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Enhancing Electrochemical Properties of BSCF-Based Cathode Composite Through Catalyst Addition for Low-Temperature Solid Oxide Fuel Cells

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Abstract

Solid oxide fuel cells (SOFCs) are promising alternative energy sources; however, their commercialisation is hindered by the requirement of high operating temperatures. The development of low-temperature SOFCs (LT-SOFCs) offers a potential solution to mitigate this limitation, with barium strontium cobalt ferrite (BSCF) emerging as a promising mixed ionic and electronic conductor (MIEC) material for cathode applications. Nevertheless, the advancement of BSCF-based cathodes necessitates further enhancements in both conductivity and stability to achieve optimal performance. This study investigates the incorporation of 1, 3, and 5 wt.% argentum (Ag) as a catalyst material into a BSCF-samarium doped ceria (BSCF-SDC) composite cathode, with the objective of improving its chemical, physical, thermal, and electrochemical properties for LT-SOFC operation within the temperature range of 400 - 600°C. The particle size increases with the increment of Ag addition, enhancing the triple-phase boundary (TPB) length at the cathode-electrolyte interface. The composite cathodes exhibited optimised porosity ranging from 35.34% to 36.45%, falling within a sufficient porosity of 20% - 40% for SOFC cathode components. The TEC analysis revealed improved compatibility with the electrolyte as Ag content increased, with BS-Ag5% showing the lowest TEC mismatch (2.1%), indicating enhanced thermal stability. The electrochemical performance, ASR, also increased with higher Ag content while maintaining a consistent trend across operating temperatures. By this outcome, the presence of secondary phases, such as $BaFe_2O_4$ and CeO_2, did not adversely affect cell performance; instead, they may have contributed to catalytic activity and structural stability. The study concludes that BS-Ag composite cathodes exhibit significant potential for LT-SOFC cathode materials.

1. Introduction

The global demand for energy continues to rise at an unprecedented rate, driven by a combination of population growth, rapid industrialisation, and advancement in technology. This escalating reliance on conventional primary energy sources, such as coal, natural gas, and oil, has raised significant concerns regarding their finite availability and the detrimental environmental impact associated with their extraction and consumption, including greenhouse gas emissions and climate change [1-2]. In response to these challenges, there has been a concerted global effort to transition towards alternative energy technologies that are not only sustainable and efficient but also environmentally friendly. Among the various alternatives being explored, hydrogen energy, particularly fuel cells, has emerged as a promising solution. Fuel cells are advanced electrochemical devices that directly convert chemical energy into electrical energy, offering a highly efficient energy conversion process with minimal environmental impact [3]. Solid oxide fuel cells (SOFCs), a prominent type of fuel cell, are particularly notable for their high energy conversion efficiency, versatility in fuel usage, and compatibility with renewable biofuels, making them a key candidate for addressing future energy needs while mitigating environmental concerns [4].

However, conventional SOFCs typically operate at high temperatures, often exceeding 1000°C, which introduces a range of technical and economic challenges. These include accelerated material degradation, difficulties in achieving effective sealing, and elevated manufacturing and operational costs, all of which hinder their widespread adoption and long-term viability [5]. These issues have spurred research into lowering the operating temperature of SOFCs to the intermediate range of 600-800°C and even below 600°C. Lowering the operating temperature offers several advantages, such as reduced material degradation, improved thermal compatibility, simplified sealing mechanisms, and decreased overall costs, thereby enhancing the durability and commercial feasibility of SOFC systems [6-7]. Nevertheless, achieving high electrochemical performance at these reduced temperatures remains a formidable challenge, as it necessitates the development of advanced materials with superior ionic and electronic conductivity, enhanced catalytic activity, and improved stability under operational conditions [8]. Thus, the focus of ongoing research is on innovating novel electrolyte, electrode, and interconnect materials, as well as optimising cell architectures, to enable efficient and reliable SOFC operation at lower temperatures, paving the way for their broader application in sustainable energy systems [9].

One of the most significant challenges in advancing SOFC technology lies in the identification and development of suitable materials that can effectively address its inherent limitations. Recently, $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_3$ (BSCF) has garnered considerable attention as a cathode material due to its exceptional electrochemical stability and compatibility with SOFC systems [10]. BSCF exhibits high oxygen permeability and robust structural stability under operational conditions, making it an ideal candidate for enhancing the performance of SOFCs, particularly at intermediate and lower operating temperatures [11]. In addition, the electrolyte components also play a crucial role in determining the overall efficiency and durability of SOFCs, as they directly influence the reaction pathway and ionic conductivity. Since the electrolyte interacts with both the anode and cathode, it must maintain chemical stability across a wide range of oxygen partial pressures and temperatures [12]. Doped ceria-based materials, such as gadolinium-doped ceria (GDC) and samarium-doped ceria (SDC), have been widely recognised as excellent electrolyte choices due to their high oxygen ion conductivity, especially at intermediate temperatures (600-800°C) [13]. Recent studies have further demonstrated that BSCF-SDC composites exhibit highly encouraging performance characteristics, including enhanced ionic conductivity and improved interfacial compatibility, making them particularly suitable for low-temperature SOFC applications [14]. To further enhance cathode performance, the incorporation of catalyst materials, such as argentum (Ag), has gained significant attention. Ag serves as an effective catalyst by facilitating oxygen surface adsorption, dissociation, and permeation processes, thereby accelerating the oxygen reduction reaction (ORR) and significantly improving the overall electrochemical efficiency of the cell [15].

Moreover, for materials to be considered viable candidates for cathode components in SOFC, they must exhibit several critical properties, including sufficient porosity and a thermal expansion behaviour (TEC) that is compatible with other cell components [16]. Porosity is a fundamental requirement, as it facilitates the diffusion of gases and the transport of oxygen within the cathode structure, ensuring efficient electrochemical reactions at the triple boundaries (TPB) where the electrolyte, cathode, and gas phase interact [17]. Without adequate porosity, the ORR would be hindered, leading to diminished cell performance. Equally important are the TEC values of the cathode material, as mismatches in the TEC between the cathode and electrolyte can result in significant thermal stresses during operational thermal cycling. These stresses can cause delamination, cracking, or mechanical failure, ultimately compromising the structural integrity, durability, and long-term performance of the SOFC [18]. The TEC determines the compatibility between the cathode and electrolyte, as mismatches can lead to thermal stress, delamination, or cracking during operation, ultimately compromising the cell's durability and performance [19]. Therefore, achieving an optimal balance between porosity and TEC is essential for developing high-performance cathode materials that can withstand the thermal and mechanical demands of SOFC operation. This balance not only enhances the electrochemical efficiency but also ensures the reliability and longevity of the fuel cell, making it a critical consideration in the design and optimisation of SOFC systems.

This study focuses on the development and optimisation of BSCF-SDC composite cathodes incorporating Ag as a catalyst addition, specifically tailored for LT-SOFC applications. The primary objective is to systematically investigate the influence of varying Ag content on the chemical, physical, thermal, and electrochemical properties of the composite cathode. By elucidating the relationship between Ag incorporation and cathode performance, this research seeks to identify the optimal composition that enhances ORR kinetics, improves interfacial compatibility, and mitigates thermal stress-related issues. Furthermore, this work aims to advance the understanding of material design principles for SOFC cathodes, particularly in the context of low-temperature operation, where achieving high electrochemical efficiency and long-term durability remains a significant challenge. The findings from this study are expected to contribute to the broader development of SOFC technology, providing critical insights into the design of high-performance, cost-effective, and durable cathode materials. Ultimately, this research strives to support the transition towards more sustainable and efficient energy systems by making SOFCs more viable for widespread adoption in both stationary and mobile energy applications.

2. Materials and Methods

Commercial powder of $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_3$ (BSCF) and $Sm_{0.2}Ce_{0.8}O_{1.9}$ (SDC) (Kceracell, Korea) was employed to prepare the BSCF-SDC composite cathode powder. The BSCF and SDC commercial powders were meticulously mixed in a 50:50 weight ratio. The mixture was then subjected to a calcination process to produce the BSCF-SDC composite cathode powder. To fabricate the BS-Ag composite, commercial argentum (Ag) powder (Alfa Aesar, USA) was incorporated into the BSCF-SDC mixture using a dry milling method. The Ag content was systematically varied at 1 wt.%, 3 wt.%, and 5 wt.% to investigate its catalytic influence on the composite properties. All composite powders were uniaxially pressed into pellet form and sintered at 900°C.

The chemical, physical, thermal, and electrochemical properties of all composite pellets were comprehensively characterised to evaluate their suitability for LT-SOFC applications. Phase identification was conducted using X-ray diffraction (XRD) (Bruker D8 Advance, Germany) with Cu Kα radiation (λ = 0.15418) at room temperature. The diffraction patterns were scanned over a range of 20° to 90° with a step size of 0.02°, and the acquired data were analysed using EVA software to identify crystalline phases and assess phase purity. The particle size of the cathode composite was analysed using a nanoparticle Zeta-Sizer (Zetasizer Nano ZS, Malvern, United Kingdom) machine. The average particle size result was derived based on 100 readings per run. The porosity and density of the sintered pellets were determined using the Archimedes method (Density Kit AY220, Shimadzu, Japan), which provides critical insights into the microstructural characteristics essential for gas diffusion and electrochemical performance. The thermal expansion coefficient (TEC) of the composites was measured using a dilatometer (Linseis, DIL L75V, Germany) over a temperature range from ambient to 900°C, following the ASTM E228-11 standard, to evaluate thermal compatibility with other SOFC components. The electrochemical performance was evaluated using electrochemical impedance spectroscopy (EIS) (Autolab AUT302 FRA) with data analysis performed using Nova software to determine key parameters such as ionic conductivity and interfacial resistance.

3. Results and Discussion

The XRD analysis was performed to investigate the phase composition and stability of the BSCF-SDC and BS-Ag (1, 3, and 5 wt.%) composite cathode pellets sintered at 900ºC. The XRD diffractograms, as illustrated in Fig. 1, confirmed the presence of three primary phases: BSCF, SDC, and Ag. These phases were identified by their spectral peaks with the Joint Committee on Powder Diffraction Standard (JCPDS) pattern numbers 00-055-0563 for BSCF, 01-075-0157 for SDC, and 00-041-1402 for Ag. In addition, two secondary phases were detected in the sintered pellets. The first secondary phase, barium ferrite ($BaFe_2O_4$), was identified at JCPDS number 00-025-1191. This phase exhibits an orthorhombic lattice structure with a lattice parameter of *a* = 19.05000 nm and a space group of *Pnma* (62). The second secondary phase, cerium oxide (CeO_2), was observed at JCPDS number 00-043-1002. CeO_2 shows a face-centred cubic (FCC) crystal structure with a lattice parameter of *a* = 5.41134 nm and a space group of *Fm-3m* (225). The presence of these secondary phases suggests potential interactions or phase transformations during the sintering process.

The formation of $BaFe_2O_4$ in the BS-Ag composite cathode pellets aligns with findings from prior research, which indicate that this phase typically emerges at sintering temperatures ranging between 700ºC and 1000ºC [20-21]. The presence of $BaFe_2O_4$ is likely attributed to the decomposition of residual carbonates and the thermal conditions during the sintering process. At elevated temperatures, residual carbonates from the precursor materials decompose, leading to the formation of a secondary phase [22]. Furthermore, $BaFe_2O_4$ is also recognised for its catalytic properties, including its ability to facilitate redox reactions and act as an oxygen carrier, which could contribute positively to the electrochemical performance of the composite cathode [23]. In addition, CeO_2 was also identified as a secondary phase in the BS-Ag composite cathode pellets. Its formation is attributed to crystallite growth and particle agglomeration during sintering, particularly at elevated temperatures [24]. As the temperature increases, enhances atomic and ionic mobility facilitates the coalescence of smaller crystallites into larger ones, while also promoting particle agglomeration. Notably, the porosity values of all composite samples remain within the acceptable range for SOFC cathode materials, suggesting that the secondary phase (CeO_2) has negligible influence on whole porosity. However, uncontrolled crystallite growth may lead to residual or closed porosity, which could adversely affect the microstructure and properties of the material. A detailed discussion on porosity and density characteristics will be presented in the following section. Additionally, the secondary peaks observed in the XRD analysis are more likely to arise at the nearness of the primary peaks of BSCF, SDC, and Ag. This phenomenon can be explained by the interaction between the adsorption and desorption of CO_2 with these primary peak phases during the sintering process [16]. The incorporation of Ag as a catalytic material may further accelerate specific chemical reactions, interacting with the high-temperature sintering environment that promotes the formation of these secondary phases [25]. Furthermore, the observed secondary phase formation can be understood as a thermodynamically driven phase separation process, where the detachment of iron ions reduces the overall system energy through lattice relaxation [26]. Crucially, this phenomenon does not appear to compromise cathode performance, as evidenced by maintained electrochemical functionality. This aligns with established reports by Shurui *et al.* (2025) and Yangyang *et al.* (2025) demonstrating that similar structural evolutions in perovskite-based cathodes often remain electrochemically benign when the primary conduction pathways remain intact. This is consistent with the findings that even in systems experiencing phase transitions, the electrochemical performance of the cathode remains largely unaffected, as the electrode-electrolyte interface retains its functionality. This will be supported by the electrochemical analysis discussed in subsequent sections.

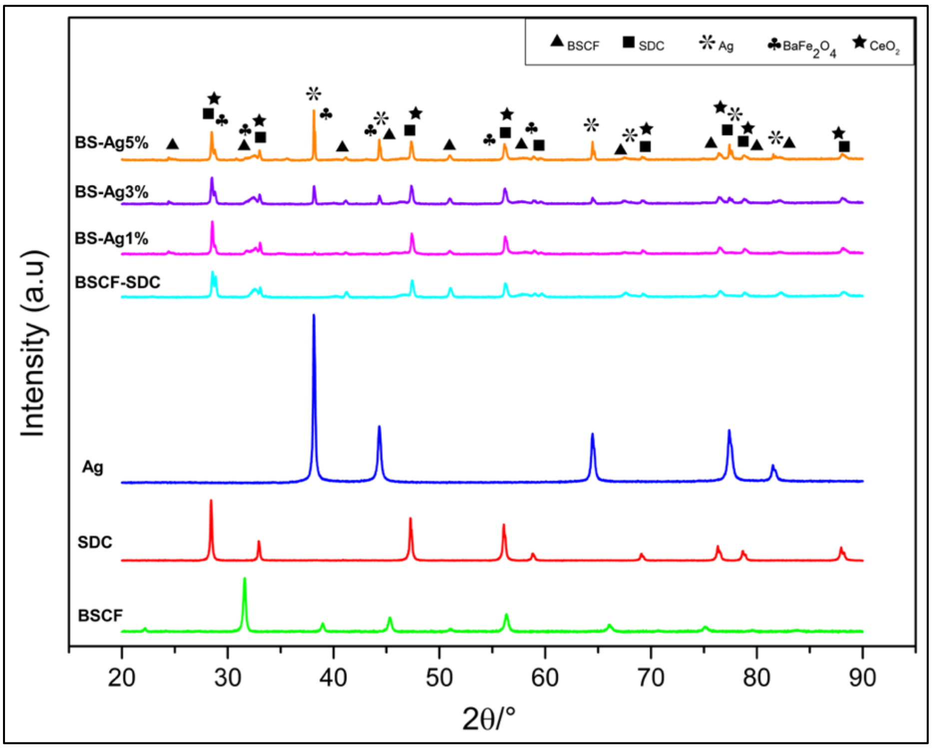

Fig. 1 *XRD spectrum pattern for the commercial powder, BSCF-SDC, and BS-Ag 1, 3, and 5 wt.% composite cathode pellets*

The particle size analysis conducted using Zeta-sizer ZS, as shown in Table 1, revealed that the BSCF-SDC composite cathode has a smaller particle size compared to samples with Ag additions (1, 3, and 5 wt.%). The larger particle sizes observed in the Ag-added samples are primarily attributed to the presence of Ag elements, which have a particle size of 1300 nm. The data presented in Table 1 reveal a clear and consistent trend: as the Ag content increases, the particle size of the composite cathode also increases, demonstrating a direct correlation between the amount of Ag added and particle size enlargement. This phenomenon can be attributed to the agglomeration of smaller particles during the heat treatment process, where elevated temperatures enhance atomic diffusion and promote particle bonding and compaction [24].

Despite the observed increase in particle size, all samples remain within the acceptable range for cathode materials, with particle sizes below 1 µm [26]. This is particularly significant because nano-powders within this size range play a critical role in optimising the triple-phase boundary (TPB) length at the interface between the cathode and electrolyte layers [29-30]. An optimised TPB is essential for enhancing the oxygen reduction reaction (ORR) kinetics, as it provides a greater active area for the electrochemical reactions to occur, thereby improving the overall electrochemical performance of the material. Furthermore, the retention of particle sizes below 1 µm ensures a high surface area-to-volume ratio, which is crucial for facilitating efficient ion and electron transport within the cathode structure [31]. These characteristics make the composite cathode highly suitable for efficient SOFC applications, where high catalytic activity and ionic conductivity are paramount. Additionally, the controlled particle size distribution and microstructure achieved in these materials contribute to their long-term stability and durability under operating conditions, further underscoring their potential for use in advanced energy conversion technologies.

Table 1 *The average particle sizes of each sample*

Samples	Average particle sizes (nm)
BSCF	524.1 ± 0.01
SDC	217.4 ± 0.01
Ag	1300.0 ± 0.01
BSCF-SDC	351.6 ± 3.46
BS-Ag1%	493.5 ± 5.80
BS-Ag3%	856.2 ± 6.29
BS-Ag5%	1181.0 ± 5.66

Achieving optimal porosity is a critical factor in the production of high-quality composite cathode pellets, as it directly influences oxygen transport and electrochemical performance. Porosity plays a vital role in facilitating the ORR by enabling efficient oxygen diffusion through the cathode-electrolyte interface. The optimal porosity range for SOFC cathodes typically falls between 20% and 40%, as this ensures a balance between sufficient gas transport and robust electrochemical activity [32]. The porosity and density measurements for the BSCF-SDC and BS-Ag composite cathode pellets are presented in Table 2 and illustrated in Fig. 2. The BSCF-SDC sample exhibited the highest porosity at 36.45%, with a corresponding density of 3.95 g/cm^3. As the Ag content increased, a consistent trend was observed: the density of the pellets increased, while the porosity experienced a slight decrease.

This behaviour can be attributed to the greater particle agglomeration and larger grain sizes resulting from the addition of Ag, which contributed to the observed reduction in porosity. These findings align with previous findings, which have shown that increased particle size and agglomeration lead to lower porosity levels. Despite these variations, the differences in porosity between the samples were minimal (less than 1%), and all samples demonstrated porosity values within the desirable range of 35.0% to 36.5%. This range falls well within the acceptable 20-40% porosity (60-80% relative density) required for SOFC electrodes, ensuring optimal gas transport and electrochemical activity while maintaining sufficient mechanical strength [33]. The porosity of 35.34% has 64.66% relative density which remains suitable for cathode performance, as it promotes effective oxygen diffusion and surface reactions without significantly compromising structural integrity [34].

Table 2 *The average of porosity and density values for BSCF-SDC and BS-Ag (1, 3, and 5 wt.%) composite cathode pellets*

Samples	Average porosity (%)	Average density (g/cm^3)
BSCF-SDC	36.45 ± 0.92	3.95 ± 0.02
BS-Ag1%	36.34 ± 0.90	3.97 ± 0.04
BS-Ag3%	35.40 ± 1.57	4.06 ± 0.06
BS-Ag5%	35.34 ± 0.53	4.14 ± 0.05

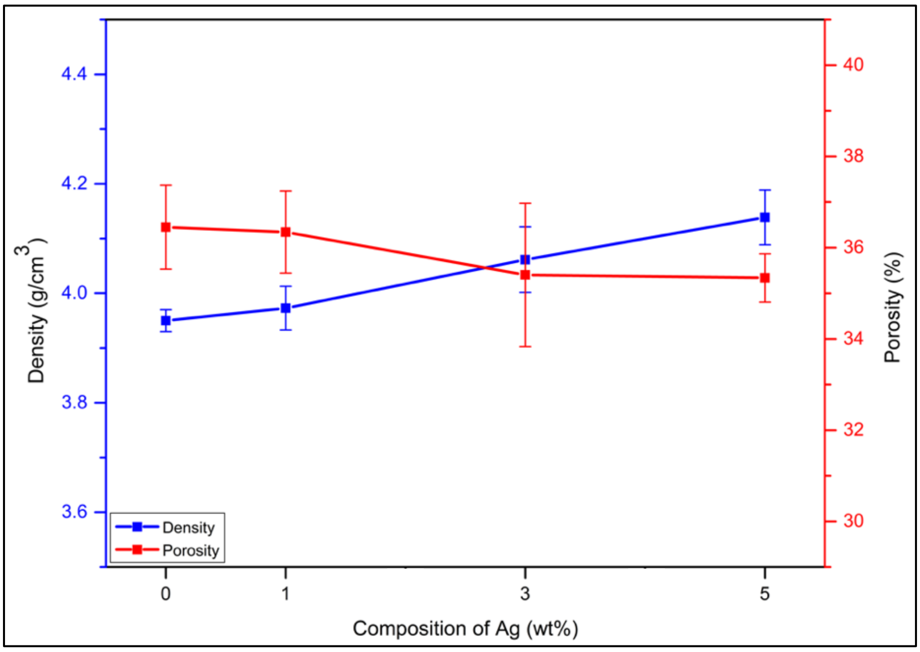

Fig. 2 *The apparent percentage of porosity and density of BSCF-SDC and BS-Ag (1, 3, and 5 wt.%) composite cathode pellets*

In addition to porosity, which plays a critical role in facilitating oxygen transport and enhancing electrochemical performances, the thermal expansion coefficient (TEC) is another key factor that significantly influences the compatibility and stability of SOFC components. A well-matched TEC between the cathode and electrolyte is essential to prevent thermal stress, cracking, or delamination during thermal cycling and ensure the long-term durability and reliability of the cell. Table 2 displays the TEC values of SDC as an electrolyte, as well as for the BSCF-SDC and BS-Ag (1, 3, and 5 wt.%) composite cathodes, measured at a temperature range of 30°C to 600°C. These measurements provide critical insights into the thermal compatibility of the materials, which is vital for maintaining structural integrity and operational stability under the thermal gradients experienced during SOFC operation. By ensuring that the TEC values of the cathode and electrolyte are closely aligned, the risk of mechanical failure due to thermal mismatch is significantly reduced, thereby enhancing the overall performance and lifespan of the fuel cell [35].

Table 3 *The TEC value measured at a temperature range of 30°C to 600°C*

Samples	TEC value (10^{-6} K^{-1})
SDC	10.44 ± 0.1
BSCF-SDC	15.27 ± 0.6
BS-Ag1%	14.48 ± 0.6
BS-Ag3%	11.44 ± 0.6
BS-Ag5%	10.23 ± 0.6

The addition of Ag to the BSCF-SDC composite cathode had a significant impact on the TEC values, with higher Ag content leading to a progressive decrease in TEC values. This reduction resulted in better alignment with the TEC of the electrolyte, thereby improving thermal compatibility. For example, the BS-Ag5% sample exhibited the lowest TEC mismatch of 2.01% relative to the electrolyte, making it the most thermally compatible among the tested samples. As reported by the previous study, to mitigate excessive stress, which can lead to cracking and spallation during operation, the TEC mismatch between SOFC components should be maintained below 10% [36].

As shown in Table 3, the BS-Ag3% sample also demonstrated a TEC mismatch below 10%, while the BSCF-SDC and BS-Ag1% samples exceeded this threshold. This trend indicates that higher Ag content improves thermal compatibility, reducing the risk of thermal stress and enhancing the mechanical stability of the cathode-electrolyte interface. Moreover, materials with higher TEC, such as cobalt-based perovskite, are known for their superior electrochemical activity due to enhanced oxygen diffusion, and the lower TEC values achieved in this study suggest improved thermal stability [37]. The electrochemical performance of the composite cathodes, discussed in the subsequent sections, further validated the impact of TEC on the overall cell functionality and durability of the SOFC. These findings highlight the dual benefits of Ag addition: improved thermal compatibility and enhanced electrochemical performance, making it a promising strategy for advancing SOFC cathode materials.

To the understanding, porosity and TEC are critical factors that significantly influence the performance and durability of SOFC cathodes. Porosity plays a vital role in facilitating oxygen transport and gas diffusion, ensuring efficient electrochemical reactions at the TPBs. Meanwhile, a well-matched TEC between the cathode and electrolyte is essential to maintain mechanical stability, prevent thermal stress cracking or delamination, and ensure long-term operational reliability. Together, porosity and TEC are key factors influencing the overall functionality and durability of SOFC cathodes. To evaluate the electrochemical performance of the composite cathode samples, electrochemical impedance spectroscopy (EIS) was employed. The area-specific resistance (ASR) values of all samples, measured at operating temperatures ranging from 400°C to 600°C, are summarised in Table 4. These measurements provide critical insights into the electrochemical efficiency of the cathodes, further highlighting the interplay between porosity, TEC, and overall cell performance.

Table 4 *The value of area-specific resistance (ASR) for symmetrical cell samples at various operation temperatures*

Operating temperature (°C)	Samples	ASR (Ωcm^2)
400	BSCF-SDC	12.7638
	BS-Ag1%	0.9496
	BS-Ag3%	5.8599
	BS-Ag5%	17.7127
500	BSCF-SDC	1.1435
	BS-Ag1%	0.6044
	BS-Ag3%	1.1428
	BS-Ag5%	6.4091
600	BSCF-SDC	0.1723
	BS-Ag1%	0.1267
	BS-Ag3%	0.1907
	BS-Ag5%	0.4954

The EIS data revealed a positive correlation between Ag content and ASR, with BS-Ag1% exhibiting the lowest ASR value of 0.1267 Ωcm^2, while BS-Ag5% showed the highest ASR value of 0.4954 Ωcm^2 at 600°C. This trend was consistent across all operating temperatures (400°C, 500°C, and 600°C), indicating that higher Ag content led to increased ASR values. Despite this, BS-Ag5% demonstrated the best TEC mismatch between cell components, along with sufficient porosity, resulting in good ASR performance at each operating temperature. The increase of ASR value amongst each sample indicates better performances for the cell samples. Moreover, among the tested samples, BS-Ag1% exhibited the smallest particle size and showed the lowest ASR values. In contrast, increasing the Ag content by 5% resulted in larger particle sizes and a higher ASR value. This trend was consistent across all operating conditions, indicating that particle size significantly influences the surface area and, consequently, the electrochemical performance of the composite cathodes. Smaller particles increase the surface area and expand the TPB, where the ORR occurs, leading to enhanced cell performance. As highlighted by a previous study, cathode performance depends on factors such as operating temperature, preparation process, microstructure, and grain size [38-39]. This emphasised that an increased TPB area significantly improved electrode performance by facilitating the reaction of gas molecules [40]. Additionally, the presence of secondary phases, such as $BaFe_2O_4$ and CeO_2, did not adversely affect electrochemical performances. Instead, these phases contributed to catalytic activity and structural stability, further enhancing the functionality of the cathode. These findings proved the good effects of incorporating Ag as catalyst material into the BSCF-SDC composite cathode, as it improves thermal compatibility, maintains sufficient porosity, and enhances catalytic activity, all of which are critical for optimising the performance and durability of SOFC cathodes.

4. Conclusion

In conclusion, this study demonstrates that the incorporation of Ag into BSCF-SDC composite cathodes significantly influences their physical, thermal, and electrochemical properties. The optimised porosity range of 35.34% to 36.45% ensures efficient gas diffusion and oxygen transport, which are critical for facilitating the ORR. Furthermore, the particle size analysis revealed a direct correlation between Ag content and particle size enlargement, with all samples maintaining particle size below 1 μm. This is particularly advantageous as nano-powders within this range optimise TPB length, enhancing ORR kinetics and overall electrochemical performance. Additionally, the TEC values improve with increasing Ag content, with the BS-Ag5% sample exhibiting the lowest TEC mismatch (2.1%) relative to the electrolyte, highlighting its superior thermal stability and compatibility. Electrochemical performance analysis revealed that while the ASR tends to increase with higher Ag content, the samples consistently demonstrate favourable performance across all operating temperatures, maintaining a good trend in electrochemical activity. Following this, the appearance of secondary phases ($BaFe_2O_4$ and CeO_2) on the composite cathode pellets after the sintering process did not adversely affect the cell performances; instead, they may have provided catalytic benefits and structural stability. Overall, the BS-Ag composite cathodes exhibit promising potential for low-temperature SOFCs, with their performance strongly dependent on a balance of porosity, particle size, TPB optimisation, and TEC properties. These findings underscore the importance of meticulous material design and processing to develop reliable and efficient cathode materials for advanced SOFC systems, paving the way for their broader use in sustainable energy technologies.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Umira Asyikin Yusop, Hamimah Abd Rahma, Jarod Roharjo;* ***data collection:*** *Umira Asyikin Yusop, Wan Nor Anasuhah Wan Yusoff, Nurul Akidah Baharuddin;* ***analysis and interpretation of results:*** *Umira Asyikin Yusop, Tan Kang Huai;* ***draft manuscript preparation:*** *Umira Asyikin Yusop, Nurul Farhana Abd Rahman, Hamimah Abd Rahman. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Ritchie, H., Roser, M. and Rosado, P. (2022). Energy. Published online at OurWorldInData.org. Retrieved from https://ourworldindata.org/energy.

[2] Satar Bakhsh, Wei Zhang, Kishwar Ali & Judit Olah (2024). Strategy towards sustainable energy transition: The effect of environmental governance, economic complexity and geopolitics. *Energy Strategy Reviews*. 52, 101330, https://doi.org/10.1016/j.esr.2024.101330

[3] Ryan P. O'Hayre (2017). Fuel cells for electrochemical energy conversion. *The European Physical Journal*. 148, 00013, http://dx.doi.org/10.1051/epjconf/201714800013

[4] Jingjing Li, Junhan Cheng, Yubing Zhang, Zhonghao Chen, Mahmoud Nasr, Mohamed Farghali, David W. Rooney, Pow-Seng Yap & Ahmed I. Osman (2024). Advancements in Solid Oxide Fuel Cell Technology: Bridging Performance Gaps for Enhanced Environmental Sustainability. *Advanced Energy and Sustainability Research*. 5, 2400132, https://doi.org/10.1002/aesr.202400132

[5] Orlando Corigliano, Leonardo Pagnotta & Petronilla Fragiacom (2022). On the Technology of Solid Oxide Fuel Cell (SOFC) Energy Systems for Stationary Power Generation: A Review. *Sustainability*. 14, 15276, https://doi.org/10.3390/su142215276

[6] Kairat A. Kuterbekov, Alexey V. Nikonov, Kenzhebatyr Zh. Bekmyrza, Nikita B. Pavzderin, Asset M. Kabyshev, Marzhan M. Kubenova, Gaukhar D. Kabdrakhimova & Nursultan Aidarbekov (2022). Classification of Solid Oxide Fuel Cells. *Nanomaterials*. 12, 1059, https://doi.org/10.3390/nano12071059

[7] Nagihan Delibaş, Soudabeh Barhami Gharamaleki, Masrour Mansouri & Aligholi Niaie (2022). Reduction of operation temperature in SOFCs utilising perovskites: Review. *International Advanced Research and Engineering Journal*. 06(01), pp. 056-067, http://dx.doi.org/10.35860/iarej.972864

[8] Ruijia Xu, Shuai Liu, Meiting Yang, Guangming Yang, Zhixin Luo, Ran Ran, Wei Zhou & Zongping Shao (2024). Advancements and prospects of perovskite-based fuel electrodes in solid oxide cells for CO_2 electrolysis to CO. *Chemical Science*. 15, pp. 11166-11187, https://doi.org/10.1039/D4SC03306J

[9] Kairat A. Kuterbekov, Asset M. Kabyshev, Kenzhebatyr Zh. Bekmyrza, Marzhan M. Kubenova, Gaukhar Kabdrakhimova, Iroda Abdullayeva & Abebe Temesgen Ayalew (2025). Advancements in electrolyte materials and hybrid integration for enhanced solid oxide fuel cell performance. *International Journal of Low-Carbon Technologies*. 20, pp. 353–367, https://doi.org/10.1093/ijlct/ctaf007

[10] Catarina Mendonca, Antonio Ferreira & Diogo M. F Santos (2021). Towards the Commercialisation of Solid Oxide Fuel Cells: Recent Advances in Materials and Integration Strategies. *Fuels*, 2(4), pp. 393-419, https://doi.org/10.3390/fuels2040023

[11] Shammya Afroze, AfizulHakem Karim, Quentin Cheok, Sten Eriksson & Abul Azad (2019). Latest development of double perovskite electrode materials for solid oxide fuel cells: a review. *Front Energy*. 13(4), pp. 770–797, http://dx.doi.org/10.1007/s11708-019-0651-x

[12] Prerna Vinchhi, Mukesh Khandla, Kiran Chaudhary & Ranjan Pati (2023). Recent advances on electrolyte materials for SOFC: A review. *Inorganic Chemistry Communications*. 152, 110724, https://doi.org/10.1016/j.inoche.2023.110724

[13] Huangang Shi, Chao Su, Ran Ran, Jiafeng Cao & Zongping Shao (2020). Electrolyte materials for intermediate-temperature solid oxide fuel cells. *Progress in Natural Science: Materials International*. 30, pp. 764–774, https://doi.org/10.1016/j.pnsc.2020.09.003

[14] Tan Kang Huai., Hamimah Abd Rahman, Mohammad Saifulddin Mohd Azami, Umira Asyikin Yusop, Nurul Akidah Baharuddin & Muhammad Izzat Nor Ma'arof (2022). Electrochemical and material characteristics of $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$-$Sm_{0.2}Ce_{0.8}O_{1.9}$ carbonate perovskite cathode composite for low-temperature solid oxide fuel cell. *Ceramics International*. 48, pp. 34258–34264, https://doi.org/10.1016/j.ceramint.2022.07.325

[15] Umira Asyikin Yusop, Hamimah Abd Rahman & Tan Kang Huai (2019). Effect of Ag Addition on the Structural Properties of $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$-$Sm_{0.2}Ce_{0.8}O_{1.9}$ Composite Cathode Powder. The *International Journal of Integrated Engineering*. 11(7), pp. 169-175, https://doi.org/10.30880/ijie.2019.11.07.022

[16] Sanaz Zarabi Golkhatmi, Muhammad Imran Asghar & Peter D. Lund (2022). A review on solid oxide fuel cell durability: Latest progress, mechanisms, and study tools. *Renewable and Sustainable Energy Reviews*. 161, 112339, https://doi.org/10.1016/j.rser.2022.112339

[17] M. Enterría, A. Letona-Elizburu, L. Medinilla, M. Echeverría & N. Ortiz-Vitoriano (2022). Controlling the triple-phase boundary on Na-O_2 battery cathodes with perfluorinated polymers. *Electrochimica Acta*. 435, 141375, https://doi.org/10.1016/j.electacta.2022.141375

[18] Ling Hu, Defeng Zhou, Xiaofei Zhu, Ning Wang, Jinghe Bai, Huifang Gong, Youjie Zhang, Yunlong Chen, Wenfu Yan, Qiurong Zhu (2024). A high-performance composite cathode based on thermal expansion complementation for SOFC. *Fuel*. 362, 130864, https://doi.org/10.1016/j.fuel.2024.130864

[19] Nilam Shah, Tianjiu Zhu, Desheng Feng, Xiaoyong Xu, Fengli Liang, Hao Wang, Zhonghua Zhu & Lei Ge (2024). Fine-tuning thermal expansion characteristics of solid oxide fuel cell cathode via composite cathode fabrication. *Journal of Power Sources*. 616, 235143, https://doi.org/10.1016/j.jpowsour.2024.235143

[20] Kursat Icin, Sultan Ozturk, Damla Dilara Çakil & Sefa emre Sunbul (2020). Effect of the stoichiometric ratio on phase evolution and magnetic properties of SrFe12O19 produced with mechanochemical process using mill scale. *Ceramics International*. 46, pp. 14150-14160, http://dx.doi.org/10.1016/j.ceramint.2020.02.222

[21] Abdulmumeen Lohmaah, Komkrich Chokprasombat, Supree Pinitsoontorn & Chitnarong Sirisathitkul (2021). Magnetic Properties and Morphology Copper-Substituted Barium Hexaferrites from Sol-Gel Auto-Combustion Synthesis. *Materials*. 14, 5873, https://doi.org/10.3390/ma14195873

[22] Siti Fairus Mohammad, Sufizar Ahmad1, Hamimah Abdul Rahman & Andanastuti Muchtar (2019). Effect of SSC Loading and Calcination Temperature on The Phase and Microstructure Formation of SSC-SDCC Cathode. *International Journal of Integrated Engineering*. 11(7), pp. 162-168, https://doi.org/10.30880/ijie.2019.11.07.021

[23] Jingchun Yan, Rong Sun, Laihong Shen, Hongcun Bai, Shouxi Jiang, Yan Xiao & Tao Song (2020). Hydrogen-rich syngas production with tar elimination via biomass chemical looping gasification (BCLG) using BaFe2O4/Al2O3 as oxygen carrier. *Chemical Engineering Journal*. 387, 124107, http://dx.doi.org/10.1016/j.cej.2020.124107

[24] Thanh Son Cam, Shamil Omarovich Omaroy, Maria Igorevna Chebanenko, Svetlana Georgievna Izotova & Vadim Igorevich Popkov (2022). Recent progress in the synthesis of CeO_2-based nano catalysts towards efficient oxidation of CO. Journal of Science: *Advanced Materials and Devices*. 7(1), 100399, https://doi.org/10.1016/j.jsamd.2021.11.001

[25] Tafadzwa Precious Mabate, Nomathamsanqa Prudence Maqunga, Sinemihlali Ntshibongo, Mulisa Maumela & Ndzondelelo Bingwa (2023). Metal oxides and their roles in heterogenous catalysis: special emphasis on synthesis protocols, intrinsic properties, and their influence in transfer hydrogenation reactions. *SN Applied Sciences*. 196(5), http://dx.doi.org/10.1007/s42452-023-05416-6

[26] Marvin Cronau, Marc Duchardt, Marvin Szabo & Bernhard Roling (2022). Ionic Conductivity versus Particle Size of Ball-Milled Sulfide-Based Solid Electrolytes: Strategy Towards Optimized Composite Cathode Performance in All-Solid-State Batteries. *Batteries & Supercaps*. 5(6), https://doi.org/10.1002/batt.202200041

[27] Shurui Tang, Min Fu, Zhenhao, Qin, Yang Gao & Zetian Tao (2025). Topological Ion Optimized Composite Cathode for Proton-Conducting Solid Oxide Fuel Cells. *Advanced Functional Materials*. 2501995, https://doi.org/10.1002/adfm.202501995

[28] Yangyang Wang, Chaofan Li, Huiling Guo, Shabir Ahmad, Wasif ur Rehman, Pan Zhang, Chunmei Ban, Xue-Ping Gao (2025). Origin and suppression of structural degradation in Ni-rich layered oxide cathodes at elevated temperatures. *Energy Storage Materials*. 80, 104413, https://doi.org/10.1016/j.ensm.2025.104413

[29] Shuai He & San Ping Jiang (2021). Electrode/electrolyte interface & interface reactions of solid oxide cells: Recent development and advances. *Progress in Natural Science: Materials International*. 31(3), pp. 341-372, https://doi.org/10.1016/j.pnsc.2021.03.002

[30] Muhammed Ali Shaikh Abdul Kader Abdul Hameed, Andanastuti Muchtar, Jarot Raharjo & Deni Shidqi Khaerudini (2022). A Review on the Process-Structure-Performance of Lanthanum Strontium Cobalt Ferrite Oxidefor Solid Oxide Fuel Cells Cathodes. *International Journal of Integrated Engineering*. 14(2), pp. 121-137, https://doi.org/10.30880/ijie.2022.14.02.017

[31] Sangbong Ryu, Jaewon Hwang, Sanghoon Lee, Wonyeop Jeong, Myung Seok Lee, Wonjong Yu & Suk Won Cha (2025). Nanostructured thin film $SrCo_{0.8}Nb_{0.1}Ta_{0.1}O_{3-\delta}$ cathode for low-temperature solid oxide fuel cells. *International Journal of Hydrogen Energy*. 104, pp. 558-565, https://doi.org/10.1016/j.ijhydene.2024.08.349

[32] Mohsen Fallah Vostakola & Bahman Amini Horri (2021). Progress in Material Development for Low-Temperature Solid Oxide Fuel Cells: A Review. *Discover Nano*. 18, 89, https://doi.org/10.3390/en14051280

[33] Ashok Kumar Baral, Sungmin Choi, Byung Kook Kim & Jong-Ho Lee (2014). Processing and characterizations of a novel proton-conducting $BaCe_{0.35}Zr_{0.50}Y_{0.15}O_{3-\delta}$ electrolyte and its nickel-based anode composite for anode-supported IT-SOFC. *Material Renew Sustain Energy*. 3(35), https://doi.org/10.1007/s40243-014-0035-4

[34] Ting Chen, Huilin Zhang, Guozhu Zheng, Qiang Xue, Zuzhi Huang, Yucun Zhou & Shaorong Wang (2024). A High-Strength Solid Oxide Fuel Cell Supported by an Ordered Porous Cathode Membrane. *Membranes*. 14(2), 44, https://doi.org/10.3390/membranes14020044

[35] Saman Rashidi, Nader Karimi, Bengt Sunden, Kyung Chun Kim, Abdul Ghani Olabi & Omid Mahian (2022). Progress and challenges on the thermal management of electrochemical energy conversion and storage technologies: Fuel cells, electrolysers, and supercapacitors. Progress in Energy and Combustion Science—Google Search, 88, 100966, https://doi.org/10.1016/j.pecs.2021.100966

[36] Mudasir A. Yatoo, Faiza Habib, Akhtar Hussain Malik, Mohsin Jahan Qazi, Sharique Ahmad, Mohd Azhardin Ganayee & Zubair Ahmad (2023). Solid-oxide fuel cells: A critical review of materials for cell components. *MRS Communications*. 13, pp. 378-384, http://dx.doi.org/10.1557/s43579-023-00371-0

[37] Mojgan Ahmadrezaei, Muhammad Ali Shaikh Abdul, Andanastuti Muchtar, Tan, C. Y. & Mahendra Rao Somalu (2014). Thermal expansion behaviour of the $Ba_{0.2}Sr_{0.8}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF) with $Sm_{0.2}Ce_{0.8}O_{1.9}$. *Ceramics*. 58(1), pp. 46-49, https://doi.org/10.6084/M9.FIGSHARE.4203384.V2

[38] Mandeep Singh, Dario Zappa & Elisabetta Comini (2021). Solid oxide fuel cell: Decade of progress, future perspectives and challenges. *International Journal of Hydrogen Energy*. 46(54), pp. 27643-27674, https://doi.org/10.1016/j.ijhydene.2021.06.020

[39] Adi Subardi, Ade Intra, Jan Setiawan & Yen-Pei Fu (2023). Structural and Electrochemical Analysis of Sm Ba0.8Sr0.2Co2O5+δ Cathode Oxide for IT-SOFCs. *International Journal of Integrated Egineering*. 15(1), pp. 173-179, https://doi.org/10.30880/ijie.2023.15.01.015

[40] Anil Kumar Yadav, Shailendra Sinha & Anil Kumar (2024). Advancements in composite cathodes for intermediate-temperature solid oxide fuel cells: A comprehensive review. *International Journal of Hydrogen Energy*. 59, pp. 1080-1093, https://doi.org/10.1016/j.ijhydene.2024.02.124