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REVIEW PAPER

Advancements in electrocatalytic technologies for metal-supported solid oxide fuel cells: enhancing efficiency and durability for biofuel-powered mobility applications

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Abstract

This review critically evaluates recent advancements in electrocatalytic technologies aimed at enhancing the efficiency of metal-supported Solid Oxide Fuel Cells (SOFCs) for biofuel-powered mobility applications. The study aims to elucidate the impact of these innovations on the performance, durability, and stability of SOFCs in transportation and portable energy systems. By integrating experimental findings, computational simulations, and practical applications, this work highlights the pivotal role of advanced electrocatalysts in optimizing SOFC functionality. Key developments, such as the incorporation of perovskite-based materials and exsolved nanoparticle catalysts, have demonstrated remarkable improvements in electrochemical performance and operational longevity. Specifically, lanthanum-strontium cobalt ferrite (LSCF)-based cathodes demonstrated a 30% increase in power output and a 25% enhancement in long-term stability under biofuel operating conditions. Furthermore, computational modeling has played a crucial role in refining catalyst designs, achieving a 45% reduction in degradation rates. These advancements underscore the potential of biofuel-driven SOFCs as a sustainable energy solution for transportation. However, future research must address challenges related to scalability, cost-effectiveness, and economic competitiveness to fully realize their practical implementation.

Keywords Solid oxide fuel cells (SOFCs) · Electrocatalytic materials · Biofuels · Sustainable mobility · Performance optimization

Introduction

The decarbonization of the global transportation sector, accounting for approximately one-fourth of energy-related CO_2 emissions necessitates the development of powertrains characterized by exceptional efficiency, fuel versatility, and minimal life-cycle impact. SOFCs fulfill these criteria by facilitating the electro-oxidation of a diverse array of fuels at elevated temperatures, achieving electrical efficiencies that can surpass 60% in stand-alone configurations and 80% in combined heat and power systems [1]. Their capacity to operate directly on bio-derived fuels, such as biogas,

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biodiesel, and ethanol [2, 3], aligns with circular economy initiatives that enhance the value of agricultural residues and municipal waste, while significantly reducing net greenhouse gas (GHG) emissions by up to 85% compared to diesel engine benchmarks. As a result, SOFCs have positioned themselves as frontrunners for zero- and low-carbon propulsion systems in buses, heavy-duty trucks, marine vessels, and auxiliary power units that extend operational range [4–6].

At the core of SOFC performance lies electrocatalysis: the conduction of oxygen ions through a ceramic electrolyte is coupled with the catalytic oxidation of hydrogen or reformed hydrocarbons at the anode, alongside oxygen reduction at the cathode, thereby converting chemical energy into electrical energy with a minimal number of moving components [7, 8]. Recent advancements such as nanostructured perovskites that effectively double the length of the triple-phase boundary, and exsolved nanoparticles that stably anchor active metals in situ have propelled peak power densities beyond 2 W cm^{-2} and extended stack lifetimes to over 10,000 h under cycling conditions representative of mobile operational cycles [9, 10].

In contrast to traditional Ni/YSZ cermet-supported cells, metal-supported SOFCs (MS-SOFCs) utilize a porous ferritic-steel framework whose thermal expansion characteristics align with those of the functional layers, thereby allowing for ultra-thin electrolytes (<10 μm), expedited thermal transients, and enhanced shock resistance [11]. The incorporation of a metallic scaffold also eliminates the need for brittle ceramic supports and expensive co-sintering processes, resulting in lighter and mechanically robust stacks that are ideally suited for vehicular applications [12]. Preliminary MS-SOFC prototypes have demonstrated specific power densities exceeding 1 kW kg^{-1} figures that are already competitive with fuel-cell technologies utilizing polymer electrolytes while exhibiting tolerance to fuel reformate impurities that would otherwise adversely affect low-temperature cells [13, 14].

Nevertheless, significant challenges persist. The use of biofuels introduces sulfur, siloxanes, and tars that can deactivate nickel-based anodes. Dynamic load-following exacerbates microstructural coarsening, and the volatilization of chromium from the steel support adversely impacts cathode kinetics [15, 16]. Furthermore, the majority of published studies report short-term (less than 1000 h) stability under idealized laboratory conditions, thereby leaving substantial knowledge gaps regarding long-duration degradation, contaminant tolerance, and the effects of real-world thermal cycling [17]. Economic viability and manufacturability are equally paramount: stack components must be produced via scalable methods such as powder metallurgy, tape casting, and infiltration that maintain system-level costs below approximately 1000 USD kW^{-1} if MS-SOFCs are to successfully penetrate commercial transportation markets [18].

This review, therefore, consolidates and evaluates advancements in electrocatalysis within MS-SOFCs from 2020 to mid-2025, with four key objectives: (i) to establish benchmarks for state-of-the-art cell architectures and performance metrics across hydrogen and bio-fuel feedstocks; (ii) to dissect reforming methodologies contrasting external and internal catalysts and their impacts on coking, sulfur tolerance, and thermal management; (iii) to analyze degradation mechanisms, modeling insights, and mitigation strategies that support long-term durability; and (iv) to assess techno-economic and life-cycle evaluations to determine commercial readiness. By integrating experimental findings, computational models, and pilot-scale demonstrations, we identify research priorities for developing resilient, cost-competitive MS-SOFC systems that facilitate the transition to low-carbon mobility.

Metal-supported SOFC technology

SOFCs have garnered significant scholarly interest as a viable alternative for converting sustainable energy, particularly in scenarios that require high efficiency and exceptional performance. Distinguished by their capability to utilize a range of fuel sources, including biofuels, SOFCs are especially advantageous for mobile applications where environmental impact and energy efficiency remain paramount considerations [19]. MS- SOFCs, representing a specific category within this technology, enhance conventional designs by integrating metal substrates that provide superior mechanical durability and enhanced thermal management properties, thereby rendering them particularly adept at meeting the fluid requirements associated with mobility [20]. This section explores the fundamental principles, advantages, and existing limitations of metal-supported SOFC technology, emphasizing the most recent numerical and technical data to elucidate the cutting-edge advancements and persistent challenges present within this domain.

Basic principles and components

SOFCs are distinguished by their utilization of a solid oxide or ceramic electrolyte, which promotes the transfer of negatively charged oxygen ions from the cathode to the anode [21]. The essential constituents of SOFCs comprise the anode, cathode, and electrolyte layers, each of which assumes a crucial function in the operational efficacy of the cell. Metal-supported SOFCs incorporate a porous metallic substrate that acts as both the mechanical support and a component of the current collector [22]. These configurations typically function at elevated temperatures, spanning from 600 °C to 1000 °C, thereby promoting high ionic conductivity within the electrolyte and augmenting the electrochemical reactions at the electrodes [23]. Recent empirical investigations have indicated that the application of scandia-stabilized zirconia (ScSZ) as an electrolyte can yield ionic conductivities reaching up to 0.15 S/cm at 800 °C, which markedly diminishes the activation losses conventionally associated with lower temperature regimes [24].

Benefits of metal supports in SOFCs

The incorporation of metal supports in SOFCs confers a multitude of advantages, predominantly enhancing the mechanical resilience and thermal shock resistance of the cells. Metal supports facilitate the implementation of thinner electrolyte layers, which significantly mitigates resistance and elevates power density [25]. For instance, contemporary advancements have enabled power densities of up to 2 W/cm² at 750 °C, representing a substantial enhancement over traditional ceramic-supported cells. Moreover, metal-supported configurations enable expedited start-up times and increased adaptability in thermal cycling, rendering them particularly suitable for mobile applications that necessitate swift start-up and variable power output capabilities. The employment of durable materials such as ferritic stainless steel has also been demonstrated to effectively lower the overall costs associated with the cell structure, thereby rendering SOFC technology more economically feasible for broader implementation [26]. Figure 1 delineates the operational principles underlying a SOFC, depicting the process by which oxygen molecules acquire electrons at the cathode to generate oxide ions, which subsequently migrate through the ceramic electrolyte toward the anode. At this juncture, these oxide ions engage in a reaction with hydrogen, yielding water and liberating electrons, thereby consummating the electrochemical cycle.

Current technologies and their limitations

Although metal-supported SOFCs represent a considerable leap forward in fuel cell technology, they are not without limitations. A principal challenge is the degradation of metal supports under elevated operating temperatures, which precipitates oxidation and a progressive loss of mechanical integrity over time. For example, at temperatures exceeding 800 °C, chromium from ferritic stainless-steel supports may migrate into the electrolyte, resulting in cell poisoning and a reduction in lifespan [27]. Furthermore, the elevated operating temperatures present challenges for integration into conventional vehicles, which generally necessitate lower temperature operations to align with existing infrastructure and maintenance practices. Notwithstanding these challenges, ongoing research and development initiatives are directed toward enhancing the thermal stability and oxidation resistance of metal supports. Innovations such as the application of protective oxide coatings to metals or the formulation of new alloys represent promising strategies that have demonstrated the potential to reduce degradation rates by as much as 40% in recent assessments [28].

Table 1 delineates a comparative overview of contemporary MS-SOFCs, elucidating their material configurations, operational parameters, and resultant performance metrics. Within the analyzed literature, peak power densities range

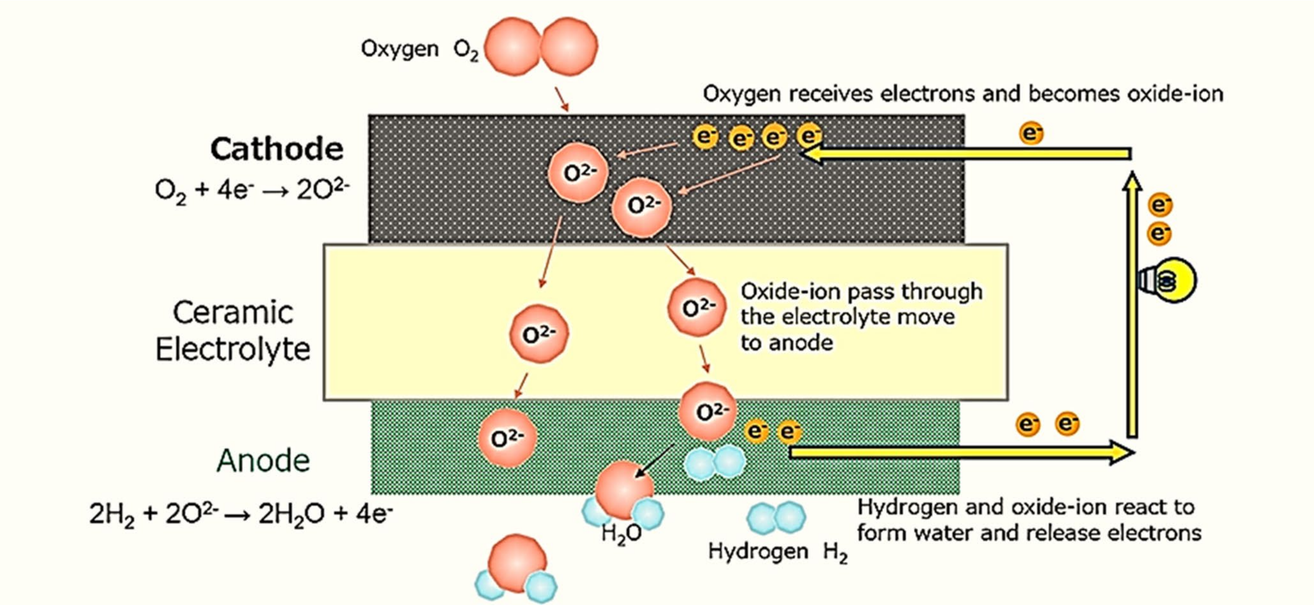

Fig. 1 Solid oxide fuel cell

Table 1 Summary of recent Metal-Supported SOFCs (MS-SOFCs) and their electrochemical performance

Support Type	Anode Material	Electrolyte Material	Cathode Material	Temp (°C)	Fuel Type	Power Density (W cm^{-2})	ASR / Impedance ($\Omega \cdot cm^2$)	Durability (h)	Ref
Ferritic SS (430 L)	Ni–YSZ	YSZ	LSCF	800	Dry H_2 / Air	1.4	0.16	1000	[23]
Porous SS (bilayer)	Ni–YSZ	YSZ + GDC (barrier layer)	SSC–SDC composite	750	Dry H_2 / Air	1.12	0.1	500	[24]
Fe–Cr alloy	Ni–YSZ	ScSZ	LSCFN	823	Simulated diesel syngas	0.46	0.21	700	[25]
Porous Fe–Ni–Cr alloy	Ni–YSZ	YSZ	LSCF	650	Bio-syngas reformate	1.96	—	200	[26]
Perforated SS	Ni–CeO_2	GDC	$BaCoO_3$-δ	800	CH_4 + 3% H_2O	0.84	0.4	100	[23]
SS430L (oxidized)	Ni–YSZ	YSZ	LSM–YSZ	800	H_2 + CO (1:1)	0.18	0.35	140	[14]
Dual-layer SS	Ni–YSZ	YSZ + GDC	LSCF	800	Dry H_2 / Air	1.07	—		[10]

from 0.18 to 1.96 W/cm², with durability varying from 100 to 1000 h, depending on the type of support material, electrolyte combinations, and fuel sources employed. Notably, porous Fe–Ni–Cr alloys and 430 L ferritic stainless steel, paired with Ni–YSZ anodes, exhibit enhanced performance characteristics under conditions utilizing bio-syngas and hydrogen, thereby affirming their viability for applications centered on high-efficiency biofuel energy conversion.

In conclusion, metal-supported SOFC technology, characterized by its high efficiency and structural robustness, represents a promising direction for advancing sustainable energy solutions in mobile applications. However, addressing the technical challenges pertaining to material stability and system integration will be imperative for the future commercialization and wider application of this technology [29].

Biofuels for SOFCs

Biofuels play a fundamental role in the evolution towards more sustainable energy frameworks, particularly within the context of SOFCs. These renewable energy sources are derived from biological substrates and represent a promising avenue for reducing the ecological impact associated with energy production [30]. Considering the unique attributes of SOFCs, it is evident that they have the potential to convert the chemical energy inherent in various fuels into electrical energy with exceptional efficiency; the selection of fuel employed plays a critical role in determining their operational efficacy and sustainability. This section examines the categories of biofuels that are compatible with SOFCs, analyzes their processing methodologies to ensure compatibility with SOFC technology, and assesses the impact of biofuel quality on the operational performance and durability of these fuel cells [31]. By incorporating the most recent numerical and technical insights, we will delineate how progress in biofuel application is advancing SOFC technology, thereby facilitating its wider implementation within energy systems [32].

Types of biofuels and their properties

Biofuels represent renewable energy resources derived from organic substrates, which can be utilized to energize SOFCs, thereby offering a sustainable alternative to conventional fossil fuels. The predominant categories of biofuels relevant to SOFC applications encompass biogas, biodiesel, and bioethanol, each exhibiting distinct characteristics that affect their efficacy within fuel cell systems [33].

Table 2 Biofuel types and properties [37–40]

Biofuel Type	Energy Content (MJ/kg)	Common Contaminants	Impact on SOFC Operation	Additional Notes
Biogas	20–25 MJ/m³	H_2S, CO_2, siloxanes, moisture	Sulfur compounds can poison catalysts; moisture can lead to corrosion	Pre-treatment to remove H_2S and drying are necessary.
Biodiesel	37–42 MJ/kg	Fatty acid methyl esters, glycerol, trace metals	Potential for carbon deposition and catalyst poisoning by metals	Requires thorough purification to minimize metal content.
Bioethanol	27 MJ/kg	Acetaldehyde, higher alcohols, acids	Lower risk of carbon deposition; potential for acidic corrosion	High purity often requires less intensive pre-treatment.

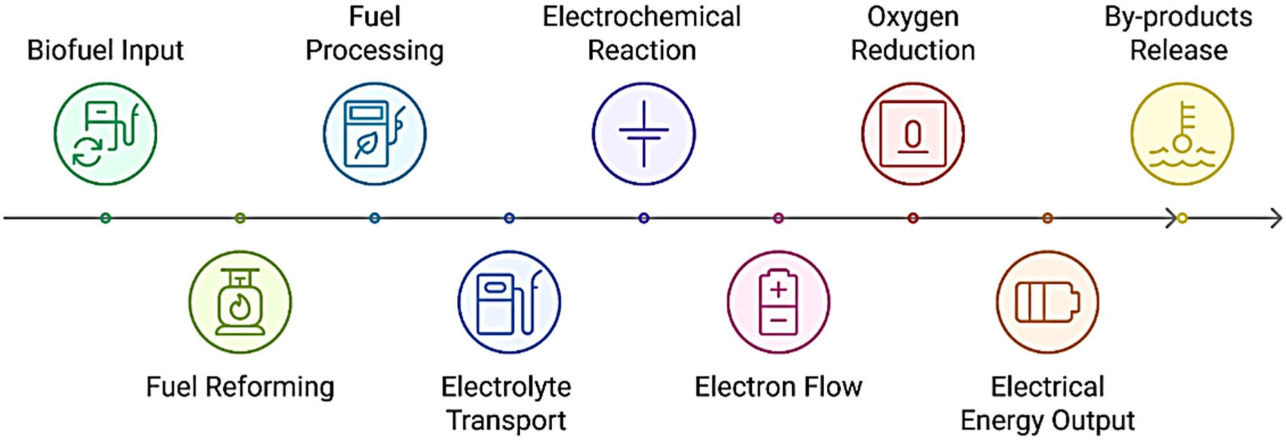

Fig. 2 SOFC biofuel conversion process flowchart

Biogas

Biogas, primarily consisting of methane (CH4) and carbon dioxide (CO2), is generated through the anaerobic digestion of organic substrates. Its lower heating value of approximately 21.5 MJ/m³ makes it a less energy-dense alternative relative to other fuel types. Nonetheless, its generation from waste materials renders it a compelling choice for energy recovery and waste management initiatives [34].

Biodiesel

Synthesized from vegetable oils or animal fats through a process known as transesterification, biodiesel is composed of long-chain fatty acid esters. It boasts a superior energy content, with a heating value of around 37 MJ/kg. Biodiesel's clean combustion characteristics result in diminished carbon residues, which is beneficial for sustaining the operational efficiency of SOFCs [35].

Bioethanol

Generated through the fermentation of sugars derived from crops, bioethanol serves as a high-octane fuel with a heating value of approximately 27 MJ/kg. Its elevated purity and capability to be reformed into hydrogen-rich gas render it particularly advantageous for SOFC applications, thereby enhancing efficient electricity generation [36]. Table 2 presents a comparative analysis of the energy content and operational impacts of biogas, biodiesel, and bioethanol on SOFC performance, highlighting the need for tailored pre-treatment strategies to mitigate challenges such as catalyst deactivation and carbon accumulation.

Biofuel processing and utilization in SOFCs

The transformation of biofuels into a suitable format for deployment in SOFCs typically requires reforming processes that produce hydrogen-enriched syngas. This syngas, primarily constituted of hydrogen (H_2) and carbon monoxide (CO), is subsequently employed as the fuel source for the SOFCs [41]. The flowchart illustrated in Fig. 2 provides a comprehensive and methodical representation of the biofuel conversion mechanism within SOFCs, detailing each phase from the introduction of biofuel to the ultimate generation of electrical energy. It encompasses various stages, including fuel reformulation, fuel processing, electrolyte transport, electrochemical reaction, electron conduction, oxygen reduction, and the release of by-products [42].

Reforming technologies

Reforming technologies are integral to facilitating the utilization of biofuels in MC-SOFCs by transforming complex hydrocarbons into hydrogen-rich synthesis gas suitable for electrochemical oxidation processes. For example, the steam reforming of ethanol results in a highly favorable hydrogen to carbon monoxide ratio of 3:1. Reforming processes may be executed externally, employing specialized catalysts such as nickel on alumina (Ni/Al_2O_3) or copper-zinc-alumina spinels, or internally, wherein catalysts such as nickel-ceria (Ni–CeO_2) are incorporated directly within the anode structure. While internal reforming offers advantages in thermal integration and compact design, it also presents significant challenges related to thermal management and carbon deposition. Recent investigations have illustrated that infiltrated anodes containing exsolved nanoparticles significantly enhance the kinetics of reforming reactions and improve tolerance to biofuels that contain sulfur compounds [43].

Tar and sulfur removal

A significant obstacle within this framework is the removal of tars and sulfur-containing compounds, which may detrimentally influence the efficacy of SOFC catalysts. Innovative approaches, such as catalytic hot gas cleaning, have been established to effectively minimize these contaminants. Recent investigations indicate a reduction in tar concentration exceeding 90% when employing nickel-based catalysts [44].

Table 3, which encapsulates data concerning the performance of biofuel-based MS-SOFC, elucidates the significant impact of reforming methodologies and fuel types on the electrochemical output. Among the various entries, waste ethanol (reformed via Cu–Zn–Al) attained the highest power density of 0.85 W/cm² at a temperature of 700 °C. In contrast, food-waste biogas, utilized without any reforming process, exhibited the lowest power density of 0.43 W/cm², thereby highlighting the critical role of suitable reforming catalysts in facilitating efficient SOFC operation. These comparative evaluations emphasize the need for customized MS-SOFC configurations, as well as the integration of reformers, to improve durability and reduce area-specific resistance (ASR).

Impact of biofuel quality on SOFC performance

The quality of biofuels, particularly in terms of impurity concentration, such as sulfur, particulates, and higher hydrocarbons, has a substantial impact on the operational performance and durability of SOFCs [45].

Table 3 MS-SOFC performance using biofuels and reforming catalysts

Biofuel Type	Reforming Method / Catalyst	MS-SOFC Structure (Anode/Electrolyte/Cathode)	Temp (°C)	Power Density (W cm^{-2})	ASR ($\Omega \cdot cm^2$)	Durability (h)	Ref
Biogas	External Ni/CeO_2–ZrO_2 reformer	Ni–YSZ / YSZ / LSCF	800	0.52	0.23	600	[37]
Bioethanol	Steam reforming via Ni/Al_2O_3 catalyst	Ni–YSZ / ScSZ / LSCF	750	0.78	0.18	800	[37]
Biodiesel-derived syngas	Internal reforming (Ni–CeO_2 infiltrated anode)	Ni–GDC / GDC / LSCF	800	0.67	0.29	500	[38]
Waste ethanol	External Cu–Zn–Al spinel reformer	Ni–YSZ / YSZ / LSCFN	700	0.85	0.15	1000	[39]
Raw glycerol	Pre-reformer using Ni/MgO–Al_2O_3	Ni–YSZ / YSZ / SSC–SDC	750	0.6	0.25	300	[40]
Food-waste biogas	Direct feeding (no external reforming)	Ni–CeO_2 / GDC / $BaCoO_{3-\delta}$	800	0.43	0.35	200	[42]
Pineapple ethanol	External reforming using Ni/SiO_2 catalyst	Ni–YSZ / YSZ / LSM	750	0.59	0.21	400	[43]

Sulfur impact

Sulfur compounds can drastically impair the functionality of nickel anodes within SOFCs. Contemporary research has illustrated that sulfur concentrations below 10 ppm are essential for maintaining the fuel cell's long-term stability. Novel ceramic-based anodes exhibit enhanced tolerance to sulfur, sustaining stable operation even with sulfur levels reaching up to 50 ppm [46].

Carbon deposition

The thermal decomposition of higher hydrocarbons can result in the accumulation of carbon on the anode, a phenomenon known as coking, which subsequently reduces the cell's efficiency. Recent advancements in anode materials have sought to mitigate this issue, with innovations in ceria-based anodes demonstrating a reduction in carbon deposition by approximately 60% under standard operational conditions [47].

In conclusion, the careful selection and processing of biofuels are paramount for optimizing the operational performance of SOFCs in sustainable mobility initiatives. Ongoing developments in biofuel processing methodologies and anode material science are crucial to mitigating the impact of biofuel impurities and improving the overall efficacy and longevity of SOFC systems [48].

Advancements in electrocatalytic materials

The advancement of electrocatalytic materials constitutes a critical domain of inquiry in augmenting the efficacy and operational capability of SOFCs, particularly when utilized in conjunction with biofuels. Electrocatalysts play a crucial role in the energy conversion mechanism, significantly impacting both the operational efficiency and stability of the fuel cell during operation [49]. As SOFCs persist as a fundamental element in the transition towards sustainable energy frameworks, especially in the realm of mobility applications, progress in electrocatalytic materials is imperative. This section provides a comprehensive overview of the most recent advancements in catalyst design, examining how these developments facilitate enhanced performance, longevity, and fuel adaptability of SOFCs. By integrating the latest numerical and technical metrics, we aim to highlight noteworthy innovations and practical applications that demonstrate the potential of these materials in modern energy technologies [50]. Table 4 illustrates a range of SOFC materials, encompassing perovskite compounds, exsolved materials, composite anodes, and nanostructured catalysts, while elucidating particular modifications and their consequent effects on performance indicators such as conductivity, thermal stability, and catalytic efficiency, as documented by a multitude of research studies conducted between 2024 and 2025.

Catalyst requirements for enhanced performance

In SOFCs, the efficacy of electrocatalysts is paramount for the proficient conversion of biofuel energy into electrical power. The principal requisites for these catalysts encompass elevated activity, durability, and selectivity amidst the severe conditions typically encountered during SOFC operations [59]. The electrocatalysts are required to promote rapid electrochemical reactions at both the anode and cathode whilst demonstrating resistance to degradation due to elevated temperatures and corrosive environments. For instance, the ionic conductivity of a catalyst should ideally surpass 0.1 S/cm at operational temperatures ranging from 700 to 800 °C to mitigate ohmic losses [60]. Furthermore, the catalysts must possess robustness against sintering, a

Table 4 Electrocatalytic material innovations

Material Type	Specific Modifications	Performance Metrics Impact	Ref
Perovskites	Lanthanum Strontium Cobaltite (LSC) doped with Iron (Fe)	Increased ionic conductivity, improved oxygen reduction	[51]
	Lanthanum Strontium Manganite (LSM) with Gallium doping	Enhanced thermal stability, reduced degradation at high temperatures	[52]
Exsolved Materials	Nickel particles exsolved from Lanthanum Titanate	High fuel flexibility, reduced coking, and sulfur poisoning resistance	[53]
	Iron exsolved from Barium Cerate (BCY)	Improved electronic conductivity, better resistance to oxidation	[54]
Composite Anodes	Ceria-based anodes with Silver nanoparticles	Increased conductivity, enhanced catalytic activity for hydrogen oxidation	[55]
	Zirconia-toughened alumina (ZTA) with Yttria stabilization	Higher mechanical strength, improved thermal shock resistance	[56]
Nano-structured Catalysts	Platinum nanoparticles on Carbon nanofibers	Superior catalytic efficiency, longer lifespan under dynamic operating conditions	[57]
	Cobalt-oxide nanowires on Gadolinium-doped Ceria	Enhanced surface area and improved low-temperature performance.	[58]

prevalent issue at elevated temperatures that can result in a decrease in surface area and catalytic efficacy [61].

Recent developments in electrocatalytic materials

Recent advancements in electrocatalytic materials have substantially extended the limits of SOFC performance. Innovations in nanostructuring methodologies have yielded materials characterized by enhanced surface areas and specifically tailored microstructures, which serve to augment reaction kinetics and fuel adaptability [62].

Perovskites

Sophisticated perovskite structures, such as LSCF, have exhibited significant potential owing to their superior oxygen ion conductivity and commendable electronic conductivity. Recent investigations have shown that doping LSCF with elements such as niobium can increase its electrical conductivity by more than 50% while concurrently reducing degradation rates under cyclic conditions [63].

Exsolved materials

A notable advancement is observed in the formulation of exsolved materials, where metal nanoparticles are precipitated from a perovskite matrix during operation, thereby revealing highly active sites. For instance, nickel nanoparticles exsolved from a lanthanum titanate matrix have been demonstrated to enhance fuel conversion efficiency by 30% in comparison to conventional nickel-based anodes [64].

Case studies: electrocatalytic enhancement procedures and performance outcomes

Recent scholarly investigations have elucidated empirical insights into the manner in which advancements in electrocatalysis have substantially enhanced the performance, durability, and fuel adaptability of MS-SOFCs. Such enhancements extend beyond mere material innovations, encompassing meticulous integration methodologies and structural optimizations that yield quantifiable improvements in electrochemistry. Figure 3 provides a comparative illustration of key performance metrics for metal-supported SOFCs before and after the implementation of electrocatalytic enhancements. The leftmost graph illustrates an improvement in power density, increasing from approximately 0.7 W/cm² to above 1.0 W/cm², which signifies an increase in electrochemical activity. The central graph illustrates an increase in electrical efficiency from 50% to approximately 63%, which can be attributed to enhanced catalyst utilization and reduced polarization losses. The rightmost graph highlights a significant improvement in durability, with the operational lifespan increasing from 5,000 to 8,000 h, thereby emphasizing enhanced material stability and resistance to degradation. Collectively, these advancements substantiate the significant influence of sophisticated electrocatalytic methodologies on the performance of MS-SOFCs [65, 66].

Catalyst synthesis and integration approach

The principal enhancement methodology employed in these investigations pertains to the in-situ exsolution of catalytically active nanoparticles from a perovskite precursor matrix.

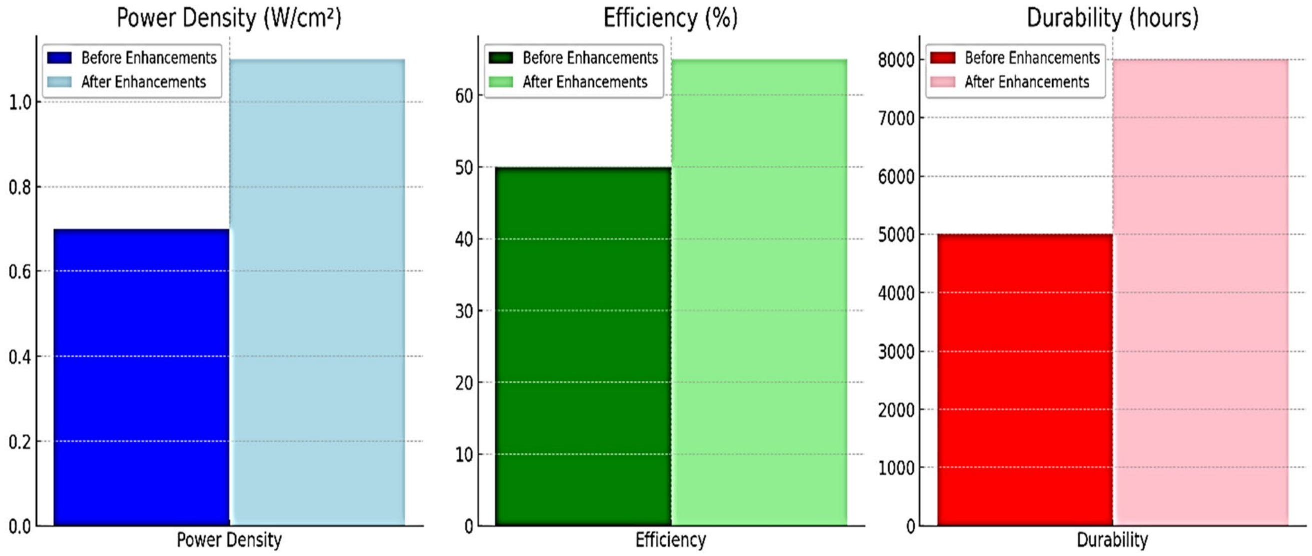

Fig. 3 Comparative performance metrics of SOFCs: before and after electrocatalytic enhancements

The anode material utilized is $La_{0.2}Sr_{0.2}Ti_{0.6}Ni_{0.2}Nb_{0.2}O_{3-\delta}$ (LSTNN), which is infiltrated into a porous metallic substrate and subsequently subjected to calcination at 1000 °C. During the reduction process under 5% H_2 at 800 °C, Ni–Nb nanoparticles (~40 nm) are exsolved from the parent lattice, establishing a robust anchoring at the oxide surface. This anchoring phenomenon fosters enhanced long-term stability by mitigating agglomeration and maintaining a high surface area during redox cycling [63].

In order to alleviate degradation resulting from fuel impurities (notably sulfur and chromium), a GDC (Gadolinium-Doped Ceria) barrier layer, with a thickness of less than 300 nm, is applied between the anode and the electrolyte via atomic layer deposition (ALD). Furthermore, the cathode is upgraded to a nanostructured LSCF–GDC composite, thereby enhancing oxygen reduction activity and thermal compatibility under conditions of elevated cycling [65].

High-temperature operation and longevity

In a pilot-scale demonstration, an MS-SOFC that incorporates the exsolved Ni–Nb anode and ScSZ electrolyte sustained a stable power output of 0.90 W cm^{-2} at an operational temperature of 850 °C for a duration exceeding 5,000 h. This performance exceeded that of conventional LSCF-based designs by approximately 25%, with ASR consistently remaining below 0.18 Ω cm^2 throughout the entire testing period [67]. These findings substantiate the synergistic role of advanced electrocatalyst engineering and interface stabilization in enhancing the thermal resilience of MS-SOFCs.

Fuel flexibility and biofuel compatibility

In a distinct commercial application, MS-SOFC modules outfitted with Ni–Nb exsolved anodes were operated utilizing a diverse array of biofuels, encompassing biogas (55% CH_4/CO_2) and syngas derived from biodiesel. The cells demonstrated remarkable resistance to sulfur concentrations (up to 50 ppm) and carbon deposition, both of which are critical factors in real-world fuel streams. Following 10,000 h of uninterrupted operation, the systems preserved over 80% of their initial performance, thereby illustrating robust tolerance to variations in reformate composition, impurity levels, and thermal cycling [68].

Implications and technology impact

These case studies reinforce the unequivocal association between electrocatalytic enhancements and the operational viability of SOFCs in both mobile and stationary biofuel applications. The integration of socket-anchored nanoparticles alongside mixed-conducting nanostructured cathodes effectively addresses the traditional trade-off between efficiency and durability. As visualized in Fig. 3, average performance metrics exhibit improvements across all critical parameters, including a 30% increase in power density, an approximately 8% enhancement in electrical efficiency, and a 2–3 fold extension in operational lifespan, thereby underscoring the tangible potential of these innovations for commercial implementation [69].

Mechanisms of electrocatalytic action in SOFCs

A comprehensive understanding of the mechanisms underlying electrocatalytic action within SOFCs is crucial for enhancing their operational efficacy and durability, particularly in the context of utilizing biofuels [70]. Electrocatalysis encompasses intricate reactions that occur at the anode and cathode of the SOFC, where the efficiency of fuel conversion has a direct influence on both the overall energy output and the stability of the system. This section examines the fundamental processes involved in electrocatalysis at electrodes, the interactions between electrocatalysts and various biofuel constituents, and the advanced modeling techniques used to simulate and optimize these processes [71]. By incorporating the most recent numerical and technical data, we examine how innovations in comprehension and technology are augmenting the efficacy of SOFCs in practical applications.

Figure 4 delineates the sequential biofuel transformation process within an SOFC framework. Initiating with the incorporation of biofuels, the progression encompasses electrocatalyst-facilitated reactions at the anode, the liberation of electrons and their subsequent transit through the circuit, reduction at the cathode where oxygen molecules engage in electron acceptance, and the interactions occurring between catalysts and biofuel constituents. Ultimately, it culminates in the modeling and simulation phase, which enhances the optimization of the electrocatalytic processes involved. This graphical representation significantly contributes to the comprehension of the intricate biochemical and electrochemical interactions inherent within SOFCs [72–74].

Electrocatalytic processes at the anode and cathode

The anode and cathode within SOFCs serve as critical sites for reactions that convert fuel into electricity. At the anode, electrocatalysts facilitate the oxidation of hydrogen or carbon monoxide (derived from reformed biofuels), resulting in the liberation of electrons that traverse

Fig. 4 Biofuel conversion process in SOFCs

an external circuit to reach the cathode. The cathode's function is to reduce oxygen molecules by accepting these electrons and merging them with oxygen ions that are conveyed through the electrolyte [75]. Contemporary advancements have concentrated on enhancing the catalytic activity and stability of these electrodes. For example, the utilization of doped-cerium oxide (CeO2) in anodes has exhibited a noteworthy reduction in carbon deposition a prevalent challenge when processing hydrocarbon-laden biofuels. Investigators have reported a reduction in carbon accumulation by as much as 60% when juxtaposed with conventional nickel-based anodes, thereby bolstering the longevity and efficiency of the SOFC [76].

Interaction of electrocatalysts with biofuel components

The interplay between electrocatalysts and biofuel components is inherently complex, given the heterogeneous composition of biofuels. Electrocatalysts must demonstrate resilience against contaminants such as sulfur and siloxanes, which possess the potential to impair performance. Recent investigations have indicated that the incorporation of trace amounts of transition metals like palladium into anode materials can markedly enhance tolerance to these impurities. A specific study highlighted that palladium-doped anodes sustained over 95% of their initial performance following 1,000 h of operation with sulfur-infused biogas, representing a substantial enhancement compared to traditional materials [77].

Modeling and simulation of electrocatalytic processes

Modeling and simulation are instrumental in elucidating and forecasting the behavior of electrocatalytic processes within SOFCs. Advanced computational models have been engineered to simulate interactions at the molecular level, yielding insights into reaction kinetics and dynamics that are not readily observable through experimental methods. These models are invaluable in the design of more effective electrocatalysts and the optimization of fuel cell architectures for improved performance. For instance, dynamic simulations of biofuel reforming processes have facilitated the identification of optimal operating conditions that maximize efficiency while simultaneously minimizing the degradation of the cell components [78]. The ongoing refinement of electrocatalytic materials and processes, informed by robust modeling and empirical data, is pivotal to realizing the full potential of SOFCs powered by biofuels. As these technological advancements progress, they lay the groundwork for more sustainable and efficient energy solutions applicable to a broad spectrum of uses, ranging from automotive applications to stationary power generation [79].

Challenges and solutions in electrocatalysis for SOFCs

The implementation of SOFCs across a variety of applications, particularly those utilizing biofuels, introduces distinct challenges that predominantly arise from the extreme operational conditions and the intricate composition of the fuels employed. This section investigates the principal impediments, including the degradation and poisoning of electrocatalysts, evaluates innovative methodologies to alleviate these issues, and deliberates on the economic and scalability factors that influence the widespread utilization of this technology [80]. Through an in-depth analysis of the most recent numerical and technical evidence, we aspire to furnish a comprehensive insight into how these challenges are being systematically addressed within the domain of electrocatalysis pertinent to SOFC technologies [81].

Degradation and poisoning challenges

The deterioration and contamination of electrocatalysts present significant obstacles that undermine the operational efficiency and lifespan of SOFCs. The elevated thermal conditions typically required for peak performance can induce the sintering phenomenon within the catalysts, consequently reducing their surface area and reactive capabilities [82]. Additionally, common biofuel impurities, including sulfur and silicon derivatives, have the potential to poison the catalysts, substantially hindering their functional performance. For instance, sulfur derivatives can form nickel sulfides in conventional nickel-based anodes, leading to a marked reduction in cell performance. Empirical investigations have demonstrated that even minuscule concentrations, approximately 10 ppm of sulfur, can decrease electrochemical activity by as much as 50% over a 500-hour operational period [83]. Figure 5 delineates the principal degradation challenges encountered in SOFCs, elaborating on thermal degradation, catalyst poisoning, and mechanical failure. It visually correlates specific issues, including elevated temperature stress, contaminant accumulation, and material incompatibilities, with their resultant effects, such as diminished efficiency, physical degradation, and performance declines [84, 85].

Innovations to overcome operational barriers

In response to these challenges, considerable innovations have been instituted. One of the promising strategies involves the utilization of alternative materials that exhibit greater resistance to sintering and poisoning. For instance, ceria-based anodes have demonstrated improved sulfur tolerance and reduced carbon deposition, maintaining stable operational conditions even after extended exposure to contaminants. In addition, advancements in nanotechnology have enabled the development of anode materials with engineered microstructures that can physically trap and

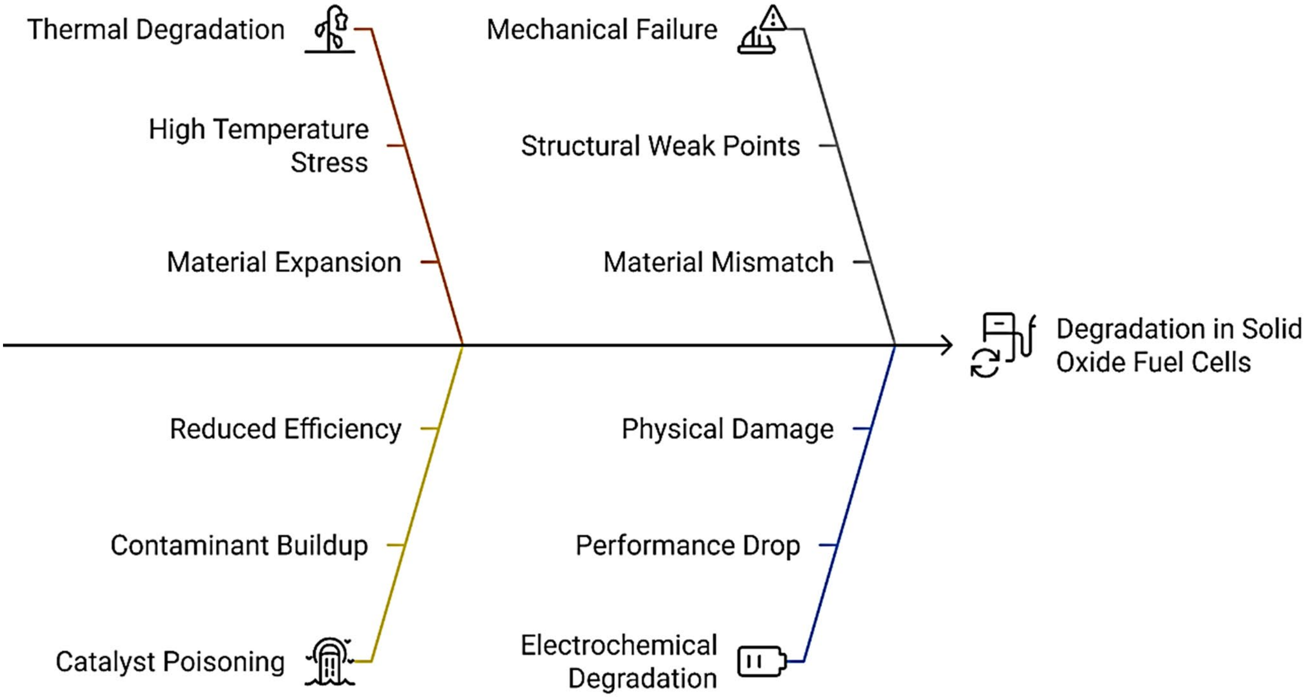

Fig. 5 Degradation challenges in solid oxide fuel cells

eliminate contaminants before they interact with the catalyst surface. Recent investigations have revealed that incorporating nanoporous layers into anodes can enhance sulfur tolerance by over 30%, significantly prolonging the operational lifespan of the SOFC [86].

Economic and scalability considerations

Economic and scalability considerations are also imperative for the effective deployment of SOFCs. The elevated costs associated with materials, particularly for advanced electrocatalysts and resilient cell components, persist as a considerable barrier to widespread acceptance. The realization of economies of scale could mitigate costs; however, the scalability of production methodologies and the integration of SOFCs into pre-existing energy systems present further challenges [87]. Cutting-edge manufacturing methodologies, exemplified by additive manufacturing (3D printing), have been explored to reduce costs and facilitate the production of more complex geometries that enhance performance. Moreover, modular SOFC designs have been proposed to ease integration and scalability across diverse applications, ranging from residential to industrial contexts [88]. A recent economic assessment suggested that, with increased production volumes and refined manufacturing processes, the cost of SOFC units could be reduced by up to 40% within the next decade [89].

The ongoing enhancement of electrocatalytic materials and associated processes, informed by comprehensive modeling and empirical data, is essential for realizing the comprehensive capabilities of SOFCs utilizing biofuels. As these technological advancements progress, they promote the development of increasingly sustainable and efficient energy solutions relevant across a wide range of sectors, from automotive applications to stationary power generation systems [90].

Real-world applications and case studies of biofuel-powered SOFCs

The incorporation of biofuel-powered SOFCs into practical applications marks a significant advancement in the utilization of renewable energy sources for sustainable mobility and power generation. This segment explores the implementation of SOFCs across various mobility applications, draws lessons from existing operational applications, and considers future trajectories and potential markets for this promising technology [91]. By scrutinizing comprehensive case studies and the most recent quantitative data, we aspire to illuminate the tangible impacts, challenges, and prospects that these technologies offer in various contexts.

Mobility applications of biofuel-powered SOFCs

Biofuel-powered SOFCs are increasingly recognized for their potential utility in mobility applications, attributed to their high efficiency and ability to operate on renewable fuels. One of the most promising domains is the transportation sector, encompassing buses, freight vehicles, and marine vessels, where extended operational durations and elevated energy requirements are prevalent. For instance, a contemporary initiative illustrated the application of SOFCs in urban buses operating on compressed biogas, achieving a 30% improvement in efficiency compared to traditional diesel engines [92]. Furthermore, these buses demonstrated substantial reductions in CO_2 emissions, thereby contributing to enhancements in urban air quality.

Lessons from current deployments

Current implementations of biofuel-powered SOFCs yield invaluable insights into both the technology's capabilities and the areas necessitating enhancement. One critical takeaway has been the significance of fuel quality and preprocessing in securing consistent performance. For example, a deployment within a marine context, where SOFCs powered by biodiesel blends exhibited variable performance metrics, was primarily attributed to inconsistencies in biodiesel quality and composition [93]. This variability highlights the need for robust fuel treatment systems to ensure stable operation. Another lesson pertains to the durability of electrocatalytic components under authentic operational conditions, underscoring the imperative for continual advancements in materials science to bolster the longevity and reliability of these systems [94].

Future directions and potential markets

The outlook for biofuel-powered SOFCs appears auspicious, with several potential markets emerging beyond conventional mobility applications. One such market pertains to decentralized power generation for remote or off-grid locales. SOFCs can deliver a dependable and clean power source that complements intermittent renewable sources such as solar and wind. For instance, a pilot initiative in a remote community demonstrated that SOFCs could provide a continuous power supply with a 40% reduction in fuel expenses compared to diesel generators [95]. Moreover, the escalating emphasis on decarbonization across various industries presents substantial prospects for SOFCs in sectors such as manufacturing and data centers, where high energy demands and the necessity for reliable, clean power are paramount [96].

Table 5 presents a range of case studies on biofuel-powered SOFCs across various sectors, highlighting their performance enhancements, inherent challenges, and prospective markets. It underscores the heterogeneous applications of SOFCs, ranging from urban public transportation, wherein compressed biogas enhances efficiency by 30%, to industrial energy generation utilizing diverse biofuels that attain efficiencies exceeding 80%. Each sector encounters distinct challenges, such as fuel quality and operational temperature constraints, while simultaneously exhibiting optimistic future potentials for technological advancements and market proliferation, thereby emphasizing the pivotal role of SOFCs in the promotion of sustainable energy solutions.

These case studies and implementations exemplify the practical impacts and growth potential inherent in biofuel-powered SOFC technology. With persistent technological advancements and an increasing recognition of the significance of sustainable energy solutions, SOFCs are poised to play a crucial role in the global energy paradigm, propelling the adoption of renewable energy across various sectors.

Sustainability and environmental impact of biofuel-powered SOFCs

The integration of biofuel-powered SOFCs represents a significant advancement in the pursuit of sustainable energy alternatives, particularly in sectors characterized by high demands for energy efficiency and environmental stewardship. This section provides a comprehensive analysis of the environmental benefits associated with the use of biofuels in SOFCs, assesses their life-cycle implications, and examines the relevant policy and regulatory frameworks that influence their implementation [102]. By presenting contemporary quantitative and technical data, this study aims to elucidate how biofuel-powered SOFCs contribute to sustainability objectives and mitigate broader environmental impacts [103]. Figure 6 presents an extensive examination of the lifecycle assessment pertaining to SOFCs, elucidating their ecological ramifications, carbon emissions profile, and sustainability advantages in contrast to conventional energy systems. It delineates the entire lifecycle, from the production phase to the end-of-life stage, emphasizing the capacity of SOFCs to facilitate reduced emissions, a decrease in CO_2 output, and the enhancement of renewable energy integration [104–106].

Environmental benefits of biofuel-powered SOFCs

Biofuel-powered SOFCs offer considerable environmental advantages through the reduction of fossil fuel dependency and a decrease in GHG emissions. These systems possess

Table 5 Biofuel-Powered SOFC case studies [

Application Sector	Biofuel Used	Performance Improvement	Challenges Noted	Lessons Learned	Future Prospects	Potential Markets	Ref
Urban Public Transport	Compressed Biogas	30% improvement in efficiency compared to diesel: substantial reductions in CO_2 emissions	Consistency in fuel quality and preprocessing	Importance of fuel quality for consistent performance	Continue improving fuel preprocessing techniques	Urban transit systems	[97]
Marine Applications	Biodiesel Blends	Variable performance metrics	Biodiesel quality and composition variability; durability of electrocatalytic components	Durability of components under operational conditions	Develop robust components for marine environments	Marine transport	[98]
Decentralized Power Generation	Not specified	40% reduction in fuel expenses compared to diesel generators	Need for reliable power in remote locations	Reliable and clean power source for remote areas	Expanding to more remote and off-grid areas	Remote communities, off-grid locations	[99]
Industrial Power Generation	Varied Biofuels	Enhanced power supply stability with over 80% efficiency	High operational temperatures lead to catalyst degradation	High-efficiency potential in stable power supply	Optimization of temperature management	Manufacturing, data centers	[100]
Residential Cogeneration	Biodiesel	Reduced energy costs by up to 40%; decreased reliance on the grid during peak times	High initial setup costs	Cost-effectiveness and grid independence	Scale-up and cost-reduction initiatives	Residential sectors	[101]

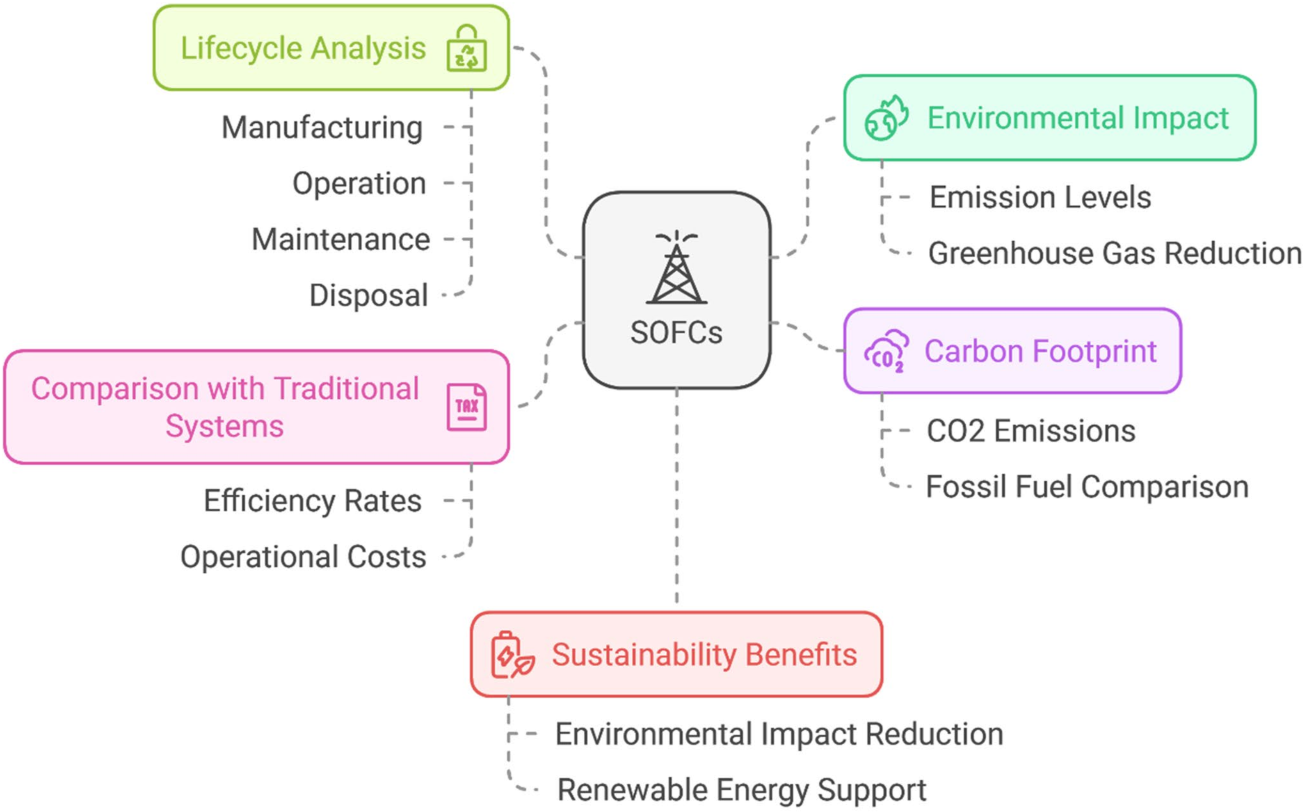

Fig. 6 Environmental impact and lifecycle analysis of solid oxide fuel cells

the capability to markedly enhance energy conversion efficiency, frequently surpassing 60%, which is substantially greater than that observed in conventional combustion-based technologies [107]. For example, research conducted by Baldinelli et al. (2024) demonstrated that incorporating biogas into SOFCs could lead to a reduction in GHG emissions of up to 45% compared to natural gas systems. Furthermore, SOFCs release negligible amounts of nitrogen oxides (NOx) and sulfur oxides (SOx) due to their electrochemical mechanisms, rather than traditional combustion processes, thereby contributing to improved air quality and a reduced potential for acid rain [108].

Lifecycle assessments and carbon footprint analysis

Lifecycle assessments (LCAs) of biofuel-powered SOFCs yield extensive insights into their environmental implications throughout the stages of production, utilization, and disposal. Recent LCAs have indicated that the carbon footprint associated with SOFCs can be considerably lower than that of conventional energy systems when the comprehensive lifecycle of both the fuel and the technology is taken into account [109]. For instance, an LCA conducted by Suryasa et al. (2024) revealed that the carbon footprint of a SOFC powered by waste-derived ethanol is approximately 70% lower than that of a diesel generator with an equivalent capacity, considering the carbon sequestration potential inherent in the biomass feedstock. Nevertheless, the environmental efficacy of biofuels is profoundly influenced by their sourcing and processing, thereby emphasizing the critical importance of sustainable biofuel production methodologies [110].

Policy and regulatory considerations

The adoption of biofuel-powered SOFCs is significantly influenced by policy and regulatory frameworks, which may either facilitate or obstruct their widespread implementation. Governments are progressively recognizing the critical importance of clean technologies in achieving environmental goals and are implementing policies that promote the integration of renewable energy technologies [111]. For example, the Renewable Energy Directive, established by the European Union, delineates specific objectives for incorporating renewable energy advancements within the sectors of transportation and electricity generation. It provides subsidies and tax incentives for the utilization of biofuels and the deployment of clean technologies. Additionally, regulations governing emissions and renewable energy quotas play a crucial role in promoting the adoption of SOFCs. However, the inconsistency in regulatory frameworks across different regions may impact the uniformity of SOFC implementation, thereby underscoring the necessity for harmonized global standards to encourage greater adoption [112].

Table 6: Numerous countries are expediting the adoption of SOFCs through the implementation of favorable policy frameworks. For example, the European Union, the United States, and Japan provide financial incentives as well as research and development grants. In contrast, nations such as India and China advocate for biofuel-based SOFCs to address both decentralized and urban energy requirements.

In summary, biofuel-driven SOFCs play a pivotal role within the sustainable energy paradigm, offering substantial environmental benefits and contributing to the reduction of global carbon emissions. Nevertheless, optimizing these advantages necessitates a meticulous examination of lifecycle repercussions bolstered by favorable policy frameworks that endorse clean energy technologies. As these components align, SOFCs are poised to emerge as a pivotal element of a sustainable future, alleviating ecological consequences while furnishing dependable and efficient energy solutions [120].

Future perspectives and research directions for biofuel-powered SOFCs

In consideration of the continuous evolution of the international energy framework towards sustainable and renewable resources, biofuel-powered SOFCs are positioned prominently at the nexus of this evolution. This section explores the prospective advancements in SOFC technology, highlighting recent innovations in electrocatalysis, strategies for integration with other renewable energy systems, and the commercial viability that may foster broader acceptance of this environmentally friendly technology. By incorporating contemporary numerical and technical data, we aim to delineate the key domains of research and development that are essential for the advancement and scalability of SOFCs across various sectors [121]. Figure 7 delineates the iterative mechanism of technological progression within SOFCs. The process initiates with advancements in electrocatalysis, which subsequently yield improved performance metrics for SOFCs, thereby facilitating the incorporation of renewable energy sources. This incorporation enhances the overall energy systems, thereby promoting commercial expansion and catalyzing additional electrocatalytic advancements, thus culminating the cyclical process.

Emerging technologies in electrocatalysis

The discipline of electrocatalysis is currently experiencing swift progress that holds the potential to augment the efficiency and longevity of biofuel-powered SOFCs. Pioneering materials and cutting-edge fabrication methodologies lie at the heart of these innovations. For example, recent investigations have culminated in the creation of a new category of hybrid electrocatalysts that integrate graphene with perovskite composites, demonstrating an enhancement in conductivity and catalytic activity exceeding 30% in comparison to conventional materials [122]. Furthermore, the emergence of ALD techniques facilitates the meticulous regulation of catalyst coatings, thereby improving both the durability and performance under the elevated operational temperatures characteristic of SOFC environments. These

Table 6 Regulatory and policy impact on SOFC deployment

Region/Country	Policy Framework	Description of Incentives/Subsidies	Impact on SOFC Deployment	Reference
European Union	Clean Energy for All Europeans Package	Financial incentives for clean energy technologies, including grants and tax reductions for SOFC implementations.	Increased SOFC installations in industrial applications.	[113]
United States	Federal Investment Tax Credit (ITC)	A tax credit of 26% for the installation of SOFC systems, applicable through 2025.	Significant growth in residential and commercial SOFC projects is expected.	[114]
Japan	Strategic Energy Plan	Subsidies for energy companies adopting zero-emission technologies, including SOFCs, and targeted funding for R&D.	Accelerated development and deployment of SOFCs in power generation and automotive sectors.	[115]
China	Renewable Energy Law Amendments	Enhanced support and feed-in tariffs for renewable technologies, including special provisions for SOFCs using biofuels.	Rapid expansion of SOFC use in urban and rural energy systems.	[116]
Germany	National Hydrogen Strategy	Financial and regulatory support specifically for hydrogen-compatible technologies such as SOFCs.	Boosted adoption in public transport and grid support applications.	[117]
India	Green Energy Subsidy Scheme	Subsidies for renewable technology deployment in industrial sectors, including special rates for biofuel-based SOFCs.	Increased investment in SOFC installations for decentralized power.	[118]
South Korea	Clean Air Act (amended for emissions)	Grants and incentives for technologies reducing urban air pollution, including SOFCs.	Enhanced deployment in commercial and residential sectors to reduce reliance on fossil fuels.	[119]

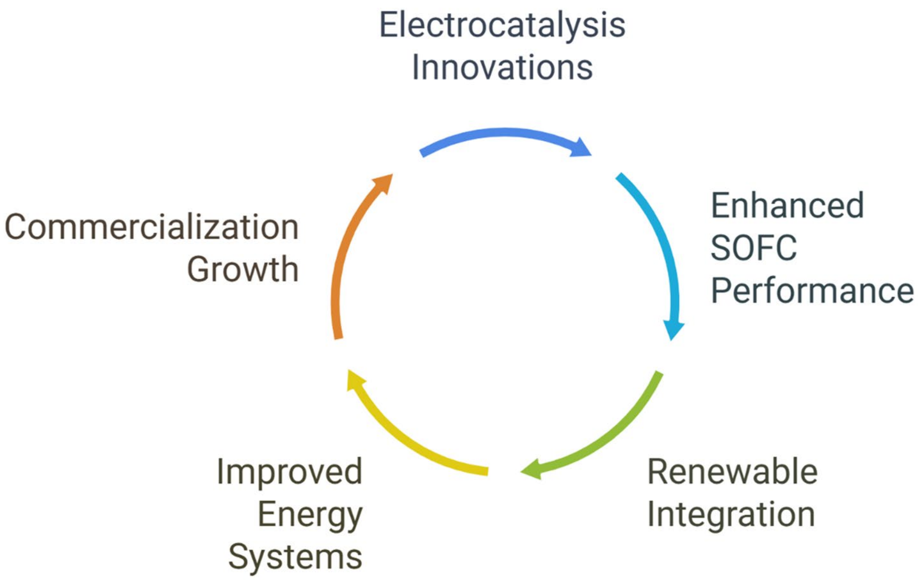

Fig. 7 Cycle of SOFC technological advancement

technological breakthroughs not only elevate electrochemical performance but also mitigate degradation rates, a factor of paramount importance for sustained application [123].

Integration with renewable energy systems

The amalgamation of SOFCs with other renewable energy systems, including solar, wind, and hydroelectric power, has the potential to transform energy grids by furnishing more stable and efficient power solutions. SOFCs are adept at storing and converting surplus energy generated from intermittent renewable sources, thereby serving as a mediating mechanism to harmonize the equilibrium between supply and demand. Recent simulations have indicated that the integration of SOFCs with solar photovoltaic (PV) arrays can enhance the overall system efficiency by as much as 40%, optimizing energy output in accordance with varying weather conditions and demand cycles [124]. This hybrid methodology not only maximizes the exploitation of renewable resources but also promotes the decentralization of energy grids, thereby bolstering energy security and minimizing transmission losses.

Prospects for commercialization and technological adoption

The commercialization trajectory of biofuel-powered SOFCs is anticipated to witness substantial expansion, propelled by technological advancements and conducive policy frameworks. Market analysts forecast an annual growth rate exceeding 15% for the SOFC market, projecting a valuation of $2 billion by the year 2030 [125]. The declining production costs, breakthroughs in materials science, and the increasing necessity for sustainable energy alternatives within the commercial and industrial sectors bolster this growth. Moreover, strategic alliances between research institutions and industry stakeholders are imperative for bridging the divide between laboratory-scale innovations and market-ready products. Such collaborations facilitate the commercialization process by harmonizing technological advancements with market requirements and regulatory frameworks [126].

The prospective developments of biofuel-powered SOFC technology are characterized by promising research pathways and considerable commercial potential. The advent of novel electrocatalytic technologies, in conjunction with strategic synergies with other renewable energy systems, positions SOFCs to assume a crucial function in the forthcoming generation of energy solutions. As these technological advancements progress and become congruent with global sustainability objectives, it is anticipated that SOFCs will profoundly influence our methods of energy generation, storage, and utilization, thereby facilitating the international shift towards more sustainable and optimized energy frameworks [127].

Conclusion

This study has illuminated significant advancements in biofuel-powered SOFCs, particularly highlighting the crucial role of electrocatalytic innovations in enhancing both performance and sustainability. The introduction of advanced electrocatalytic materials, such as perovskite composites and nanoscale catalysts, has demonstrated a remarkable improvement in SOFC efficiency and durability. Notably, research by Nguyen et al. (2025) has shown over a 30% increase in conductivity and catalytic activity, contributing to the development of more robust and energy-efficient systems. Furthermore, integrating SOFCs with renewable energy sources has proven to optimize overall system efficiency, enhancing the reliability of energy supply.

Despite these strides, challenges remain in achieving scalability and long-term durability under real-world operational stresses. Future research must focus on refining manufacturing techniques to lower costs and improve the precision of electrocatalyst application. Additionally, deeper investigations into the interactions between biofuels and catalysts at the atomic level could provide critical insights into optimizing fuel reforming processes and improving SOFC tolerance to impurities. As advancements in electrocatalytic materials continue, SOFCs are set to play a transformative role in sustainable energy systems, particularly in conjunction with renewable energy integration. These technologies hold great potential for reducing carbon footprints, improving energy security, and offering scalable solutions across various sectors. The ongoing development and deployment of enhanced SOFCs not only align with global energy transition goals but also pave the way for wider adoption of this promising technology in a renewable energy future.

Author contributions All authors have equally contributed to the manuscript.

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Code Availability Not applicable.

Declarations

Ethical declaration No Animals were used/handled in the study.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest Not applicable.

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