Research Article

Comparative Study of SSC Cathode Materials for IT-SOFC Applications: Short Review

Mohammad Fikrey Roslan[1], Hamimah Abd Rahman[2, *], Rafidah Abd Karim[3], and Mohamed Saiful Firdaus Hussin[4]

1 Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia 1; fikrey.roslan@gmail.com; 0000-0003-4010-5790
2 Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia 2; hamimah@uthm.edu.my; 0000-0001-5258-3656
3 Department of English and Linguistics, Universiti Teknologi Mara, Tapah Campus, Malaysia 3; feida16@uitm.edu.my; 0000-0001-9147-6191
4 Faculty of Technology and Mechanical Engineering, Universiti Teknikal Malaysia Melaka 4; mohamed.saiful@utem.edu.my; 0000-0002-0734-8806
* Correspondence: hamimah@uthm.edu.my; 0197512707.

Abstract: *Solid Oxide Fuel Cells (SOFCs) have the potential to revolutionize the energy landscape with their high efficiency and clean operation. However, a major hurdle lies in their traditional high operating temperatures, which translate to longer startup times and expensive materials. Intermediate-Temperature SOFCs (IT-SOFCs) offer a solution by operating at significantly lower temperatures, but their efficiency relies heavily on the performance of the cathode, the component responsible for the critical oxygen reduction reaction. This review investigates Sm0.5Sr0.5CoO3-δ (SSC) as a promising cathode material for IT-SOFCs due to its inherent activity and compatible thermal expansion. We explore how scientists are pushing the boundaries of SSC performance through various strategies like doping with specific elements, optimizing the internal microstructure, and even creating composites with other materials. By comparing the performance and activity of different modified SSC cathodes reported in recent research, the review sheds light on the most promising approaches. However, challenges remain, including maintaining activity at even lower temperatures and ensuring long-term stability. The future of SSC research lies in addressing these challenges and exploring exciting avenues like identifying new dopants or composite materials. By overcoming these hurdles, SSC has the potential to become a key player in the development of highly efficient and commercially viable IT-SOFCs, paving the way for a cleaner and more sustainable energy future.*

Keywords: IT-SOFC (Intermediate-Temperature Solid Oxide Fuel Cell), Cathode Materials, SSC (Sm0.5Sr0.5CoO3-δ).

DOI: 10.5281/zenodo.11163849

1. INTRODUCTION

1.1 Introduction of Solid Oxide Fuel Cells (SOFCs)

SOFCs, which stand for solid oxide fuel cells, are a promising technology in the field of clean energy owing to the high energy conversion efficiency they possess as well as the possible environmental advantages they might provide. In comparison to other electrolysis methods and fuel cells, solid oxide fuel cells (SOFCs), which are made up entirely of solid components, have a number of benefits (Hauch et al., 2020; Shu et al., 2023) as shown in Figure 1. According to Wu (2023), one of the most significant benefits of solid oxide fuel cells (SOFCs) is their high energy conversion efficiency, which makes them a feasible alternative for achieving carbon neutralization and lowering emissions of greenhouse gases. In addition, solid oxide fuel cells (SOFCs) have the capability of functioning at lower temperatures, which results in faster start-up times and increased long-term stability. This is an essential feature for a wide range of applications, ranging from small-scale portable devices to large distributed power generating systems (Lee et al., 2014).

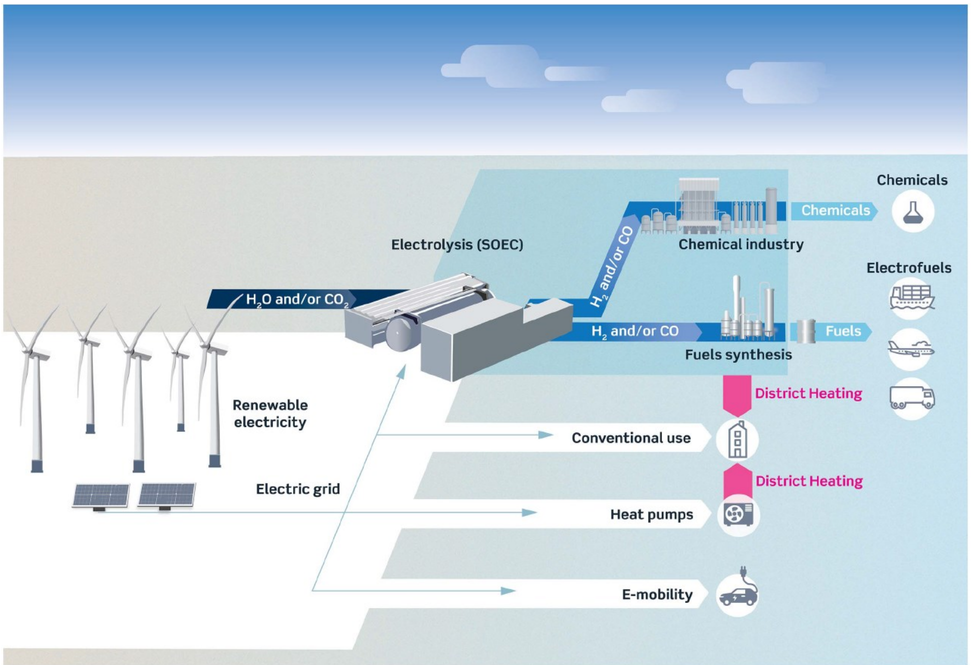

Figure 1. Illustration of energy system based 100% on renewable energy (Haunch et al., 2020).

Additionally, Solid Oxide Electrolysis Cells (SOECs), which are a form of Solid Oxide Fuel Cells (SOFCs) that operate in a reversible mode, make it possible to produce hydrogen through high-temperature electrolysis. Not only does this approach lessen the demand for power, but it also eliminates the requirement for noble metals to be used as electrode catalysts. As a result, it provides an alternative for the creation of hydrogen that is both cost-effective and environmentally friendly (Bi et al., 2014). Because of their adaptability, solid oxide fuel cells (SOFCs) can operate in both fuel cell and electrolysis modes, which shows their potential to make a substantial contribution to the shift towards a cleaner and more sustainable energy environment.

In conclusion, Solid oxide fuel cells (SOFCs) have garnered significant interest for their notable efficiency, ability to use many fuels, and environmentally friendly nature (Roslan, M. F. et al., 2023). SOFCs represent a cutting-edge technology with the potential to revolutionize the energy sector by offering high efficiency, environmental benefits, and versatility in various applications. Continued research and development in this field are essential to unlock the full potential of SOFCs and accelerate their adoption on a larger scale, ultimately contributing to a greener and more sustainable future.

1.2 Intermediate-Temperature SOFCs (IT-SOFCs) and their operational advantages

Intermediate-Temperature Solid Oxide Fuel Cells, also known as IT-SOFCs, are a variation of solid oxide fuel cells (SOFCs) that function at temperatures that are lower than those of conventional high-temperature SOFCs. The temperature range in which IT-SOFCs commonly operate is between 500 and 700 degrees Celsius, which provides a number of operating benefits (Gao et al., 2016; Zhang & Hu, 2021). According to Gao et al. (2016), one of the most significant benefits of IT-SOFCs is that they have a lower working temperature. This results in shorter start-up times and less thermal stress on the materials, which in turn contributes to increased durability and a longer lifespan for the electrochemical cells. Additionally, working at intermediate temperatures enables the utilization of materials and components that are less expensive, which has the potential to cut the costs of production and make IT-SOFCs more economically viable (Chasta et al., 2022).

Furthermore, IT-SOFCs have demonstrated excellent performance in terms of efficiency and power output, which makes them appropriate for a variety of applications in the production of electricity, including those that are fixed and mobile (Zhang & Hu, 2021). There is also the possibility of using proton-conducting oxides as electrolytes, which can further improve the overall performance and efficiency of the cells (Zhang & Hu, 2021). This is made possible by the lower operating temperatures of IT-SOFCs. Furthermore, it has been determined that IT-SOFCs are an essential technology for applications such as electrolyzers and thermochemical water splitting, which highlights the adaptability and promise of these devices in the field of clean energy (Cavallaro et al., 2021).

Despite the fact that IT-SOFCs have a number of benefits, there are a few obstacles that have been observed. One of these challenges is higher polarization losses in the intermediate temperature range, which can have an effect on the overall performance of the cells (Yu et al., 2020). In order to further maximize the efficiency and reliability of IT-SOFCs for wider deployment in a variety of energy applications, it is essential to address these problems via continued research and development.

In conclusion, Intermediate-Temperature Solid Oxide Fuel Cells offer operational advantages such as improved durability, lower manufacturing costs, enhanced efficiency, and versatility in applications, positioning them as a promising technology in the transition towards a more sustainable and efficient energy landscape.

1.3 Importance of cathode materials in SOFC performance

Because they promote the interaction between oxygen in the air and ions from the electrolyte, the cathode materials are crucial components in Solid Oxide Fuel Cells (SOFCs). As a result, they have an effect on the performance of the cell (Ren et al., 2020; Kim et al., 2014). It is essential for cathode materials to possess tailored features, such as strong proton conductivity and optimal oxygen vacancy concentration, in order to facilitate rapid and effective proton transport inside the cell (Xu et al., 2022).

In comparison to other cathode materials, triple-conducting layered perovskites have been shown to possess higher proton-conducting capabilities, which makes them a potentially useful alternative for solid oxide fuel cell (SOFC) cathodes, according to research conducted by. The in-situ synthesis of Co3O4 as a result of Li-evaporation in LiCoO2 has also been demonstrated to considerably improve cathode performance. This is accomplished by lowering the formation energy of oxygen vacancies, as demonstrated by. In order to enhance the performance of solid oxide fuel cells (SOFCs), our findings highlight the significance of developing novel methods to the design of cathode materials.

According to Ren et al.'s research from 2020, the movement of electrons, protons, and oxygen ions within the cathode is an essential factor in determining the efficiency of solid oxide fuel cells (SOFCs). In addition, research has been conducted to investigate the utilization of high-entropy spinel ceramic oxides as cathode materials. These oxides have demonstrated their potential to offer superior performance and efficiency in proton-conducting solid oxide fuel cells (Kim et al., 2014) also showed in Figure 2. Consequently, these improvements highlight the significant role that cathode materials play in increasing the functionality and efficiency of solid oxide fuel cells (SOFCs), thereby opening the way for the development of fuel cell technologies of the next generation.

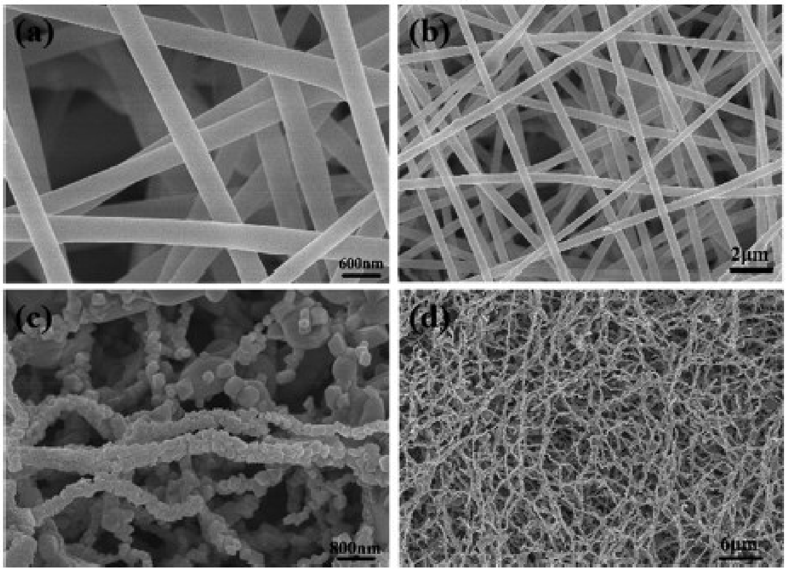

Figure 2. SEM micrographs of PVP/CuCo2O4-ESB composite fiber precursors at (a) 20k and (b) 7k. The morphologies of CuCo2O4-ESB complex fibers after calcination in air at (c) 15k and (d) 2.2k (Yu et al., 2020).

Therefore, in order to improve the performance, efficiency, and dependability of solid oxide fuel cells (SOFCs), it is of the utmost importance to carefully choose and design the cathode materials. Research that is now being conducted with the objective of enhancing the characteristics of cathode materials is very necessary for the development of solid oxide fuel cell technology and the promotion of its widespread use in a variety of energy applications.

1.4 Introduce $Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ (SSC) as a promising cathode material for IT-SOFCs

Due to its remarkable features and performance characteristics, Sm0.5Sr0.5CoO3-δ (SSC) has demonstrated its potential as a cathode material for Intermediate-Temperature Solid Oxide Fuel Cells (IT-SOFCs), as stated by Ju et al. (2014) in Figure 3. Research conducted by Ju et al. (2014) has revealed that the incorporation of SSC into a double columnar functional interlayer (DCFL) with Sm0.2Ce0.8O2-δ (SDC) has the potential to improve cathodic performance by enhancing oxygen diffusivity and reduction activity. The potential of SSC to improve the functionality and efficiency of IT-SOFC cathodes is shown by this new technique, which highlights the promise of SSC.

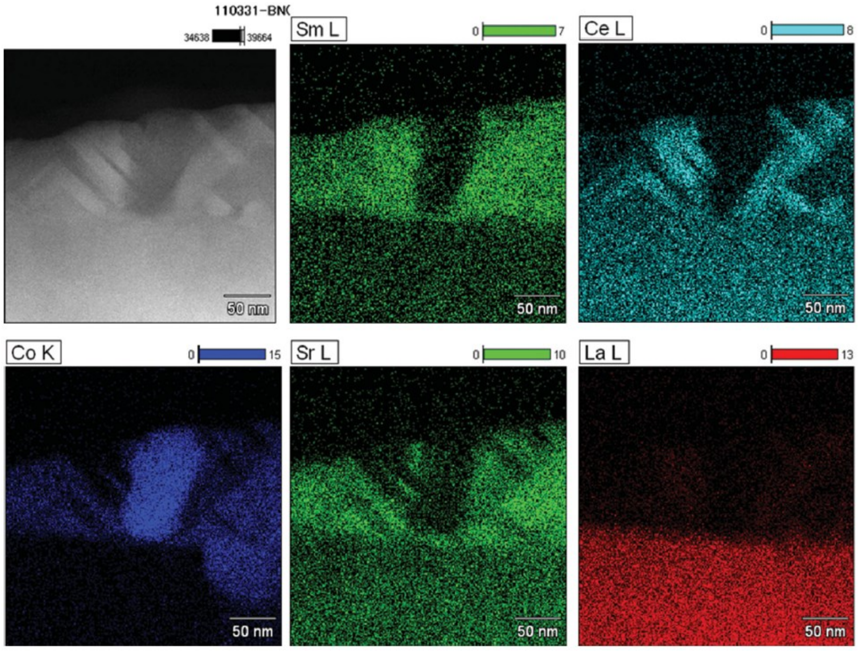

Figure 3. Elemental distributions in the deposited fi lms: SDC, SSC and LSGM (Ju et al. (2014)).

Furthermore, spray pyrolysis has been used to successfully apply SSC in thin layers at the electrode-electrolyte interface. This was proved by the fact that According to Kamecki et al. (2021), this technique makes it possible to produce thin layers of mixed ionic and electronic conductors, one example of which is SSC. These layers have the potential to improve the performance of the oxygen electrode in IT-SOFCs. The application of SSC in such configurations exemplifies the versatility and adaptability of the material as a cathode for the purpose of enhancing the overall performance of solid oxide fuel cells (SOFCs).

SSC is a material that is appropriate for use in IT-SOFC cathodes due to its significant qualities, such as its strong ionic and electronic conductivity. These properties make it possible for SSC to facilitate effective oxygen reduction processes at intermediate temperatures. The current research and development efforts that are focused on SSC highlight its potential to enhance IT-SOFC technology, which will ultimately contribute to the creation of energy conversion systems that are more efficient and sustainable.

SSC is a potential cathode material for IT-SOFCs, delivering higher performance, improved oxygen electrode functioning, and the ability to stimulate innovation in solid oxide fuel cell technology. In conclusion, SSC makes a promising contribution to the field of solid oxide fuel cells.

2. BACKGROUND ON IT-SOFCS AND CATHODE MATERIALS

2.1 Operating temperature range of IT-SOFCs

When compared to high-temperature solid oxide fuel cells (SOFCs), intermediate-temperature solid oxide fuel cells (IT-SOFCs) often operate at a lower temperature range. This provides a number of benefits, including increased efficiency and compatibility with a wider variety of materials (Cascos et al., 2020; Radenahmad et al., 2020). IT-SOFCs are able to work well at temperatures ranging from 600 to 850 °C, whereas high-temperature SOFCs are often only able to function at temperatures that are higher than 800°C (Cascos et al., 2020). This lower working temperature range of IT-SOFCs makes it possible to use a wider variety of materials that are compatible with one another and makes it easier to include innovative materials for the cathode, electrolyte, and anode (Cascos et al., 2020).

Using a BCFZY-ZnO electrolyte, research conducted by has proven that it is possible to operate IT-SOFCs within the temperature range of 400-500 degrees Celsius. This demonstrates the possibility for obtaining high ionic conductivity and power densities at these lower temperatures (Chen et al., 2019). This exemplifies the versatility of IT-SOFCs to function well within temperature ranges that are lower, which enables improved performance and efficiency in energy conversion.

According to Radenahmad et al.'s research from 2020, high-temperature solid oxide fuel cells (SOFCs), which include those that use yttria-stabilized zirconia (YSZ) electrolytes, generally function at temperatures that range from 700 to 1000 degrees Celsius. The lower working temperatures of IT-SOFCs provide advantages in terms of material compatibility, decreased thermal stress, and possible cost savings (Cascos et al., 2020). High-temperature SOFCs have been widely utilized and explored, while IT-SOFCs have lower operating temperatures.

Generally speaking, as shown in Figure 4, the operating temperature range of IT-SOFCs, which commonly falls between 600 and 850 degrees Celsius, is a viable alternative to high-temperature SOFCs. This option offers enhanced material flexibility, efficiency, and performance in a variety of applications that include energy conversion systems.

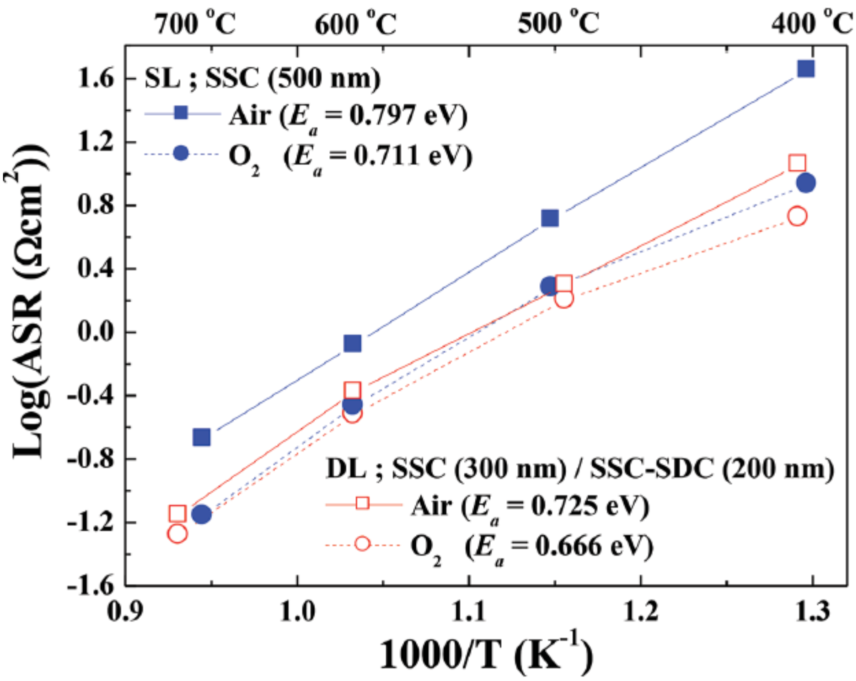

Figure 4. Temperature dependence of the ASR for the *SL* sample (Sm 0.5 Sr 0.5 CoO 3−δ ; SSC) and the *DL* sample (SSC/SSC–Sm 0.2 Ce 0.8 O 2− δ : SDC) in air and O 2 (Ju et al., 2014).

2.2 Role of the cathode in the electrochemical reactions within an SOFC

It is necessary for the cathode in a Solid Oxide Fuel Cell (SOFC) to provide catalytic activity and extend active sites throughout the whole cathode surface in order to facilitate electrochemical processes, notably the oxygen reduction reaction (ORR). This is because the cathode is responsible for maximizing the number of active sites that are available. In order to improve the catalytic activity of the ORR, the cathodes of solid oxide fuel cells (SOFCs) are commonly constructed out of mixed ionic and electronic conductors (MIECs) (Kim et al., 2014).

In Protonic Ceramic Fuel Cells (PCFCs) and dual-ion Fuel Cells (FCs), cathodes that have a high proton conductivity are essential for encouraging cathodic reactions. This is accomplished by extending electrochemically active sites from the triple-phase boundaries (TPB) over the whole surface of the cathode (Song et al., 2019). Because of this increase of active sites, proton transport inside the cathode may be carried out with greater efficiency, which in turn makes it easier for the processes that are required for energy conversion within the cell.

Furthermore, the choice of cathode materials has a substantial influence on the movement of protons, oxygen ions, and electrons inside the cathode, all of which are essential for achieving optimal cathode performance in solid oxide fuel cells (SOFCs) (Yang et al., 2022). According to Xu et al.'s research from 2022, the efficiency and stability of the cell are also affected by the interactions that take place between the cathode material, the electrolyte, and the anode layers.

To summarize, the cathode of a solid oxide fuel cell (SOFC) plays a significant role in promoting electrochemical processes, particularly the oxygen reduction reaction (ORR), by means of catalytic activity, the expansion of active sites, and the efficient transport of proton. One of the most important factors in improving the performance and efficiency of solid oxide fuel cells (SOFCs) and expanding the technology behind solid oxide fuel cells is the careful selection and design of cathode materials.

2.3 Key properties desired in IT-SOFC cathode materials (e.g., high ionic and electronic conductivity, good electrocatalytic activity for oxygen reduction reaction (ORR), thermal expansion coefficient compatibility with electrolyte)

There are several key properties that are desired in cathode materials for Intermediate-Temperature Solid Oxide Fuel Cells (IT-SOFC). These properties include high ionic and electronic conductivity, good electrocatalytic activity for the oxygen reduction reaction (ORR), and thermal expansion coefficient compatibility with the electrolyte (Duan et al., 2015; Kim et al., 2014; Wang et al., 2022; Yin, 2023; Yang et al., 2022).

According to Duan et al. (2015), increased ionic and electronic conductivity is essential for effective charge transfer inside the cathode material. This facilitates the initiation of electrochemical processes at a faster rate and improves the overall performance of the cell. In order to enhance the oxygen reduction reaction kinetics at intermediate to low temperatures, materials such as BaCo (0.4)Fe(0.4)Zr(0.1)Y(0.1)O(3-δ) (BCFZY0.1) have been created. These materials demonstrate the significance of conductivity in cathode materials, as the research conducted by Duan et al. in 2015 has also demonstrated as Figure 5.

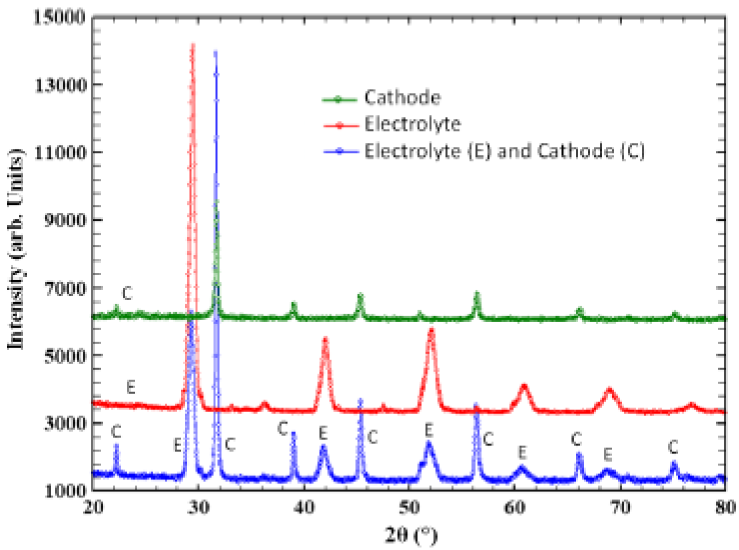

Figure 5. The XRD profiles of pure BSCF cathode, pure BSCZYSm electrolyte, and BSCZYSm–BSCF (Radenahmad et al., 2020).

The oxygen reduction process is a critical phase in the energy conversion process that takes place within SOFCs (Kim et al., 2014; Yin, 2023). It is vital for the ORR to have good electrocatalytic activity in order to promote the oxygen reduction process. To greatly improve fuel cell efficiency, cathode materials that possess better electrocatalytic characteristics, such as triple-conducting materials, can be utilized. This is accomplished by increasing the reaction active area and aiding efficient oxygen reduction reaction (ORR) (Yin, 2023).

In addition, it is essential to ensure that the thermal expansion coefficient is compatible with the electrolyte in order to reduce mechanical stress and guarantee the structural integrity of the SOFC components while they are conducting their operations (Yang et al., 2022). According to Yang et al.'s research from 2022, materials such as Ba0.5Sr0.5Co0.8Fe0.2O3−δ, which include Co3O4 additions, have been demonstrated to boost the performance of cathodes in proton-conducting solid oxide fuel cells (SOFCs) and promote catalytic activity as showed in Figure 6.

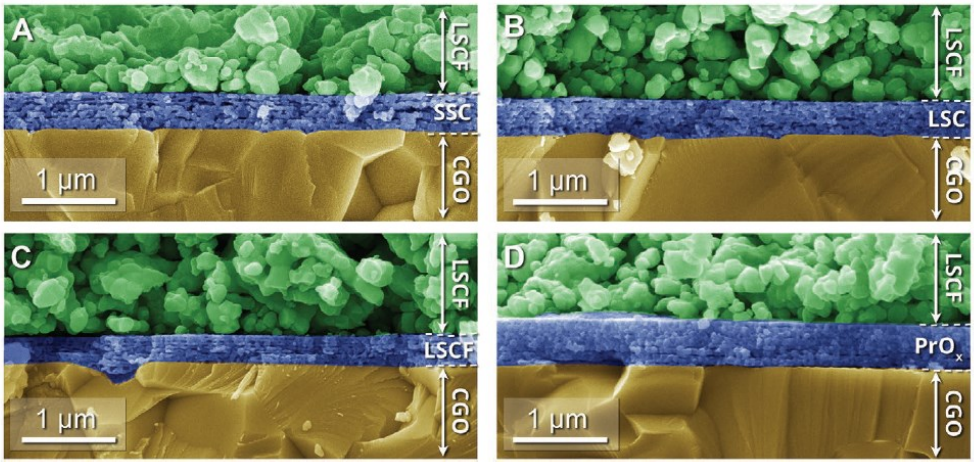

Figure 6 SEM fracture images of the electrolyte–electrode interfaces (observed after the symmetrical electrode test with a maximum exposure temperature of 700 °C) (Kamecki et al.,.2021)

In conclusion, in order to guarantee the effective and dependable functioning of the fuel cell system, the cathode materials of the IT-SOFC should have a high ionic and electronic conductivity, demonstrate a strong electrocatalytic activity for the ORR, and retain thermal expansion coefficient compatibility with the electrolyte.

3. PROPERTIES OF SSC FOR IT-SOFC APPLICATIONS

3.1 The crystal structure and composition of SSC

SSC, which is also known as Sm0.5Sr0.5CoO3-δ, is a material that belongs to the perovskite category and is frequently employed as a cathode in Solid Oxide Fuel Cells (SOFCs) because to its advantageous features. According to Shimada et al. (2016), the crystal structure of SSC is characterized by a cubic perovskite lattice. Within the crystal structure, the A-site is occupied by Sm and Sr ions, while the B-site is occupied by Co ions. This configuration is one of the factors that leads to the high ionic and electronic conductivity of SSC, which makes it an effective material for aiding electrochemical processes in solid oxide fuel cells (SOFCs).

Samarium (Sm) and strontium (Sr) are both present in equal molar ratios in the composition of SSC, which is represented by the formula Sm0.5Sr0.5CoO3-δ. Cobalt (Co) is also present in the molar ratios. As a result of the absence of oxygen (δ) in the formula, oxygen vacancies can be created inside the crystal lattice. These oxygen vacancies are crucial for the transportation of oxygen ions during the electrochemical processes that take place in solid oxide fuel cells (SOFCs) (Shimada et al., 2016). According to Shimada et al. (2016), the nanostructured SSC particles have a narrow size distribution, and each individual particle is made of nano-sized SSC and SDC fragments. This results in an increase in the cathode material's catalytic activity and performance (Roslan, M. F. et al.,2023).

In general, the crystal structure of SSC, which is characterized by its perovskite lattice arrangement, as well as its composition of Sm, Sr, Co, and oxygen vacancies, contribute to its high conductivity, electrocatalytic activity, and suitability as a cathode material in solid oxide fuel cells (SOFCs). This, in turn, enables efficient energy conversion processes within the fuel cell system.

3.2 The advantages of SSC for IT-SOFCs:

3.2.1 High intrinsic electrocatalytic activity for ORR

In example, due to its high intrinsic electrocatalytic activity for the Oxygen Reduction Reaction (ORR), SSC displays considerable benefits for Intermediate-Temperature Solid Oxide Fuel Cells (IT-SOFCs) (Chang-xin et al., 2020; Zhu et al., 2017). However, these advantages are not the only reason why SSC is advantageous. The structure and composition of SSC, which is based on perovskite, contribute to its remarkable catalytic performance, which in turn makes it an effective cathode material for IT-SOFCs.

According to research conducted by Zhu et al. (2017), perovskite oxides, such as SSC, have been shown to possess a high intrinsic catalytic activity for oxygen reduction reaction (ORR). This implies that they have the potential to serve as viable substitutes for noble metal-based catalysts owing to their cost-effectiveness and availability. According to Chang-xin et al.'s research from 2020, the atomic efficiency and one-of-a-kind chemical structures of SSC contribute to strengthen its catalytic performance, which in turn leads to an improvement in the efficiency of the ORR inside SOFCs.

Furthermore, the strong interaction that exists between the crystalline structure of SSC and the carbon framework guarantees the rapid transit of charge, which in turn improves the performance of the ORR and increases the efficiency of energy conversion in IT-SOFCs (Lin et al., 2019). According to Xu et al. (2018), the high electrocatalytic activity of SSC plays a crucial role in enabling the discharge/charge processes that occur within the fuel cell, which eventually results in an improvement in the fuel cell's overall performance and dependability as showed in Figure 7.

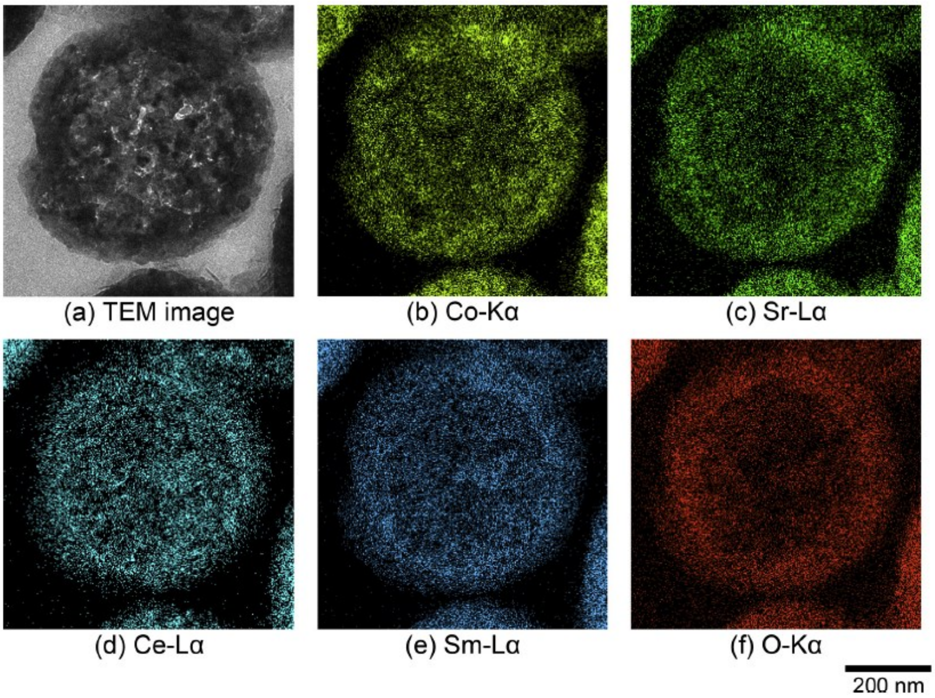

Figure 7. TEM-EDX images of as-prepared SSC-SDC nano-composite powder: (a) TEM image, (b) Co-Ka mapping, (c) Sr-La mapping, (d) Ce-La mapping, (e) Sm-La mapping, and (f) Oka mapping (Shimada et al.,2016).

In conclusion, the high intrinsic electrocatalytic activity of SSC for the ORR validates its status as a cathode material that is both efficient and effective for IT-SOFCs. Because of its one-of-a-kind characteristics and catalytic performance, it contributes to the development of solid oxide fuel cell technology, which provides a solution that is both environmentally friendly and economical for applications involving energy conversion.

3.2.2 Manageable thermal expansion coefficient

SSC provides a number of significant benefits for Intermediate-Temperature Solid Oxide Fuel Cells (IT-SOFCs), one of which is a thermal expansion coefficient that is controllable. This is an essential factor in preserving the structural integrity and lifetime of the fuel cell system (Ding et al., 2014; Hai et al., 2022). According to Hai et al. (2022), it is vital to ensure that the cathode material, electrolyte, and other components are compatible with one another in terms of their thermal expansion coefficient in order to reduce mechanical stress and to keep the stability of the SOFC while it is in operation.

According to research conducted by Hai et al. (2022), the significance of managing thermal expansion coefficients in solid oxide fuel cells (SOFCs) has been brought to light. This is done with the aim of preventing thermal degradation, expansion mismatch, and potential reactions between cell components. These factors can ultimately have an effect on the useful lifetime and performance of the fuel cell system. In addition to contributing to the overall dependability and endurance of IT-SOFCs, the capability of SSC to maintain a thermal expansion coefficient that is controllable ensures that the devices will continue to function consistently over lengthy periods of time (Hai et al., 2022).

Furthermore, the regulated thermal expansion capabilities of SSC play a significant role in minimizing structural damage and preserving the efficiency of the fuel cell, which eventually results in an improvement in the fuel cell's performance and operational stability (Ding et al., 2014). SSC establishes itself as a dependable and efficient cathode material for IT-SOFCs, so making a contribution to the development of solid oxide fuel cell technology. This is all down to the fact that it provides a thermal expansion coefficient that is adequate.

I would like to conclude that the controllable thermal expansion coefficient of SSC is a significant benefit for IT-SOFCs. This advantage ensures the structural integrity, reliability, and long-term performance of the fuel cell system.

3.2.3 Other relevant properties (e.g., chemical stability, sintering behaviour)

In addition to its high inherent electrocatalytic activity, solid-state combustion (SSC) has a number of beneficial features for intermediate-temperature solid oxide fuel cells (IT-SOFCs). According to Filonova and Medvedev (2022), one of the most significant benefits may be attributed to its exceptional chemical stability, which guarantees the fuel cell system's long-term performance and endurance. There is a correlation between the chemical stability of SSC and the dependability of IT-SOFCs. SSC's chemical stability helps to limit deterioration and assures constant functioning over extended periods of time.

Furthermore, SSC demonstrates a favorable sintering behavior, which makes it possible for dense and well-connected structures to be formed inside the cathode material (Mohammad et al., 2019). The microstructure and porosity of the cathode are impacted by the sintering behavior of SSC, which in turn has an effect on the cathode's electrochemical performance and efficiency in solid oxide fuel cells (SOFCs). Additionally, the regulated sintering process boosts the overall stability and functionality of the cathode material, thus increasing the performance of IT-SOFCs.

In addition, the thermal behavior and transport characteristics of SSC are extremely important factors in the utilization of this material as a cathode material in solid oxide fuel cells (SOFCs). In order to optimize the working conditions and efficiency of IT-SOFCs, it is vital to have a solid understanding of the thermal properties of SSC. This will ensure that the performance of the devices remains consistent even when subjected to variable temperatures (Filonova & Medvedev, 2022).

In conclusion, solid sulphur carbide (SSC) is a cathode material for IT-SOFCs that is particularly favorable due to its chemical stability, sintering behavior, and thermal characteristics. This material contributes to the dependability, durability, and efficiency of solid oxide fuel cell systems.

3.3 The limitations of SSC for IT-SOFCs:

3.3.1 Dependence of ORR activity on temperature

One of the drawbacks of $Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ (SSC) for Intermediate-Temperature Solid Oxide Fuel Cells (IT-SOFCs) is that the activity of Oxygen Reduction Reaction (ORR) is dependent on temperature. Specifically, a drop-in activity is found at lower temperatures, as stated by Ding et al. (2014). This behavior, which is reliant on temperature, has the potential to have an effect on the overall performance and efficiency of the fuel cell system, particularly in situations where lower operating temperatures are sought.

Recent research conducted by Ding et al. (2014) has demonstrated that the ORR activity of cathode materials such as SSC can change depending on the temperature. Specifically, a drop-in catalytic activity has been seen at lower temperatures. The total energy conversion efficiency of IT-SOFCs may be negatively impacted as a result of this constraint, which may make it difficult to maintain optimal fuel cell performance under situations of variable temperatures.

The fact that the activity of the ORR is dependent on the temperature in the SSC underscores the necessity of rigorous temperature control and optimization measures in IT-SOFCs in order to guarantee consistent and reliable functioning throughout a wide variety of operating circumstances. In order to improve the performance and stability of SSC-based cathodes in IT-SOFCs, it is essential to address this constraint through the development of unique material designs and methods to system optimization.

In conclusion, the temperature-dependent drop-in ORR activity of SSC provides a major constraint for its implementation in IT-SOFCs. This limitation highlights the need of comprehending and managing this dependence in order to maximize the effectiveness and dependability of solid oxide fuel cell systems.

3.3.2 Other potential limitations (e.g., reactivity with certain electrolytes)

Among the possible limitations of Sm0.5Sr0.5CoO3-δ (SSC) for Intermediate-Temperature Solid Oxide Fuel Cells (IT-SOFCs), one potential constraint is its reactivity with specific electrolytes. This reactivity can have an influence on the stability and performance of the fuel cell system, as stated by He et al. (2022) and Wang et al. (2018) and others. It is possible that the interaction between SSC and certain electrolytes can result in chemical reactions or degradation of the cathode material, which will have an impact on the capacity of the cathode to catalyze processes and the overall efficiency of SOFCs.

Studies have demonstrated that the reactivity of perovskite-type materials, such as SSC, with electrolytes might have an effect on the electrochemical processes that take place within the fuel cell, which may result in a decrease in the cathode's durability and dependability (He et al., 2022). When it comes to preserving the integrity and operation of the SOFC components, the compatibility between SSC and electrolytes is of the utmost important. This highlights the significance of selecting materials that demonstrate little reactivity with the electrolyte.

Furthermore, the influence of gas humidification on the characteristics and performance of perovskite-type functional materials, such as SSC, in proton-conducting solid oxide cells highlights the necessity of addressing possible limits linked to electrolyte interactions in solid oxide fuel cells (Wang et al., 2018). For the purpose of maximizing the performance and lifetime of IT-SOFCs, it is vital to understand and mitigate the reactivity of SSC with certain electrolytes. This will provide stable operation and efficiency in a variety of energy conversion applications.

In conclusion, the reactivity of solid silver chloride (SSC) with certain electrolytes is a possible barrier for its employment in iterative solid oxide fuel cells (IT-SOFCs). This highlights the need of taking into consideration the compatibility of materials and overcoming the issues associated with electrolyte interactions in solid oxide fuel cell technology.

4. COMPARATIVE STUDY OF SSC CATHODE MATERIALS

4.1 Strategies for improving the performance of SSC cathodes for IT-SOFCs:

4.1.1 Doping with other elements

When it comes to improving the performance of SSC cathodes in Intermediate-Temperature Solid Oxide Fuel Cells (IT-SOFCs), one popular method is to dope the cathodes with additional elements. Different dopants may be added to SSC in order to adjust its characteristics and enhance its catalytic activity for the Oxygen Reduction Reaction (ORR) (Xu et al., 2019; Wu et al., 2021; Chen et al., 2014). This can be accomplished by introducing different dopants.

One strategy includes doping the perovskite cathode with particular elements in order to modify the cations that are present in the cathode. According to Xu et al. (2019), the purpose of this technique is to improve the hydration capacity and proton migration inside the cathode material, which will ultimately result in enhanced fuel cell performance. In order to improve the efficiency of SSC in IT-SOFCs, it is possible to adjust its conductivity and reactivity by the careful selection of dopants during the process.

Zirconium doping of the conventional LaMnO3 cathode material is yet another approach that has proven to be successful. This doping technique has been demonstrated to increase the performance and stability of the cathode, bringing it back to intermediate temperatures and opening up new paths for research on LSM-based materials as cathodes for solid oxide fuel cells (Wu et al., 2021). When zinc ions are added to SSC, the electrochemical characteristics of the material can be improved, resulting in a cathode material that is more efficient for use in IT-SOFCs.

In addition, it has been established that the utilization of a three-dimensional core-shell design that is generated by infiltration and reactive sintering may improve the efficiency of SSC cathodes as well as their thermal stability. This method produces cathodes that have a high electrochemical performance and stability, which makes them appropriate for use in solid oxide fuel cells (SOFCs) for extended periods of time.

As a conclusion, doping SSC with various elements provides a varied and economical technique for boosting the performance of cathodes in IT-SOFCs. This strategy enhances the cathodes' catalytic activity, conductivity, and stability, which in turn allows for more efficient energy conversion processes.

4.1.2 Microstructure optimization (e.g., porosity control, creation of triple-phase boundaries)

In order to improve the performance of intermediate-temperature solid oxide fuel cells (IT-SOFCs), one of the most important strategies is to optimize the microstructure of the cathodes of the SSC. Microstructure optimization is a vital feature that may considerably improve the efficiency and functionality of the cathode material (Ju et al., 2014; Lichtner et al., 2015). Controlling porosity and establishing triple-phase boundaries (TPBs) are two of the most important parts of microstructure optimization.

It is possible to increase the performance of fuel cells by altering the porosity of the SSC cathode. This will allow for the optimization of the gas diffusion paths and the active surface area for electrochemical processes (Lichtner et al., 2015). According to Lichtner et al. (2015), the construction of a hierarchical porosity structure using processes such as freeze-casting enables improved gas access to TPBs, which in turn ensures effective gas-phase reactions and electron/ion transport inside the cathode.

Furthermore, the creation of TPBs at the interfaces of the cathode material, electrolyte, and anode is necessary for the promotion of electrochemical processes in fuel cells that use solid oxide fuel cells (SOFCs). According to Ju et al. (2014), strategies such as the creation of a nano gradient composite structure have the potential to boost oxygen diffusivity and reduction activity. This is accomplished by increasing the TPB density and making it easier for gas to move during the cathode material's travel.

When it comes to maximizing the performance of SSC cathodes, the dispersion and connectivity of the microstructure are also extremely important factors to consider. According to Lichtner et al. (2015), the microstructure design of IT-SOFCs should take into account a number of important factors in order to improve the efficiency and stability of the devices. These factors include ensuring high electrical and ionic conductivity, increasing TPB density, and giving sufficient gas access to TPBs.

In conclusion, microstructure modification of solid oxide fuel cell cathodes (SSC cathodes) by porosity control and the fabrication of thermoelectric power batteries (TPB) is a potential technique for increasing the performance and reliability of IT-SOFCs. This strategy enables improved energy conversion efficiency in solid oxide fuel cell.

4.1.3 Composite cathode development (combining SSC with other materials)

The creation of composite cathodes, which involves the combination of Sm0.5Sr0.5CoO3-δ (SSC) with other materials, has demonstrated potential in improving the performance of Intermediate-Temperature Solid Oxide Fuel Cells (IT-SOFCs) (Jiang et al., 2014). According to research conducted by Jiang et al. (2014), it has been established that the co-synthesis of SSC with Sm0.2Ce0.8O1.9 can result in the formation of a composite cathode, which in turn leads to enhanced electrochemical characteristics for IT-SOFCs. The incorporation of an ionic conducting second phase, such as Sm0.2Ce0.8O1.9, into the SSC material has the potential to improve cathode performance, which in turn leads to an increase in the overall efficiency of the fuel cell system.

In addition, the research conducted by emphasizes the creation of heterogeneous composite fibrous cathodes, with a particular focus on active oxygen dissociation for high-performance solid oxide fuel cells (Lee, 2023). The electrochemical reactions that take place at the cathode can be optimized by the creation of composite cathodes that blend SSC with other materials. This eventually results in improved performance and efficiency in solid oxide fuel cells (SOFCs).

In conclusion, the development of composite cathodes by the combination of SSC with other materials gives a diverse way to enhancing the performance of hybrid solid-state fuel cells (IT-SOFCs). Researchers are able to adjust critical attributes in order to obtain higher levels of efficiency, stability, and reliability in solid oxide fuel cell technology. This is accomplished through the customisation of the composition and structure of composite cathodes.

4.2 Summarize the findings from recent research comparing the performance and electrochemical activity of different modified SSC cathodes in IT-SOFC applications

Recent study has been centered around analyzing and contrasting the performance and electrochemical activity of various modified Sm0.5Sr0.5CoO3-δ (SSC) cathodes in the context of Intermediate-Temperature Solid Oxide Fuel Cell (IT-SOFC) applications. Kim et al. (2014) conducted an investigation into the electrochemical performance of NBSCF/BZCYYb/BZCYYb-NiO composite cathodes. The results showed that these cathodes exhibited remarkable long-term stability for a period of 500 hours at a temperature of 1023 K, with a high power density of 1.61 W cm (-2). The results of this study demonstrated that composite cathodes have the potential to improve the stability and performance of IT-SOFCs.

There was another study that focused on the development of heterogeneous composite fibrous cathodes for high-performance solid oxide fuel cells (Lee, 2023). The primary objective of this work was to emphasize active oxygen dissociation. It was the goal of this research to enhance the ORR characteristics of cathodes in order to meet the demand for effective electrochemical reactions in solid oxide fuel cells (SOFCs).

Furthermore, Kim et al. (2014) conducted an investigation into the utilization of chemically stable perovskites as cathode materials for solid oxide fuel cells. One example of this is the utilization of La-doped Ba0.5Sr0.5Co0.8Fe0.2O3−δ, which exhibited remarkable chemical stability under a wide range of operational circumstances. The findings of this study highlighted the significance of chemical stability in terms of improving the durability and dependability of cathode materials in solid oxide fuel cell installations.

In general, recent research has shed light on the significance of composite cathodes, active oxygen dissociation, and chemical stability in terms of optimizing the performance of SSC cathodes for

IT-SOFCs. These findings contribute to the advancement of solid oxide fuel cell systems in terms of their efficiency, stability, and longevity.

5. CONCLUSION

Within the context of the review on SSC cathodes for IT-SOFCs, the most important findings related to the optimization of cathode performance were highlighted. The development of composite cathodes, such as NBSCF/BZCYYb/BZCYYb-NiO, has been found to have the potential to result in improved long-term stability and high power density in IT-SOFCs, according to studies. 2014 findings by Babiniec et al. It has also been established that the co-synthesis of SSC with Sm0.2Ce0.8O1.9 in composite cathodes has resulted in improved electrochemical characteristics. This highlights the significance of composite materials in the process of improving fuel cell performance (Jiang et al., 2014).

Furthermore, research on heterogeneous composite fibrous cathodes has brought attention to active oxygen dissociation for high-performance solid oxide fuel cells. This demonstrates the promise of new cathode designs in optimizing electrochemical reactions in solid oxide fuel cells (Lee, 2023). In addition, the findings highlighted the significance of smaller grains and good dispersion of SSC and SDC phases within composite cathodes, which ultimately led to an increase in the three-phase boundary length and better electrochemical characteristics (Jiang et al., 2014).

Due to its strong electrocatalytic activity and stability, SSC has demonstrated significant potential for use as a cathode material in intermediate-temperature solid oxide fuel cells (IT-SOFCs) (Ding et al., 2014;). For further development to improve the performance and efficiency of SSC cathodes in IT-SOFC applications, ongoing research is essential. They are essential for further development. According to research conducted by Ding et al. (2014) and Choi et al. (2015), the commercial viability of IT-SOFCs is contingent upon the optimization of cathode materials that possess high electrocatalytic activity for the Oxygen Reduction Reaction (ORR) and great stability.

According to Choi et al. (2015), the present focus of research efforts is on the development of cathodes that have a low polarization loss capability in order to increase overall performance. In addition, the investigation of new cathode materials that possess highly mixed ionic and electronic conductivity (MIEC) as well as the development of novel composite cathode designs have the potential to substantially improve the performance of IT-SOFCs (Lee 2030). Both gaining an understanding of the influence of oxygen diffusion restrictions and modifying the composition of the cathode gas are essential components in the process of enhancing the performance of the cell (Biswas et al., 2020).

In addition, the investigation of the phase and microstructure formation of SSC-SDCC composite cathodes can provide insights into the optimization of chemical and microstructural features for improved performance of IT-SOFCs (Mohammad et al., 2019). Ongoing research plays a crucial part in the advancement of the development of SSC cathodes for IT-SOFCs. This is accomplished by continuing to investigate novel methodologies and materials, which in turn paves the way for energy conversion technologies that are both more efficient and more environmentally friendly.

Overall, the research highlighted the significance of developing composite cathodes, actively dissociating oxygen, and optimizing microstructures in order to improve the performance and efficiency of SSC cathodes for applications involving IT-SOFCs. These discoveries contribute to the advancement of the design and functionality of solid oxide fuel cell devices for the conversion of energy in a sustainable manner.

Acknowledgments: The authors would like to express their gratitude to the Malaysian Ministry of Higher Education (MOHE) for supporting this research through Fundamental Research Grant Scheme

(FRGS/1/2020/TK0/UTHM/02/22) and partially funded by Universiti Tun Hussein Onn Malaysia (UTHM) under Postgraduate Research Grant (FRGS K303).

References

Babiniec, S., Ricote, S., & Sullivan, N. (2014). Infiltrated lanthanum nickelate cathodes for use with bace0.2zr0.7y0.1o3 − δproton conducting electrolytes. Journal of the Electrochemical Society, 161(6), F717-F723. https://doi.org/10.1149/2.037406jes

Bi, L., Boulfrad, S., & Traversa, E. (2014). Steam electrolysis by solid oxide electrolysis cells (soecs) with proton-conducting oxides. Chemical Society Reviews, 43(24), 8255-8270. https://doi.org/10.1039/c4cs00194j

Biswas, N., Bhattacharya, D., Kumar, M., Mukhopadhyay, J., Basu, R., & Das, P. (2020). Effect of oxygen diffusion constraints on the performance of planar solid oxide fuel cells for variable oxygen concentration. Industrial & Engineering Chemistry Research, 59(42), 18844-18856. https://doi.org/10.1021/acs.iecr.0c00628

Cascos, V., Troncoso, L., Larralde, A., Fernandez-Diaz, M., & Alonso, J. (2020). Performance of srco1−xirxo3−δ (x = 0.10 and 0.15) perovskites as potential cathode materials for intermediate-temperature solid oxide fuel cells (it-sofc). Acs Applied Energy Materials, 3(7), 6709-6716. https://doi.org/10.1021/acsaem.0c00848

Cavallaro, A., Wilson, G., Kerherve, G., Calì, E., Bosch, C., Boldrin, P., … & Aguadero, A. (2021). Analysis of h2o-induced surface degradation in srcoo3-derivatives and its impact on redox kinetics. Journal of Materials Chemistry A, 9(43), 24528-24538. https://doi.org/10.1039/d1ta04174f

Chang-xin, Z., Li, B., Liu, J., & Zhang, Q. (2020). Intrinsic electrocatalytic activity regulation of m−n−c single-atom catalysts for the oxygen reduction reaction. Angewandte Chemie, 60(9), 4448-4463. https://doi.org/10.1002/anie.202003917

Chasta, G. and Dhaka, M. (2022). A review on materials, advantages, and challenges in thin film based solid oxide fuel cells. International Journal of Energy Research, 46(11), 14627-14658. https://doi.org/10.1002/er.8238

Chen, D., Yang, G., Ciucci, F., Tadé, M., & Shao, Z. (2014). 3d core−shell architecture from infiltration and beneficial reactive sintering as highly efficient and thermally stable oxygen reduction electrode. Journal of Materials Chemistry A, 2(5), 1284-1293. https://doi.org/10.1039/c3ta13253f

Chen, X., Mi, Y., Wang, B., Lin, B., Chen, G., & Zhu, B. (2019). Shaping triple-conducting semiconductor baco0.4fe0.4zr0.1y0.1o3-δ into an electrolyte for low-temperature solid oxide fuel cells. Nature Communications, 10(1). https://doi.org/10.1038/s41467-019-09532-z

Choi, H., Bae, K., Jang, D., Kim, J., & Shim, J. (2015). Performance degradation of lanthanum strontium cobaltite after surface modification. Journal of the Electrochemical Society, 162(6), F622-F626. https://doi.org/10.1149/2.0971506jes

Ding, D., Li, X., Lai, S., Gerdes, K., & Liu, M. (2014). Enhancing sofc cathode performance by surface modification through infiltration. Energy & Environmental Science, 7(2), 552. https://doi.org/10.1039/c3ee42926a

Ding, D., Li, X., Lai, S., Gerdes, K., & Liu, M. (2014). Enhancing sofc cathode performance by surface modification through infiltration. Energy & Environmental Science, 7(2), 552. https://doi.org/10.1039/c3ee42926a

Ding, D., Li, X., Lai, S., Gerdes, K., & Liu, M. (2014). Enhancing sofc cathode performance by surface modification through infiltration. Energy & Environmental Science, 7(2), 552. https://doi.org/10.1039/c3ee42926a

Duan, C., Tong, J., Shang, M., Nikodemski, S., Sanders, M., Ricote, S., … & O'Hayre, R. (2015). Readily processed protonic ceramic fuel cells with high performance at low temperatures. Science, 349(6254), 1321-1326. https://doi.org/10.1126/science.aab3987

Duan, C., Tong, J., Shang, M., Nikodemski, S., Sanders, M., Ricote, S., … & O'Hayre, R. (2015). Readily processed protonic ceramic fuel cells with high performance at low temperatures. Science, 349(6254), 1321-1326. https://doi.org/10.1126/science.aab3987

Filonova, E. and Medvedev, D. (2022). Recent progress in the design, characterisation and application of laalo3- and lagao3-based solid oxide fuel cell electrolytes. Nanomaterials, 12(12), 1991. https://doi.org/10.3390/nano12121991

Gao, Z., Mogni, L., Miller, E., Railsback, J., & Barnett, S. (2016). A perspective on low-temperature solid oxide fuel cells. Energy & Environmental Science, 9(5), 1602-1644. https://doi.org/10.1039/c5ee03858h

Hai, D., Hung, V., Thu, P., Dung, L., Huong, L., Anh, H., … & Lam, L. (2022). Structural and electrical properties of samarium-doped ceria electrolyte. Vnu Journal of Science Mathematics - Physics, 38(1). https://doi.org/10.25073/2588-1124/vnumap.4660

Hauch, A., Küngas, R., Blennow, P., Hansen, A., Hansen, J., Mathiesen, B., … & Mogensen, M. (2020). Recent advances in solid oxide cell technology for electrolysis. Science, 370(6513). https://doi.org/10.1126/science.aba6118

He, F., Hou, M., Zhu, F., Li, D., Zhang, H., Yu, F., … & Chen, Y. (2022). Building efficient and durable hetero-interfaces on a perovskite-based electrode for electrochemical co2 reduction. Advanced Energy Materials, 12(43). https://doi.org/10.1002/aenm.202202175

Jiang, W., Wei, B., Lü, Z., Wang, Z., Zhu, X., & Zhu, L. (2014). Co-synthesis of sm0.5sr0.5coo3-sm0.2ce0.8o1.9 composite cathode with enhanced electrochemical property for intermediate temperature sofcs. Fuel Cells, 14(6), 966-972. https://doi.org/10.1002/fuce.201400022

Jiang, W., Wei, B., Lü, Z., Wang, Z., Zhu, X., & Zhu, L. (2014). Co-synthesis of sm0.5sr0.5coo3-sm0.2ce0.8o1.9 composite cathode with enhanced electrochemical property for intermediate temperature sofcs. Fuel Cells, 14(6), 966-972. https://doi.org/10.1002/fuce.201400022

Ju, Y., Hyodo, J., Inoishi, A., Ida, S., Tohei, T., So, Y., … & Ishihara, T. (2014). Double columnar structure with a nanogradient composite for increased oxygen diffusivity and reduction activity. Advanced Energy Materials, 4(17). https://doi.org/10.1002/aenm.201400783

Ju, Y., Hyodo, J., Inoishi, A., Ida, S., Tohei, T., So, Y., … & Ishihara, T. (2014). Double columnar structure with a nanogradient composite for increased oxygen diffusivity and reduction activity. Advanced Energy Materials, 4(17). https://doi.org/10.1002/aenm.201400783

Kamecki, B., Karczewski, J., Jasiński, P., & Molin, S. (2021). Improvement of oxygen electrode performance of intermediate temperature solid oxide cells by spray pyrolysis deposited active layers. Advanced Materials Interfaces, 8(9). https://doi.org/10.1002/admi.202002227

Kim, J., Choi, S., Jun, A., Jeong, H., Shin, J., & Kim, G. (2014). Chemically stable perovskites as cathode materials for solid oxide fuel cells: la-doped ba0.5sr0.5co0.8fe0.2o3−δ. Chemsuschem, 7(6), 1669-1675. https://doi.org/10.1002/cssc.201301401

Kim, J., Sengodan, S., Kwon, G., Ding, D., Shin, J., Liu, M., … & Kim, G. (2014). Triple-conducting layered perovskites as cathode materials for proton-conducting solid oxide fuel cells. Chemsuschem, 7(10), 2811-2815. https://doi.org/10.1002/cssc.201402351

Kim, J., Sengodan, S., Kwon, G., Ding, D., Shin, J., Liu, M., … & Kim, G. (2014). Triple-conducting layered perovskites as cathode materials for proton-conducting solid oxide fuel cells. Chemsuschem, 7(10), 2811-2815. https://doi.org/10.1002/cssc.201402351

Kim, J., Sengodan, S., Kwon, G., Ding, D., Shin, J., Liu, M., … & Kim, G. (2014). Triple-conducting layered perovskites as cathode materials for proton-conducting solid oxide fuel cells. Chemsuschem, 7(10), 2811-2815. https://doi.org/10.1002/cssc.201402351

Kim, J., Sengodan, S., Kwon, G., Ding, D., Shin, J., Liu, M., … & Kim, G. (2014). Triple-conducting layered perovskites as cathode materials for proton-conducting solid oxide fuel cells. Chemsuschem, 7(10), 2811-2815. https://doi.org/10.1002/cssc.201402351

Lee, J., Park, J., & Shul, Y. (2014). Tailoring gadolinium-doped ceria-based solid oxide fuel cells to achieve 2 w cm−2 at 550 °c. Nature Communications, 5(1). https://doi.org/10.1038/ncomms5045

Lee, S. (2023). Heterogeneous composite fibrous cathode undergoing emphasized active oxygen dissociation for la(sr)ga(mg)o3-based high-performed solid oxide fuel cells. Small Structures, 5(2). https://doi.org/10.1002/sstr.202300292

Lee, S. (2023). Heterogeneous composite fibrous cathode undergoing emphasized active oxygen dissociation for la(sr)ga(mg)o3-based high-performed solid oxide fuel cells. Small Structures, 5(2). https://doi.org/10.1002/sstr.202300292

Lee, S. (2023). Heterogeneous composite fibrous cathode undergoing emphasized active oxygen dissociation for la(sr)ga(mg)o3-based high-performed solid oxide fuel cells. Small Structures, 5(2). https://doi.org/10.1002/sstr.202300292

Lee, S. (2023). Heterogeneous composite fibrous cathode undergoing emphasized active oxygen dissociation for la(sr)ga(mg)o3-based high-performed solid oxide fuel cells. Small Structures, 5(2). https://doi.org/10.1002/sstr.202300292

Lichtner, A., Jauffrès, D., Roussel, D., Charlot, F., Martín, C., & Bordia, R. (2015). Dispersion, connectivity and tortuosity of hierarchical porosity composite sofc cathodes prepared by freeze-casting. Journal of the European Ceramic Society, 35(2), 585-595. https://doi.org/10.1016/j.jeurceramsoc.2014.09.030

Lin, C., Li, X., Shinde, S., Kim, D., Song, X., Zhang, H., … & Lee, J. (2019). Long-life rechargeable zn air battery based on binary metal carbide armored by nitrogen-doped carbon. Acs Applied Energy Materials, 2(3), 1747-1755. https://doi.org/10.1021/acsaem.8b01865

Mohammad, S., Ahmad, S., Rahman, H., & Muchtar, A. (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). https://doi.org/10.30880/ijie.2019.11.07.021

Mohammad, S., Ahmad, S., Rahman, H., & Muchtar, A. (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). https://doi.org/10.30880/ijie.2019.11.07.021

Radenahmad, N., Afif, A., Abdalla, A., Saqib, M., Park, J., Zaini, J., … & Azad, A. (2020). A new high-performance proton-conducting electrolyte for next-generation solid oxide fuel cells. Energy Technology, 8(9). https://doi.org/10.1002/ente.202000486

Ren, R., Wang, Z., Meng, X., Wang, X., Chen, X., Qiao, J., … & Sun, K. (2020). Tailoring the oxygen vacancy to achieve fast intrinsic proton transport in a perovskite cathode for protonic ceramic fuel cells. Acs Applied Energy Materials, 3(5), 4914-4922. https://doi.org/10.1021/acsaem.0c00486

Roslan, M. F., Rahman, A. H., Azmi, M. A., Ismail, A., Mahzan, S., Tukimon, M. F., & Yusof, U. A. (2023). Properties of samarium strontium cobalt oxide based composite cathode with different electrolytes for intermediate temperature solid oxide fuel cell: a short review. Malaysian Journal of Microscopy Vol. 19, No. 2 (2023), Page 248-259.

Roslan, M. F. and Karim, A. R. (2023). Bridging the Gap: The Potential of Low-Temperature Solid Oxide Fuel Cells in Enhancing Virtual Reality Headset Performance. International Journal of Advanced Virtual Reality, 1(2), 79-85.

Shimada, H., Yamaguchi, T., Suzuki, T., Sumi, H., Hamamoto, K., & Fujishiro, Y. (2016). High power density cell using nanostructured sr-doped smcoo3 and sm-doped ceo2 composite powder synthesized by spray pyrolysis. Journal of Power Sources, 302, 308-314. https://doi.org/10.1016/j.jpowsour.2015.10.082

Shu, P., Yin, Z., & Xue, J. (2023). Tantalum doped la0.6sr0.4feo3−δ electrodes for symmetrical proton conducting solid oxide fuel cells. Reaction Chemistry & Engineering, 8(4), 770-777. https://doi.org/10.1039/d2re00553k

Song, Y., Chen, Y., Wang, W., Zhou, C., Zhong, Y., Yang, G., … & Shao, Z. (2019). Self-assembled triple-conducting nanocomposite as a superior protonic ceramic fuel cell cathode. Joule, 3(11), 2842-2853. https://doi.org/10.1016/j.joule.2019.07.004

Wang, N., Tang, C., Du, L., Zhu, R., Xing, L., Song, Z., … & Ye, S. (2022). Advanced cathode materials for protonic ceramic fuel cells: recent progress and future perspectives. Advanced Energy Materials, 12(34). https://doi.org/10.1002/aenm.202201882

Wang, W., Medvedev, D., & Shao, Z. (2018). Gas humidification impact on the properties and performance of perovskite-type functional materials in proton-conducting solid oxide cells. Advanced Functional Materials, 28(48). https://doi.org/10.1002/adfm.201802592

Wu, S., Xu, X., Li, X., & Bi, L. (2021). High-performance proton-conducting solid oxide fuel cells using the first-generation sr-doped lamno3 cathode tailored with zn ions. Science China Materials, 65(3), 675-682. https://doi.org/10.1007/s40843-021-1821-4

Wu, X. (2023). Novel hybrid modeling and analysis method for steam reforming solid oxide fuel cell system multifault degradation fusion assessment. Acs Omega, 8(40), 36876-36892. https://doi.org/10.1021/acsomega.3c03928

Xu, X., Wang, H., Fronzi, M., Wang, X., Bi, L., & Traversa, E. (2019). Tailoring cations in a perovskite cathode for proton-conducting solid oxide fuel cells with high performance. Journal of Materials Chemistry A, 7(36), 20624-20632. https://doi.org/10.1039/c9ta05300j

Xu, X., Wang, W., Zhou, W., & Shao, Z. (2018). Recent advances in novel nanostructuring methods of perovskite electrocatalysts for energy-related applications. Small Methods, 2(7). https://doi.org/10.1002/smtd.201800071

Xu, Y., Xu, X., & Bi, L. (2022). A high-entropy spinel ceramic oxide as the cathode for proton-conducting solid oxide fuel cells. Journal of Advanced Ceramics, 11(5), 794-804. https://doi.org/10.1007/s40145-022-0573-7

Xu, Y., Yu, S., Yin, Y., & Bi, L. (2022). Taking advantage of li-evaporation in licoo2 as cathode for proton-conducting solid oxide fuel cells. Journal of Advanced Ceramics, 11(12), 1849-1859. https://doi.org/10.1007/s40145-022-0651-x

Xu, Y., Yu, S., Yin, Y., & Bi, L. (2022). Taking advantage of li-evaporation in licoo2 as cathode for proton-conducting solid oxide fuel cells. Journal of Advanced Ceramics, 11(12), 1849-1859. https://doi.org/10.1007/s40145-022-0651-x

Xu, Y., Yu, S., Yin, Y., & Bi, L. (2022). Taking advantage of li-evaporation in licoo2 as cathode for proton-conducting solid oxide fuel cells. Journal of Advanced Ceramics, 11(12), 1849-1859. https://doi.org/10.1007/s40145-022-0651-x

Yang, X., Yin, Y., Yu, S., & Bi, L. (2022). Gluing ba0.5sr0.5co0.8fe0.2o3−δ with co3o4 as a cathode for proton-conducting solid oxide fuel cells. Science China Materials, 66(3), 955-963. https://doi.org/10.1007/s40843-022-2240-y

Yang, X., Yin, Y., Yu, S., & Bi, L. (2022). Gluing ba0.5sr0.5co0.8fe0.2o3−δ with co3o4 as a cathode for proton-conducting solid oxide fuel cells. Science China Materials, 66(3), 955-963. https://doi.org/10.1007/s40843-022-2240-y

Yin, Y. (2023). A real proton-conductive, robust, and cobalt-free cathode for proton-conducting solid oxide fuel cells with exceptional performance. Susmat, 3(5), 697-708. https://doi.org/10.1002/sus2.156

Yu, K., Sun, C., Wu, X., Sun, K., Yin, X., & Zhang, N. (2020). One-dimensional cuco2o4–er0.4bi1.6o3 composite fiber as cathode of intermediate temperature solid oxide fuel cells. Acs Sustainable Chemistry & Engineering, 8(9), 3950-3958. https://doi.org/10.1021/acssuschemeng.9b07727

Zhang, W. and Hu, Y. (2021). Progress in proton-conducting oxides as electrolytes for low-temperature solid oxide fuel cells: from materials to devices. Energy Science & Engineering, 9(7), 984-1011. https://doi.org/10.1002/ese3.886

Zhu, Y., Zhou, W., & Shao, Z. (2017). Perovskite/carbon composites: applications in oxygen electrocatalysis. Small, 13(12). https://doi.org/10.1002/smll.201603793