Original Article

http://www.tjbac.tmu.ac.in

TMU Journal of Basic & Applied Chemistry
Vol.5
Jan-December, 2025: P.27-36

Challenges and Future Prospects in Perovskite-Based Fuel Cells: A Comprehensive Review

Akanksha Sandhu,[1*] Navneet Kumar[2] and Mrinmoy Kumar Chini[3]

Author Affiliations

[1]Akanksha Sandhu
Department of Chemistry, Faculty of Engineering Teerthanker Mahaveer University, Moradabad-244001 Uttar Pradesh, India.

[2]Navneet Kumar
Department of Chemistry, Faculty of Engineering Teerthanker Mahaveer University, Moradabad-244001 Uttar Pradesh, India.

[3]Mrinmoy Kumar Chini
Department of Applied Sciences (Chemistry), Galgotias College of Engineering & Technology, Greater Noida- 201306, Uttar Pradesh, India.

***Corresponding Author**
Akanksha Sandhu
Department of Chemistry, Faculty of Engineering Teerthanker Mahaveer University, Moradabad-244001 Uttar Pradesh, India.
E- mail: akankshasandhu107@gmail.com

Received on: 10.08.2025

Revised on: 22.08.2025

Accepted on: 30.08.2025

Abstract

The remarkable ionic conductivity of the perovskites oxides, the ability to adjust its crystal structure, and its electrocatalytic capability have compelled perovskite oxides to get a prospective in to become a personal family of materials of next generation fuel cells. Their overall structure, ABO 3, allows substituting cations at either the A - or B -sites, making it possible to control precisely redox stability, electrical conductivity, and oxygen vacancy concentration. In both solid oxide and proton-conducting fuel cells, these properties of the perovskites render it attractive as a cathode (such as $La_{1-x}Sr_xCo_{1-}yFeyO_3$), anodes (such as $SrTi_{1-x}Fe_xO_3$), and electrolytes (such as $BaCeO_3$, $BaZrO_3$ systems). Recent tests illustrate how composite designs, defect engineering and nanostructuring can enhance proton transport, reduce strontium segregation as well as oxygen reduction kinetics. Nevertheless, such challenges as limited work efficiency in mid temperatures, scalability of synthesis, and long-term chemical instability at CO_2/H_2O coordinates remain great setbacks. In this review, the future development of viable, durable, and cost-effective perovskites fuel cells is provided through the review of the structural design methods, mechanism, and current perovskite fuel cell technology development.

Keywords: Perovskite materials; Fuel cells; Oxygen ion conductivity; Electrochemical performance; Energy conversion.

Introduction

Studies on fuel cell, which is famously characterized by high efficiency, flexibility with fuel accompanied by eco-friendly activities, intensified due to increasing need of environmentally friendly and sustainable energy technologies globally. Fuel cells may run on a variety of fuels and reduce greenhouse gas emissions by directly converting chemical energy in electrical power, in contrast to conventional combustion-powered systems (Steele et al., 2001 and O' Hayre et al. 2016Due to the fact that solid oxide fuel cells (SOFCs) as well as proton-conducting fuel cells (PCFCs) directly convert chemical energy into electrical power, whereas the other varieties rely on combustion, fuel cells have received a lot of interest. Still, developing high-performance electrode and other materials such as electrolytes remain a big challenge in the way toward long-life half-cost fuel cell solutions.

Perovskite oxides (general formula ABO_3) a wide category of useful fuel cell materials have become popular.

Either the A-site (rare earth as well as alkaline earth metals), or the B-site (transition metals) can be used for substitution; this allows for precise customization of physicochemical properties like oxygen vacancy concentration, ionic conductivity, electronic conductivity, as well as catalytic activity (Goodenough et al., 2007, Skinner et al., 2001, and Li et al., 2021). The tunability of perovskites renders them valuable electrolytes (e.g., $BaCeO_3$, $BaZrO_3$-based systems), anodes (e.g., $SrTi_{1-x}Fe_xO_3$, $La_{0.7}Sr_{0.3}Cr_{0.5}Mn_{0.5}O_3$), and cathodes (e.g.$_{+}Sr_{-x}Co_{0.8}Fe_{0.3}O_3$, Ba_0, $Ba_{0.3}Sr_{0.5}Co_{0.8}Fe_{0.3}O_3$, $Ba_{0.3}$, $Ba_{0.+}Fe_{0.3}O_3$, $Ba_{0.0.0.0.0.0.0.8}Fe_{0.8}Fe_{0.8}Fe_{0.8}Fe_{0.0}$.

Recently, defect engineering, nanostructuring, and even the compositing methods have been subject to improvement to reduce long-standing issues such as strontium segregation, coking, a slow oxygen reduction reaction, and even the instability during the carbon dioxide and water environments (Porotnikova et al., 2024, Laguna et al., and Li et al., 2020). The progress in making protons conduct perovskites has also enabled the usage of fuel cells in intermediate operating temperatures (400-700 degrees Celsius) which has reduced the cost of operation yet did not compromise on the performance (Rehman et al., 2024). These developments notwithstanding, chemical stability, scalability of synthesis and long term durability are key barriers to commercialization.

This paper provides a general overview of the structural features, electrochemical properties and applications of the perovskite oxides in fuel cells. We sketch the future in terms of developing reliable and effective perovskite fuel cells, illustrate the inherent difficulties, and provide an overview of the recent developments in perovskite-based cathodes, anodes, and electrolytes.

2. Structure and Properties of Perovskites

The general chemical formula for perovskite oxides is ABO3, where the A-site cation is usually a bigger rare-earth and alkaline-earth metal (like La^{3+}, Sr^{2+}, or Ba^{2+}) and the B-site cation has a smaller transition- metal (like $Mn^{3+}/^{4+}$, Fe^{3+}, Co^{3+}, or Ti^{4+}). at the ideal cubic perovskite structure, the oxygen anion at the face centers, the B-site cation at the body center, as well as the A-site cations at the unit cell's corners form an octahedral network (Muller et al., 1974 ; Howard et al., 2005). With goldschmidt tolerance factor (t), ionic size mismatch often results in deviation of the ideal cubic symmetry such as orthorhombic or tetragonal distortions.

$$t = \frac{rA + rO}{\sqrt{2}(rB + rO}$$

In which the ionic radii of A, and B, along with the radii of oxygen is expressed by rArA, rBrB, and rOrO, respectively. While aberrations show irregularities in the distribution and have a significant impact on the electrochemical characteristics of perovskites, the tolerance factor is around unity, suggesting that their distribution is stable as well as cubic in nature (Goldschmidt et al.1926).

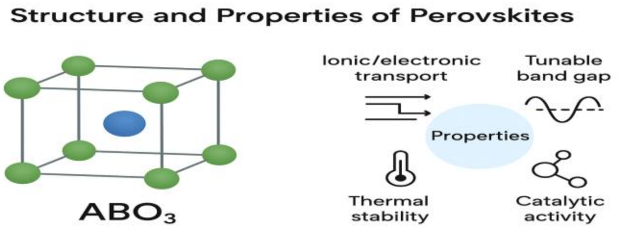

Figure 1. Structure and Properties of Perovskites

2.1 Ionic and Electronic Conductivity

One of the most important features of the perovskites relevant to fuel cell applications is mixed ionic-electronic conductivity (MIEC). Oxygen vacancies are formed by a replacement of the A-site by negatively charged cations (say with Sr^{2+} replaced by La^{3+}) in order to maintain charge neutrality and enhance oxygen diffusion. The numerous oxidation states, which B-site transition metals are able to undergo, further promote the conduction of electrons or holes (Steele et al., 2001 and Skinner et al., 2001). Because of these properties, perovskites are particularly highly suited to purpose as anodes in hydrocarbon-fueled systems, and as cathode materials in the oxygen reduction reaction (ORR).

2.2 Oxygen Vacancies and Catalytic Activity

The concentration and mobility of the vacancies in oxygen are also important parameters that influence the catalytic activities of perovskites. Large amounts of vacancy in compounds such as $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$ (LSCF) as well as $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.0}O_3$ (BSCF) enhance oxygen adsorption, dissociation, and diffusion- a key process in the ORR (Jiang et al.2019 as well as Li et al.2021). Perovskites have highly tunable catalysts because they have been utilized to fine-tune the dependence on defect chemistry or doping.

2.3 Proton Conductivity

Due to their ability to fit in protons by hydration of oxygen gaps, certain perovskites, especially $BaCeO_3$ and $BaZrO_3$ ones, can be highly protonically conducted within moisture conditions. This property makes them attractive alternatives to the electrolytes of PCFCs at the intermediate temperatures (Kreuer et al.,2003). $BaZrO_3$ offers low conductivity with greater chemical stability and $BaCeO_3$ unsustainable in atmospheres with CO 2. In order to trade off conductivity and stability, Y^{3+} or Gd^{3+}, doped solids (i.e., $BaCe_{1-x}Zr_xO_3$) have been explored (Rehman et al. 2023).

3. Perovskites as Electrodes in Fuel Cells

Electrode material results have a profound influence on the stability and electrochemical activity of the material, which affects fuel cell performance and life. Perovskite oxides are particularly impressive cathodes and anodes due to their catalytic properties, structural flexibility and mixed ionicelectronic conductivity (MIEC). They perform better than conventional electrode materials in most fuel cell configurations because of their ability to withstand the oxygen vacuity and undergo redox activation (Steele et al., 2001and Li et al., 2021).

Table — Perovskite Materials as Electrodes in Fuel Cells

Electrode type	Perovskite compositions (examples)	Function / role	Advantages	Key performance indicators	Representative references
SOFC Cathodes (MIEC)	$La_{1-x}Sr_xCo_{1-y}Fe_yO_{3-\delta}$ (LSCF), $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF)	Oxygen reduction reaction (ORR)	High mixed ionic-electronic conductivity (MIEC), fast ORR kinetics, good performance at intermediate T (600–800 °C)	Area specific resistance (ASR), oxygen surface exchange coefficient, TEC compatibility	Zhao et al.2022 as well as Shi et al.2020
Low-Co / Co-free Cathodes	Fe-based double perovskites (Sr_2FeMoO_6, $La_{0.6}Sr_{0.4}FeO_3$), $PrBaCo_2O_{5+\delta}$	ORR at intermediate –low T	Reduced Co content → lower cost, improved chemical stability	ORR activity, durability under CO_2/H_2O exposure	Kasyanova et al.2022 as well as Giddey et al.2013
SOFC Anodes	Sr_2FeMoO_6, $La_{0.4}Sr_{0.6}TiO_3$, Sr-doped ferrites	Fuel oxidation reaction	Tolerant to sulfur & coking, direct hydrocarbon operation possible	Electronic conductivity, redox stability, fuel utilization efficiency	Wang et al.2011 as well as Skutina et al.2021

Electrode type	**Perovskite compositions (examples)**	**Function / role**	**Advantages**	**Key performance indicators**	**Representative references**
Exsolution-based Electrodes	Ni/Co-doped perovskites (e.g., La_{0.6}Sr_{0.4}Fe_{0.8}Ni_{0.2}O_{3−δ})	Self-generation of embedded nanoparticles	High catalytic activity, anchored nanoparticles prevent agglomeration → long-term stability	Exsolved nanoparticle distribution, cycling stability	Kim et al.2024 as well as Zhang et al.2022
PCFC Electrodes (Triple Conductors)	BaCe_{0.7}Zr_{0.1}Y_{0.2}O_{3−δ}-based composites with perovskites	Proton, oxide-ion & electron conduction	Enhanced electrode kinetics due to triple conductivity	Proton conductivity, electrode polarization resistance, stability in CO_2/H_2O	Ding et al.2020 as well as Ni et al.2018
RSOFC Oxygen Electrodes	LSCF, BSCF, and their doped variants	Operate in both SOFC (ORR) & SOEC (OER) modes	Bifunctional activity, tunable oxygen vacancies	Symmetric polarization resistance, redox cycling stability	Zhang et al.2021 as well as Shao et al.2016

3.1 Perovskite Cathodes

The overall performance of SOFCs is limited by a thermodynamically sluggish catalyzed reactions (oxygen reductions reaction) at the cathode. The popular conventional cathodes such as $La_{1-x}Sr_xMnO_3$ (LSM), have low ionic conductivity and high stability that makes them less useful at intermediate temperatures (500 -800 °C) (Skinner et al., 2001).

Due to its higher ORR activity as well as the situation and spreading conductivity, perovskites with higher oxygen vacancy concentration -such as $La_{1-x}Sr_xCo_{1-}yFeyO_3$-(LSCF) as well as $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.3}O_3$-(BSCF) become the most promising energy source (Jiang et al., 2019). These substances facilitate faster diffusion, dissociation and adsorption of oxygen. Nevertheless, problems such as the incapacity to separate strontium on the cathode surface may deteriorate performance (Porotnikova et al.2024).

Some more recent means of circumventing them include:

- Intrusion of nanoparticles and coating the surface to prevent segregation of Sr (Li et al., 2020).
- Heterostructured cathodes, enhancing the diffusion of oxygen by mixing perovskites in ionic conductors (like Sm-doped CeO_2) (Bai et al., 2024).
- Nanostructuring and thin-film engineering, which can be used to augment the ORR and improve the active surface area (Acosta et al., 2019).

3.2 Perovskite Anodes

Traditionally used SOFC anodes like Ni-YSZ (yttria-stabilized zirconia) do not perform well in regards to redox stability, carbon deposition and sulfur poisoning when using them as fuels (Minh et al., 2004). They are however very electrically conductive. Due to their resistance to coking and their redox properties that can be switched, perovskite-based anode materials are currently under investigation as potential alternatives.

Among the outstanding ones are:

- $SrTi_{1-x}Fe_xO_3$ STFO: This high-incorporation redox-stable electronic conductor demonstrates excellent electrolyte conductivity at reducing environments.
- $La_{0.7}Sr_{0.3}Cr_{0.5}Mn_{0.5}O_3$ (LSCM) is a solid choice as highly sulfur-selective direct hydrocarbon SOFC, and tolerant of hydrocarbon fuels, and has the ability (Fu et al., 2022).
- Revamped oxygen ion mobility and strong catalytic activity of double perovskites, such as $Sr_2Fe_{1.5}Mo_{0.5}O_6$ (Du et al.2018).

Recent study contain also confirmed the establishment of composite anodes making use of perovskites with ionic conductors (e.g. Gd-doped ceria or YSZ) to form long triple-phase boundaries (TPBs), which can GIN gain significant electrochemical advantages (Senthil et al., 2021).

4. Perovskites as Electrolytes in Fuel Cells

Given that conversion of electrical energy to chemical energy and vice versa is necessary, electrolytes are indispensable parts of fuel cells since they carry ions but hinder electrical conductivity. Electrolytes of high-performance fuel cells need high ionic conductivity, chemical stability, and high compatibility with electrodes under operating conditions. Perovskite oxides (especially proton-conducting and oxygen-conducting ion channels) have attracted significant attention as both alternative electrolytes to SOFCs as well as PCFCs (Steele et al.2001 as well as Li et al.2021).

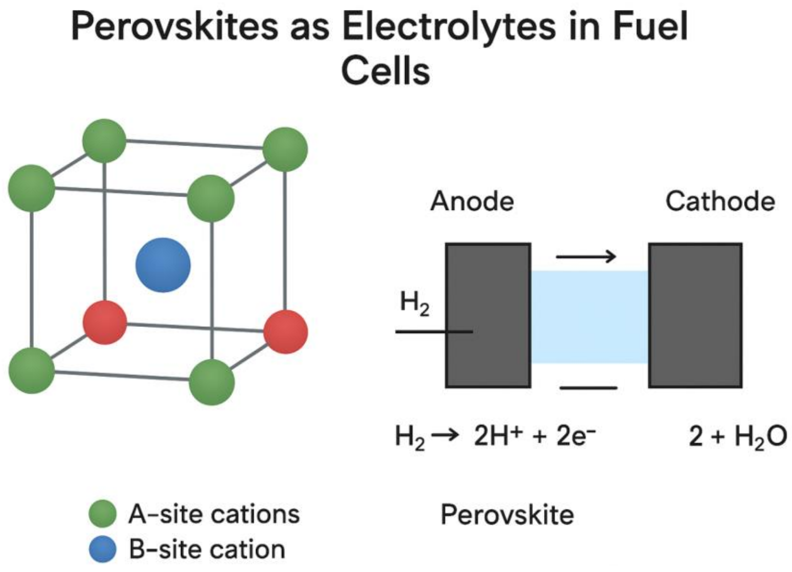

Figure 2. Perovskites as Electrolytes in Fuel Cells.

4.1 Oxygen-Ion Conducting Perovskites

High operating temperatures (800–1000 C) are necessary for adequate oxygen ion conductivity in conventional SOFC electrolytes, including yttria-stabilized zirconia (YSZ). New subsidiary oxides have been studied using $LaGaO_3$ based oxides and other perovskite based electrolytes as a means of reducing operating temperature.

- LSGM: Doping LaGaO3 with Sr and Mg increases the ionic conductivity and oxygen vacancy concentration by more than YSZ and by around 0.14 S cm^{-1} at 800 C (Ishihara et al., 1994 as well as Tao et al., 2007).
- Capturesobs block type: of intermediate-temperature SOFCs (IT-SOFCs) ULSGM would be suited because of the low activation energy and oxygen ion diffusions.

4.2 Proton-Conducting Perovskites

Proton-conducting perovskites have become suitable as the fuel cell electrolyte at temperatures of between 400 to 700 C due to the offering of better long durability and reduction in thermal stress.

$BaCeO_3$-based perovskites (BCY) are trivalent cavation doped by trivent cations such as Y^{3+}, $Gd^{3+,}$ and Sm^{3+} and show high proton conductivity (>10 -2 S cm^{-1} at 600 °C) (Kreuer et al., 2003). BCY, in contrast, is unstable chemically and forms hydroxides or $BaCO_3$ in CO_2 atmospheres and H_2O atmospheres.

- The BZY-based perovskites: barium-zirconium-yttrium based perovskites are characterized by high level of chemical stability along with slack proton conductivity due to high proton velocity (Katahira et al., 2000).
- One of the most promising alternatives to solid solutions of $Ce_{1-x}Zr_xO_3$ is Y-doped $BaCe_{0.7}Zr_{0.2}Y_{0.1}O_3$ (BCZY). The addition of Ce and Zr leads to higher conductivity and stability (Rehman et al., 2024).

5. Challenges and Limitations of Perovskite-Based Fuel Cells

Perovskite oxides are promising as fuel cell electrode and electrolyte materials, however, many scientific, engineering and marketing challenges remain. These disadvantages make their use not so widely spread as compared to the traditional NiCZ-based systems.

5.1 Chemical and Structural Instability

A wide range of perovskite oxides, particularly those doped with Sr and Ba, degrade chemically in atmospheres with high CO_2 and high H_2O concentrations. As an example, when using the electrolyte in a humidified/CO_2 rich environment, someformation of $BaCO_3$ and hydroxides is present in the $BaCeO_3$-based electolyte, one of the factors that leads to structural collapses and loss of conductivity (Kreuer et al., 2003 and Rehman et al., 2024). On the same note, insulating SrO phases Classification with deactivate oxygen reduction side (ORR) sites are produced when Sr is segregated by cathode material, e.g. LSCF and BSCF (Porotnikova et al., 2024).

5.2 Thermal and Mechanical Compatibility

The difference in thermal expansion coefficients (TECs) between perovski electrodes and electrolytes and more popular electrolytes like YSZ or GDC is a major problem in the development of perovskite-based fuel cell designs. This can lead to microcracking, interfacial delamination, as well as a gradual decrease in stability when thermal cycling is applied (Bai et al., 2024). Also, at redox conditions, part of perovskites undergo a redistribution of oxygen vacancies that varies lattice parameters and augments stress loads (Li et al., 2020).

5.3 Limited Long-Term Durability

Perovskite electrodes bought in bulk and used over the long run may also result in phase segregation, cationic migration and grain coarsening. Such events undermine the activity of electrodes and reduce ionic/electronic conductivity (Jiang et al., 2019). The movement of Co and Fe cation, e.g. has been related to prolonged utilization of LSCF cathodes leading to microstructural instability (Adlers et al., 2004).

5.4 Processing and Fabrication Challenges

Complex synthesis techniques (solid-state reaction, sol-gel, as well as pulsed laser deposition), higher sintering temperatures, and exact stoichiometry control are frequently needed to manufacture perovskite-based electrolyte and electrode (Steele et al., 2001). Due to its refractory characteristic, $BaZrO_3$-based proton conductor is extremely difficult to sinter and requires expensive sintering aids (Katahiral et al., 2000). These issues increase the cost of producing, and obscure scaling, in comparison with Ni-YSZ systems.

5.5 Intermediate-Temperature Operation Limitations

Perovskites are attractive in SOFCs with intermediate temperatures (500 -700 C), but they can be challenging to retain high conductivity and stability at such temperatures. Whereas $BaCeO_3$ -based electrolytes support high conductivity and low durability, $BaZrO_3$ -based electrolytes are stable and mixted with limited conductivity (Li et al., 2021). The optimal balance is also among the highest priorities of research.

5.6 Fuel Flexibility and Redox Cycling Issues

Although some self-anions of perovskites (e.g., LSCM and $SrTi_{1-x}Fe_xO_3$) already show the capacity to oxidize hydrocarbons, there are other issues, such as redox instability, carbon deposition and sulfur poisoning (Goodenough et al., 2007). Redox cycling and repetitive shortage of fuel may result in damage to the structural level, which is impossible to fix.

6. Future Perspectives

Amid protonic ceramic fuel cells (PCFCs) and intermediate-temperature SOFCs, perovskite-based fuel cells (PFCs) are rapidly steering towards the durability and reduction in operating temperature (around 400-600 ^{o}C). The development of highly conductive protonic perovskite electrolytes as well as triple-ionic/electronic conductor (TIEC) cathodes suggests that stability-versus-power-density trade-offs that persist into the current era can be reduced through careful A/B-site chemistry and defect/strain engineering (Zhang et al., 2024).

6.1 Materials discovery will prioritize Sr- and Co-lean perovskites, double-perovskite frameworks, and high-entropy oxide design.

Through high-throughput computation and machine learning, the direction is changing to Fe-rich double perovskites in addition to entropy-stabilized electrolytes (such as HEO Ba-cerate / zirconate solid solutions) to reduce segregation of cations, scarcity of elements / toxicity. The designs reduce the critical-metal levels and offer variable transport and increased stability limits (Zheng et al., 2024).

6.2 Controlling surface chemistry is now central to lifetime gains.

Reduction in chromium toxicity and A-site (Sr) segregation continue to require enhancement of the long-term operation of perovskite cathodes. Since surface phases are strongly linked to oxygen exchange kinetics, because the former depends on the latter, surface reconstruction, dopant, and atomic-scale surface-termination studies are becoming techniques enabling the emerging technologies, head of which are surface terminations. It is expected that the application of operando toolkits and standardized stress test will be expanded to guide the design of surfaces without surfactants (Samreen et al., 2023).

6.3 Exsolution-enabled nanocatalysis will mature from concept to process.

Perovskite matrices with in-situ dissolve socketed metal and alloy nanoparticle (Ni, Co, Fe, and Ru), are also providing electrodes with commercially-available triple-phase boundaries resistant to coke and sulfur. The next stage in restoring performance after redox abuse can be performed by the use of regeneration cycles, multi-element exsolved alloys, and spatially patterned exsolution, which is electrically or chemically induced. Coupling exsolution and 1D/2D designs (nanofibers, porous scaffolds) do not need to reduce the density of active sites, and so might be further enhanced (Xie et al., 2024).

6.4 Electrolyte breakthroughs aim at thinner, denser, more CO_2-resistant films.

Our short-term target is the scalable thin film production (inkjet/spin/PLD/ALD) of sub-micron density and low ohmic losses; the BZCYYb-based proton conductor already exhibit high conduction at <600C. In parallel, recently found mixed OH -/H + ceramic conductors provide a proving avenue to achievable even lower-temperature operation, however, there remains the need to establish how compatible they are with traditional electrode chemistries. Finally, Zr-based chemistries and protective surface coats are also useful countermeasures to the CO_2 reaction (carbonate formation) with Ba-rich perovskites, which is, however, a design drawback (Guo et al., 2022).

6.5 Manufacturing will be re-imagined around digital printing and additive routes.

High density Inkjet, aerosol and direct-ink-writing (DIW) techniques are being used to construct dense electrolytes, as well as architected electrodes with glaringly low region-specific resistances and impressive adhesion This is now also being applied to produce tubular or planar large-area cells in 3D printing and using commodity powders This is now being moved out of the laboratory, into pilot-scale, using tubular or planar large-area cells. Closed-loop control printing processes, in-line metrology especially, are also expected to become prevalent in the next three to five years (Zou et al., 2024).

6.6 System-level integration will emphasize reversibility and fuel flexibility.

Reversible SOCs (Rsocs) which employ perovskite electrodes will be made using the same material advancements, where light hydrocarbons or ammonia can be used in the intermediate temperature or they can be directly used at lower temperatures, and they can store or release them at high temperatures. Splits rings Both the SOFC and SOEC modes will require co-optimisation of the position of anode as well as cathode chemistries and supports in arrange on the way to meet the high-current density goal with minimal decrease in the degradation groups (Meisel et al., 2025).

7. Conclusion

Perovskite based materials are some of the most appealing materials to develop in fuels cell technologies due to their high activity in catalysis, dual ionic and electronic conductivity, structural manipulation and the ability to operate in intermediate temperatures. Although $LaGaO_3$-based and also $BaCeO_3$/$BaZrO_3$-based oxide are used as substitutes of traditional YSZ in reducing overall temperature, perovskite type such LSCF, BSCF and LSCM also show excellent oxygen reduction and also reduce hydrocarbons oxidation as electrodes. The ability to substitute with some kind of substitutes in the A- and B-sites makes it possible to have customized characteristics to certain electrochemical functions. Nevertheless, despite these advantages, the number of challenges and limitations is quite significant. The challenges in the large-scale commercialization include surface degradation (Sr segregation), instability under CO_2 /H_2O conditions, low long-term stability, and difficulties in fabrication. Namely, $BaZrO_3$-based solutions possess smaller yet better resilience conductivity in comparison to products based on $BaCeO_3$ that have high proton conductivity but are frail. Further besides, cost competitiveness in comparison to Ni cell based on YSZ remains a problem, interfaces and front end incompatibilities and processing constraints.

Reference

1. Steele, B. C. H., & Heinzel, A. (2001). Materials for fuel-cell technologies. *Nature, 414*, 345–352.
2. O'Hayre, R., Cha, S. W., Colella, W., & Prinz, F. B. (2016). *Fuel Cell Fundamentals*. John Wiley & Sons.
3. Minh, N. Q. (2004). Solid oxide fuel cell technology—features and applications. *Solid State Ionics, 174*(1–4), 271–277.
4. Goodenough, J. B., & Huang, Y. H. (2007). Alternative anode materials for solid oxide fuel cells. *J. Power Sources, 173*(1), 1–10.
5. Skinner, S. J. (2001). Recent advances in perovskite-type materials for solid oxide fuel cell cathodes. *Int. J. Inorg. Mater., 3*(2), 113–121.
6. Li, X., Zhao, H., Liang, J., Luo, Y., Chen, G., Shi, X., ... & Sun, X. (2021). A-site perovskite oxides: an emerging functional material for electrocatalysis and photocatalysis. *Journal of materials chemistry A*, *9*(11), 6650-6670.
7. Jiang, S. P. (2019). Development of perovskite oxide cathodes for solid oxide fuel cells. *J. Mater. Chem. A, 7*, 21933–21959.
8. Wang, T., Wang, R., Xie, X., Chang, S., Wei, T., Dong, D., & Wang, Z. (2022). Robust direct hydrocarbon solid oxide fuel cells with exsolved anode nanocatalysts. *ACS Applied Materials & Interfaces*, *14*(51), 56735-56742.
9. Porotnikova, N., & Osinkin, D. (2024). Segregation and interdiffusion processes in perovskites: a review of recent advances. *Journal of Materials Chemistry A*, *12*(5), 2620-2646.

10. Laguna-Bercero, M. A. (2012). Recent advances in high temperature electrolysis using solid oxide fuel cells: A review. *J. Power Sources*, *203*, 4–16.
11. Li, W., Wang, D., Zhang, Y., Tao, L., Wang, T., Zou, Y., ... & Wang, S. (2020). Defect engineering for fuel-cell electrocatalysts. *Advanced Materials*, *32*(19), 1907879.
12. Rehman, J., Hanif, M. B., Khan, M. Z., Ullah, M., Starostina, I. A., Muhammad, M. T., & Li, Z. (2024). A review of proton-conducting electrolytes for efficient low-temperature solid oxide fuel cells: Progress, challenges, and perspectives. *Energy & Fuels*, *38*(23), 22637-22665.
13. Muller, O., & Roy, R. (1974). *The Major Ternary Structural Families*. Springer-Verlag.
14. Howard, C. J., & Stokes, H. T. (2005). Structures and phase transitions in perovskites. *Acta Crystallogr. B*, *61*(1), 102–112.
15. Goldschmidt, V. M. (1926). Die Gesetze der Krystallochemie. *Naturwissenschaften*, *14*(21), 477–485.
16. Kreuer, K. D. (2003). Proton-conducting oxides. *Annu. Rev. Mater. Res.*, *33*, 333–359.
17. Zhao, H., Ding, D., Chen, F., & Liu, M. (2022). Cobalt-based perovskite cathodes for intermediate-temperature SOFCs. *Advanced Energy Materials*, *12*(4), 2102567. https://doi.org/10.1002/aenm.202102567
18. Shi, Y., Zhang, W., Wang, J., & Chen, F. (2020). Performance and stability of cobalt-based perovskite cathodes for SOFCs. *Journal of Power Sources*, *450*, 227623. https://doi.org/10.1016/j.jpowsour.2019.227623
19. Kasyanova, A. N., Farlenkov, A. S., Eremin, V. A., & Viskup, A. P. (2022). Fe-based double perovskite oxides as alternative cathodes for SOFCs. *International Journal of Hydrogen Energy*, *47*(31), 14025–14034. https://doi.org/10.1016/j.ijhydene.2022.01.143
20. Giddey, S., Badwal, S. P. S., Kulkarni, A., & Munnings, C. (2013). Co-free perovskite cathodes for solid oxide fuel cells. *Solid State Ionics*, *231*, 94–101. https://doi.org/10.1016/j.ssi.2012.11.019
21. Wang, S., Zhao, H., & Liu, M. (2011). Sr_2FeMoO_6-based perovskites as anodes for SOFCs operating on hydrocarbons. *Electrochimica Acta*, *56*(15), 5482–5489. https://doi.org/10.1016/j.electacta.2011.03.038
22. Skutina, L., Ivanov, V., & Filonova, E. (2021). Sr-doped ferrite-based anodes for SOFC applications. *Ceramics International*, *47*(22), 32176–32185. https://doi.org/10.1016/j.ceramint.2021.08.126
23. Kim, J., Park, S., Lim, J., & Yoo, C. Y. (2024). Exsolution-driven perovskite electrodes for long-term stable SOFCs. *Nature Communications*, *15*, 356. https://doi.org/10.1038/s41467-023-44321-8
24. Zhang, Z., Chen, Y., & Irvine, J. T. S. (2022). Exsolved nanoparticles in perovskite electrodes for SOFCs. *Advanced Energy Materials*, *12*(15), 2103740. https://doi.org/10.1002/aenm.202103740
25. Ding, H., Bi, L., Zhang, C., Liu, W., & Wang, H. (2020). Barium cerate–zirconate–yttrium oxide composite proton-conducting perovskite electrodes for PCFCs. *Journal of Power Sources*, *450*, 227636. https://doi.org/10.1016/j.jpowsour.2019.227636
26. Ni, Q., Bi, L., Tao, Z., & Wang, H. (2018). Triple-conducting perovskite electrodes for protonic ceramic fuel cells. *Energy & Environmental Science*, *11*(8), 2205–2212. https://doi.org/10.1039/C8EE00821K
27. Zhang, Y., Sunarso, J., & Liu, S. (2021). Symmetric electrodes based on LSCF/BSCF for reversible solid oxide cells. *Journal of Materials Chemistry A*, *9*, 13948–13959. https://doi.org/10.1039/D1TA01712A
28. Shao, Z., Yang, W., Cong, Y., Dong, H., Tong, J., & Xiong, G. (2016). Bifunctional oxygen electrodes for reversible SOFCs. *Nature Communications*, *7*, 11701. https://doi.org/10.1038/ncomms11701

29. Bai, J., Zhou, D., Niu, L., Zhu, X., Wang, N., Liang, Q., ... & Yan, W. (2024). Preparation of high-performance multiphase heterostructures IT-SOFC cathode materials by Pr-induced in situ assembly. *Applied Catalysis B: Environment and Energy*, *355*, 124174.
30. Acosta, M., Baiutti, F., Tarancón, A., & MacManus-Driscoll, J. L. (2019). Nanostructured materials and interfaces for advanced ionic electronic conducting oxides. *Advanced Materials Interfaces*, *6*(15), 1900462.
31. Du, Z., Zhao, H., Li, S., Zhang, Y., Chang, X., Xia, Q., ... & An, K. (2018). Exceptionally high performance anode material based on lattice structure decorated double perovskite Sr2FeMo2/3Mg1/3O6− δ for solid oxide fuel cells. *Advanced Energy Materials*, *8*(18), 1800062.
32. Senthil Kumar, S., & Aruna, S. T. (2021). Hydrocarbon compatible SOFC anode catalysts and their syntheses: A review. *Sustainable Chemistry*, *2*(4), 707-763.
33. Ishihara, T., Matsuda, H., & Takita, Y. (1994). Doped $LaGaO_3$ perovskite-type oxide as a new oxide ionic conductor. *J. Am. Chem. Soc.*, *116*(9), 3801–3803.
34. Tao, S., & Irvine, J. T. S. (2007). A redox-stable efficient anode for solid-oxide fuel cells. *Nat. Mater.*, *6*, 813–817.
35. Katahira, K., Kohchi, Y., Shimura, T., & Iwahara, H. (2000). Protonic conduction in Zr-substituted $BaCeO_3$. *Solid State Ionics*, *138*(1-2), 91–98.
36. Adler, S. B. (2004). Factors governing oxygen reduction in solid oxide fuel cell cathodes. *Chem. Rev.*, *104*(10), 4791–4844.
37. Zhang, W., Zhang, X., Song, Y., & Wang, G. (2024). Recent progress on cathode materials for protonic ceramic fuel cells. *Next Sustainability*, *3*, 100028.
38. Zheng, S., Bian, W., & Ding, H. (2024). A robust protonic ceramic fuel cell with a triple conducting oxygen electrode under accelerated stress tests. *Materials Advances*, *5*(6), 2296-2305.
39. Samreen, A., Ali, M. S., Huzaifa, M., Ali, N., Hassan, B., Ullah, F., ... & Arifin, N. A. (2024). Advancements in perovskite-based cathode materials for solid oxide fuel cells: a comprehensive review. *The Chemical Record*, *24*(1), e202300247.
40. Xie, M., Cai, C., Duan, X., Xue, K., Yang, H., & An, S. (2024). Review on Fe-based double perovskite cathode materials for solid oxide fuel cells. *Energy Materials*, *4*(1), N-A.
41. Guo, R., & He, T. (2022). High-entropy perovskite electrolyte for protonic ceramic fuel cells operating below 600 C. *ACS Materials Letters*, *4*(9), 1646-1652.
42. Zou, P., Iuga, D., Ling, S., Brown, A. J., Chen, S., Zhang, M., ... & Tao, S. (2024). A fast ceramic mixed OH−/H+ ionic conductor for low temperature fuel cells. *Nature Communications*, *15*(1), 909.
43. Maier, Joachim. "Stoichiometry effects in bulk and at interfaces: Solid state ionics and beyond." *Communications* 6 (2015): 8586.