic conductivity of BSCF composites. The alterations impact the material's effectiveness as an electrolyte or cathode in IT-SOFCs, emphasizing the essential importance of synthesis in material design and application [2-6].

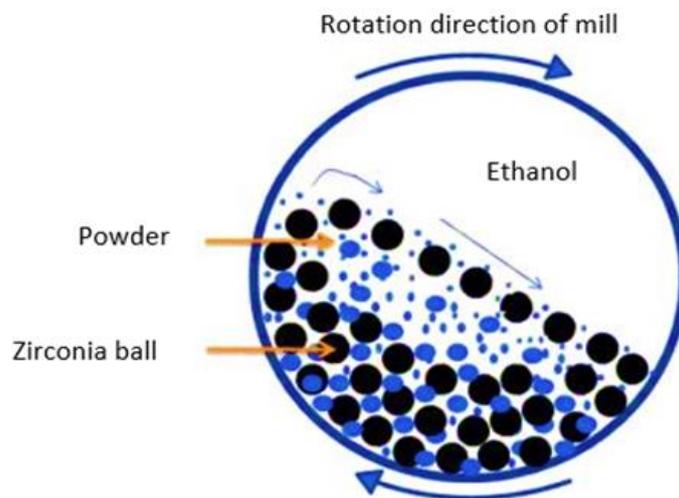
The sol-gel process is a highly advanced synthesis technique known for its remarkable ability to create composites materials with exceptional purity, homogeneity, and precise microstructural properties [7]. The uniqueness of this method stems from its utilization of a colloidal solution (sol) that transforms into an integrated network (gel), enabling the production of materials with highly customized properties [7]. Zhao et al. [8] utilized a BSCF cathode in combination with Sm-doped CeO<sub>2</sub> (SDC) by incorporating CuO to enhance the ionic conductivity of the BSCF/SDC composite cathode. The proposed composite cathode was prepared using the sol-gel method. Other than that, Sameera et al. [9] created a BSCF-GDC composite using the sol-gel technique to achieve highly homogeneous and fine composite powders. Stoichiometric amounts of Sr(NO<sub>3</sub>)<sub>2</sub>, Ba(NO<sub>3</sub>)<sub>2</sub>, cobaltus acetate, ferric nitrite, ammonium ceric nitrate, and Gd<sub>2</sub>O<sub>3</sub> were used as starting materials. The starting materials were dissolved in distilled water in stoichiometric proportions and the solutions (Ba, Sr, Co, Fe) were mixed. The solution was supplemented with citric acid and ethylene glycol, which served as chelating agents and dispersants. Subsequently, the gel was subjected to heating on a hot plate at a temperature of 100 degrees Celsius for a duration of 5-6 hours while being continuously stirred. The temperature was elevated in order to obtain a solid precursor with an ash coloration. The substance was pulverized using acetone of spectral grade and subjected to heating at a temperature of 500oC using an electrical burner in order to eliminate the organic constituents. The fine powder obtained was subjected to calcination in order to get the desired phase.

Solid-state reaction is the process where solid precursor powders react at elevated temperatures to produce a new solid-phase molecule. Solid-state synthesis is highly regarded for its simplicity, scalability, and versatility in producing materials [10]. Zhao et al. [11] applied the solid-state reaction technique to synthesize the BSCF cathode. The Ba<sub>x</sub>Sr<sub>1-x</sub>Co<sub>y</sub>Fe<sub>1-y</sub>O<sub>3-δ</sub> compounds (with x ranging from 0.2 to 0.7 and y ranging from 0 to 1) were synthesized through solid-state reactions in an air environment. The synthesis process involved heating BaCO<sub>3</sub>, SrCO<sub>3</sub>, CoCO<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> raw materials at 1000 °C for 6 hours. The performance of the BSCF cathode material was enhanced by incorporating GDC electrolyte into it. In the solid-state reaction method, powders were determined based on stoichiometric quantity and then subjected to ball milling procedure. The mixture is then uniaxially pressed into disks and sintered at the required temperature and time to produce the pellets. Shubashini et al [6] summarize the steps of the solid state reaction approach as follows:

- Ball milling- It is used to pulverize and mix materials in the presence of liquid in a rotating cylinder.
- Calcination- A thermal based process that causes thermal degradation, phase transition and the elimination of volatile fractions.
- Granulation- A process that produces uniformly shaped particles for enhanced the strength during compaction. Granulation was carried out using several grades of sieves to produce fine and uniformly shaped particles.
- Uniaxial pressing- This method compacts the powder by applying uniaxial pressure.
- Sintering- Powders are densified through the sintering process, sintering control grain development and porosity .

The next step in preparing the BSCF composite involves mechanical milling. Mechanical milling functions based on impact, shear, and friction forces generated by the motion of milling media (balls) and the material being milled in an enclosed container [13]. The energy transferred by the milling media to the material causes interactions between the precursors, facilitates diffusion, and can lead to phase changes, reduction in particle size, and improved chemical uniformity [13]. Mechanical milling is a high-energy impact operation that is commonly carried out in various types of mills, such as planetary and shaker mills, using balls inside containers [14]. Fig. 1 shows the schematic diagram for mechanical ball milling process. Yusuf et al [4] used high energy ball milling process to produce BSCF-SDC composite. The BSCF and SDC raw materials were mixed together in a zirconia jar with the addition of the zirconia balls and ethanol as a soaking medium. The obtained slurry was then dried and

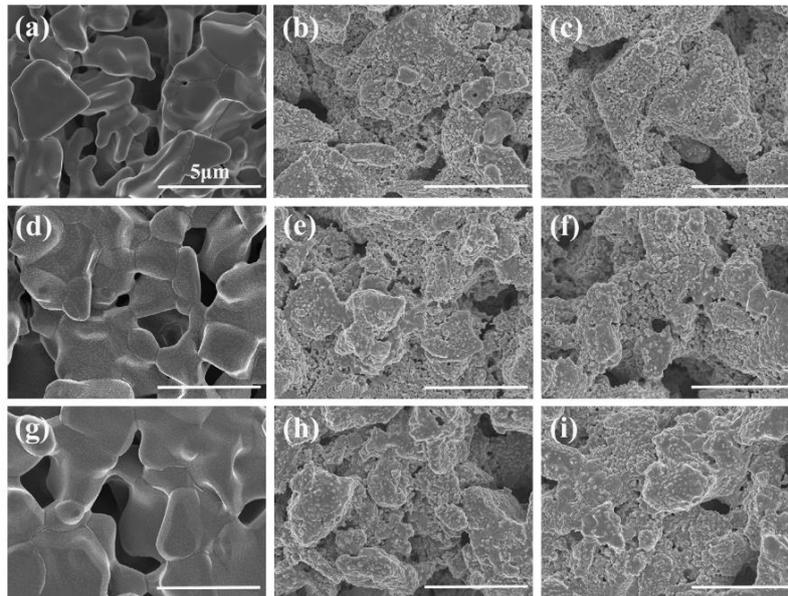
calcined before performing the characterization of BSCF-SDC composite powder. The high-energy ball milling approach was also utilized by Tan et al. [15] in order to prepare the BSCF-SDC and BSCF-SDCC composite powder. A calcination procedure is performed on the raw powder of BSCF before it is mixed with the powders of SDC and SDCC. The synthesis of BSCF-SDC and BSCF-SDCC was successfully completed, and the materials were characterized for its properties. The solid-state reaction, sol gel method and mechanical milling is still the most common way to make BSCF composite, but other methods, like hydrothermal synthesis and mechanochemical methods, have strong benefits, especially when it comes to saving energy and being able to control the properties of the material. Nevertheless, every approach has different challenges, ranging from equipment demands to scalability concerns. The selection of the synthesis technique is based on the particular needs of the material's application, such as purity, microstructure, and phase composition.



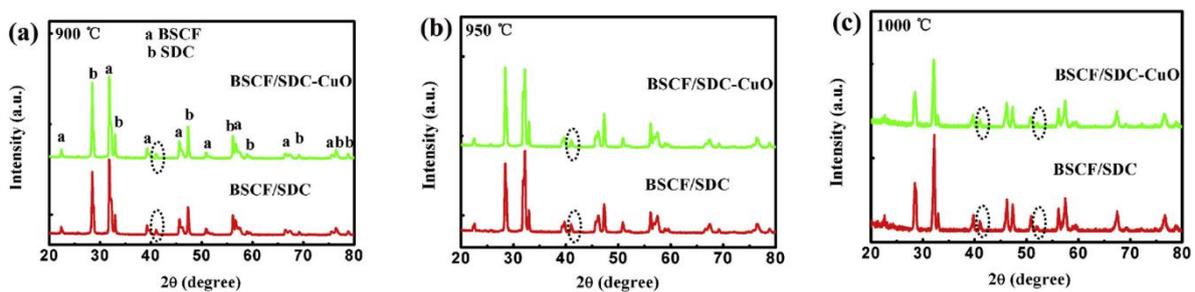
**Fig 1** Schematic diagram for the ball milling process

### 3. Characterization of BSCF Composite

The sol-gel technique enables precise control over the chemical composition and microstructure of BSCF composites, leading to enhanced homogeneity and uniformity. The selected characterization methods, such as X-ray diffraction (XRD) for identifying phases and scanning electron microscopy (SEM) for analysing microstructure, are suitable for evaluating these properties. The sol-gel technique is anticipated to produce small particle sizes and uniform distribution, which can be verified by SEM imaging and particle size analysis. Zhou et al. [8] found that the majority of the X-ray diffraction peaks observed in BSCF/SDC and BSCF/SDC-CuO samples originated from the BSCF and SDC phases. The low intensity peaks found correspond to impurity phases resulting from the reaction between the BSCF phase and the SDC phase [16]. The X-ray diffraction (XRD) patterns of the BSCF/SDC and BSCF/SDC-CuO samples, calcined at identical temperatures, exhibited similar locations, and had identical diffraction peak counts. The inclusion of CuO did not introduce any extra impurity phases in the BSCF/SDC-CuO sample. This shows that the sol-gel approach successfully produced the BSCF/SDC and BSCF/SDC-CuO composite in addition to demonstrating that there is no agglomeration occurring for BSCF/SDC or BSCF/SDC-CuO powders as shown in Fig 2, demonstrating that the composite cathode was successfully produced. Fig.3 shows the XRD pattern for BSCF/SDC and BSCF/SDC-CuO composite powders calcined at 900°C, 950°C, and 1000°C. In addition to providing valuable insights, this study revealed that BSCF/SDC and BSCF/SDC-CuO exhibited larger specific surface areas compared to BSCF. This characteristic is advantageous as it promotes an increase in the number of active sites for oxygen reduction and enhances the electrochemical reaction activity of the cathode [17].



**Fig 2** SEM images for (a), (d), and (g) BSCF, (b), (e), and (h) BSCF/SDC, and (c), (f), and (i) BSCF/SDC-CuO [8]



**Fig 3** XRD pattern for BSCF/SDC and BSCF/SDC-CuO at (a) 900°C, (b) 950°C and 1000°C [8]

In contrast to Yusuf et al., [4] mechanical milling was used to create the BSCF/SDC composite powder. Mechanical milling offers several advantages for the synthesis of BSCF composites, including the ability to achieve fine particle sizes, enhanced homogeneity, and controlled microstructural features. However, utilizing mechanical milling to produce BSCF/SDC seems somewhat less favourable when compared to the sol-gel method. As can be observed in Fig 4, the FESEM micrograph shows that the particle of prepared BSCF/SDC composite powder becomes agglomerate and stack with each particle. As mentioned by researcher, the particle become more agglomerate as the calcination temperature increases. It is possible that this phenomenon occurs due to the increase in particle size as the calcination temperature increases, resulting in a reduction of the surface area. Regarding XRD analysis in Fig 5, the milled composite powder of the BSCF-SDC sample shows the presence of secondary peaks corresponding to  $\text{BaCO}_3$  (JCPDS No: 71-2394) and  $\text{Sr}_2\text{FeO}_4$  (JCPDS No: 42-0480). The presence of the secondary phase may be attributed to the heating conditions that arise during the HEBM process. Upon calcining the composite powder at 950 °C, the secondary phase peak was clearly observed and generated multiple peaks. These phases are commonly referred to as surface carbonate, which is produced when alkaline-earth oxide (Ba and Sr) reacts with  $\text{CO}_2$  during the calcination process. It is important to eliminate the formation of secondary phase as it can have a significant impact on the electrochemical performance [18].

Tan et al., [5] created a BSCF-SDCC composite using mechanical milling and also observed the presence of a secondary phase in the XRD analysis following the calcination procedure. The substance was also determined to be  $\text{BaCO}_3$  with an orthorhombic phase, according to JCPDS reference number 00-052-1528. However, this may be attributed to the side effect of the calcination process rather than the milling procedure. This is due to the fact that the XRD study of the BSCF-SDCC without calcination reveals that there were two primary phases present: perovskite (BSCF5582) and cubic fluorite SDC where no secondary phase was found. The XRD spectra verified that, following the ball milling procedure, there was no chemical interaction between BSCF and SDCC. Remarkably, this paper stated that the SDCC composite did not affect the first phase of the SDC and instead changed carbonate into a molten state amorphous phase after being calcined at 680 °C. Fig 5 shows the XRD spectra for the prepared BSCF-SDCC composite using mechanical milling method.

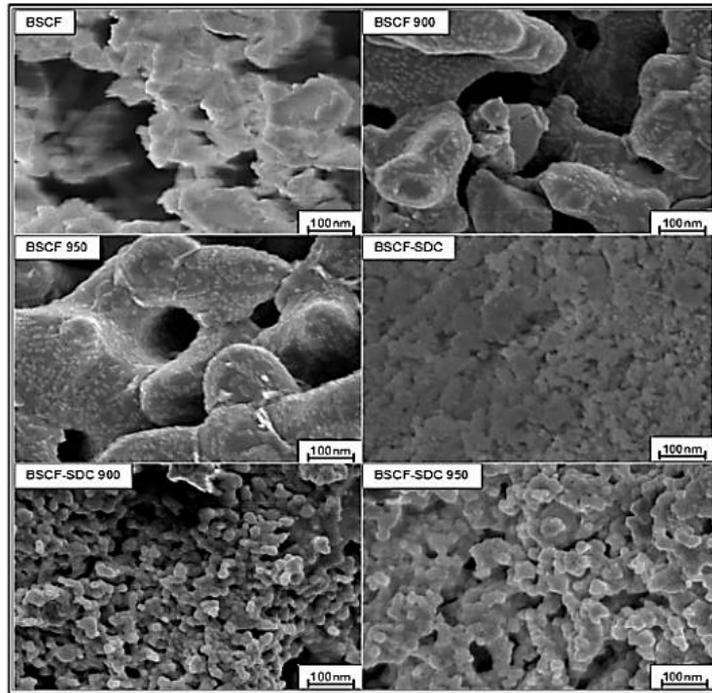


Fig. 4 FESEM micrograph for BSCF and BSCF-SDC at different calcination temperatures [4]

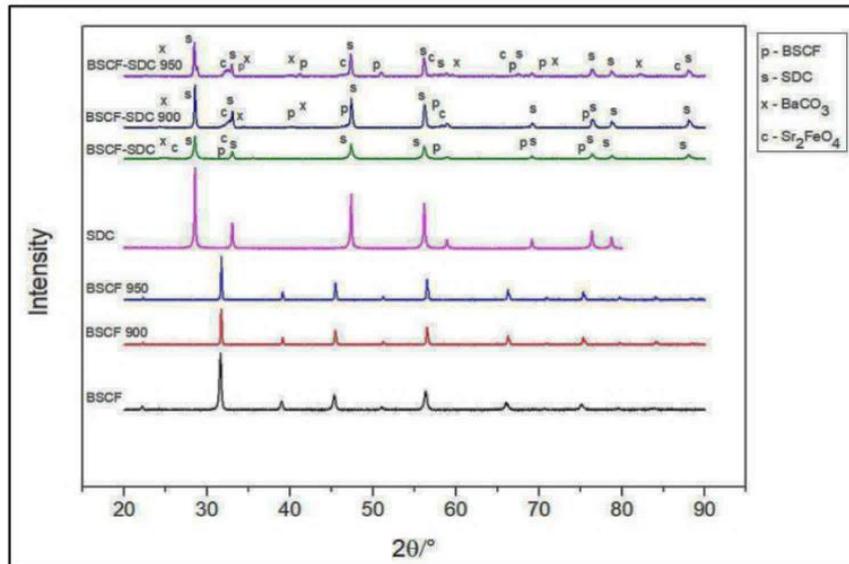


Fig. 5 XRD spectra of the uncalcined BSCF, SDC, BSCF-SDC and calcined BSCF and BSCF-SDC powders at 900°C and 950°C temperature [4]

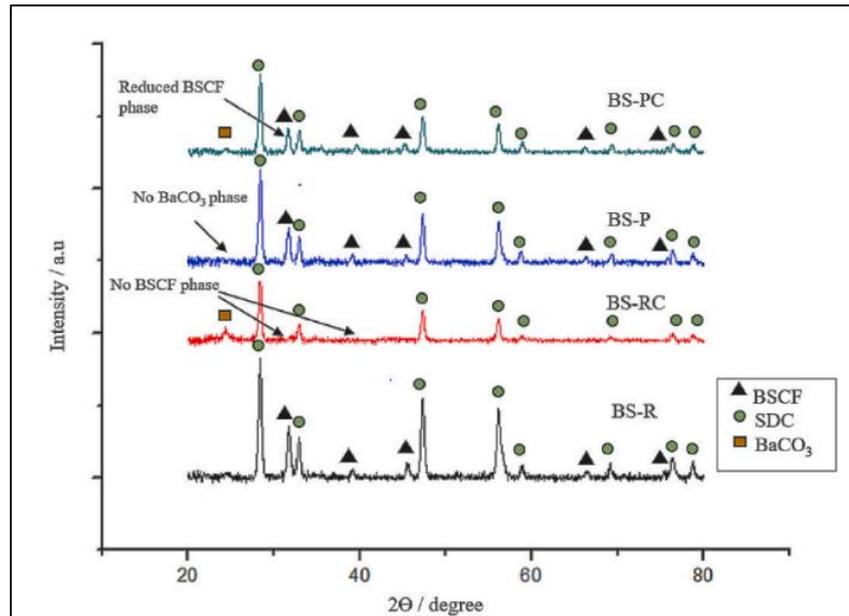


Fig. 6 XRD spectra for BSCF-SDCC composite [5]

#### 4. Issues and challenges BSCF composite at ITSOFCs

Performance stability concerns and thermal expansion mismatch are among the issues and challenges that BSCF composites encounter when subjected to intermediate temperatures due to their composition [19]. According to the findings of several studies, BSCF cathodes have encountered a significant challenge in maintaining their performance stability. There is also the problem of thermal expansion mismatch between BSCF and other materials, such as samarium-doped ceria, which has been highlighted as a significant obstacle that needs to be addressed to maximize the performance of BSCF composites [20]. Here are the common issues and challenges related to BSCF composites operating at ITSOFCs [6,19, 21]

- Chemical stability
- Sintering behaviour
- Oxygen exchange kinetics
- Electrochemical stability
- Compatibility with electrolytes
- Thermal expansion mismatch
- Cost and scalability

#### 5. Conclusion

In order to assess BSCF composites' suitability for applications involving IT-SOFCs, a thorough analysis of the materials is necessary. The performance and functionality of the synthesized BSCF composites can be thoroughly assessed by combining structural, morphological, and chemical compatibility. Through structural analysis techniques like XRD, the formation of the desired perovskite phase is confirmed, and any secondary phases are identified. These secondary phases negatively impact the electrochemical performance of the cells. Additionally, information on crystallite size and lattice strain caused by synthesis processes can also be obtained from XRD results. In addition to this, the use of SEM enables an in-depth analysis of the particle size distribution, morphology, and microstructural features of the composites. In general, the characterization of BSCF composites provides valuable insights into their structural integrity, morphological characteristics, and chemical compatibility. These insights facilitate the optimization of synthesis methods and provide guidance for the development of high-performance materials for sustainable energy technologies.

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#### Conflict of Interest

This paper has no conflict of interest regarding the publication of the paper

## Author Contribution

The author confirms contribution to the paper as follows: **literature research and writing:** Nurul Farhana Abdul Rahman; **draft manuscript preparation:** Nurul Farhana Abdul Rahman; **review and supervision:** Hamimah Abd Rahman and Tan Kang Huai.

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