Bibliometric Analysis on the Joint Application of Core-Shell Catalysts and Atomic Layer Deposition in Solide Oxide Fuel Cells

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This study presents a bibliometric analysis of the scientific output between 2010 and 2025 related to solid oxide fuel cells (SOFC), atomic layer deposition (ALD), and core-shell catalysts. Based on Scopus database records processed using the Bibliometrix R tool, various combinations of these themes were evaluated to map publications, authors, institutions, collaboration networks, geographic distribution, gaps, and emerging trends. The results indicate that the association between ALD and core-shell structures already constitutes a consolidated field, with the highest volume of publications. At the same time, approaches directly involving SOFCs remain in an emerging stage. Although no studies were found that integrate ALD, core-shell catalysts, and SOFC simultaneously, the qualitative indicators observed in the individual analyses suggest a significant gap and a promising, specialized research niche. The predominance of Asian and North American countries, such as China, South Korea, and the United States, was also observed, underscoring the strategic role of these nations in leading the development of advanced energy technologies. Overall, combining these approaches may drive significant advances in the development of more efficient and sustainable energy systems.
Keywords: SOFC. Core-Shell. ALD. Sustainability. Solid Oxide Fuel Cells. Atomic Layer Deposition. Bibliometric Analysis.

This work presents a bibliometric analysis of publications related to solid oxide fuel cells (SOFC), with emphasis on the use of core-shell catalysts and atomic layer deposition (ALD) techniques. Bibliometrics is a widely employed tool to map the development of a scientific area, identifying publication patterns, emerging trends, and connections among different fields of study [1].

Fuel cells are electrochemical devices that directly convert chemical energy into electrical energy through redox reactions, representing a clean and sustainable alternative for power generation. The first functional fuel cell was demonstrated in 1839 by William Robert Grove, who used platinum electrodes in sulfuric acid with hydrogen and oxygen gases as reactants [2]. Over time, important advances boosted the development of this technology. In 1889, Ludwig Mond and Carl Langer coined the term “fuel cell” and presented a functional prototype. Later, in 1892, Nernst discovered solid oxide electrolytes, enabling the emergence of high-temperature ceramic cells. This progress culminated in 1936, when Baur and Preis created the first ceramic cell operating at 1000 °C [3].

SOFCs are electrochemical devices that convert chemical energy into electrical energy through redox reactions, utilizing solid ceramic materials as both electrolytes and electrodes. They operate at high temperatures, between 800 and 1,000 °C, which favors reaction kinetics, eliminates the need for precious metal catalysts, and allows high energy efficiency, as well as flexibility regarding the type of fuel used [4,5]. SOFCs stand out compared to other fuel cells due to their substantial construction, high operating temperature, and greater flexibility in structural configuration [6]. The basic structure of SOFCs comprises two porous electrodes, the anode and the cathode, separated by a solid electrolyte that conducts oxygen ions (O^{2-}). At the anode, the fuel undergoes oxidation, releasing electrons that travel through an external circuit to the cathode. At this electrode, oxygen reduction

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occurs, completing the electrochemical cycle and generating electricity [6]

Core-shell nanoparticles are structures consisting of a central core surrounded by one or more external layers of different composition. These configurations may range from simple shapes to more complex structures, such as multiple shells or hollow cores [7,8]. Such particles have attracted interest in various fields, including batteries [8], biomedicine [9,10], heterogeneous catalysis [11], fuel cells [12,13], and photocatalysis [14,15]. They can be classified according to their constituent materials — inorganic-inorganic, inorganic-organic, organic-inorganic, and organic-organic — depending on the intended application, which allows tuning their physicochemical properties [7]. Another classification considers the morphology of the outer layer, which may be hollow, porous, or composed of multiple layers, features that directly influence their functionalities and applications [16].

The ALD technique began in the 1970s and gained widespread popularity in the 2000s, replacing the term ALE (Atomic Layer Epitaxy), as most deposited films did not present epitaxial structure but rather amorphous forms, suitable for dielectrics and diffusion barriers [17,18]. ALD consists of sequential, self-limiting gas-phase reactions that allow thickness control at the atomic level, ensuring high uniformity and conformality even on complex surfaces, with thicknesses typically below 20 nm [19,20]. Compared to traditional methods, such as PVD (Physical Vapor Deposition) and CVD (Chemical Vapor Deposition), ALD operates at lower temperatures and ensures the formation of continuous films with precise thickness control [21]. Among its main advantages are exceptional conformality, high film quality, the ability to operate at reduced temperatures, and the capability to form multilayered structures [21–23].

ALD can be carried out through two main variants: thermal ALD (ThALD) and plasma-enhanced ALD (PEALD). In ThALD, the energy required for surface reactions is provided by substrate heating, generally above 200 °C, using water vapor as a co-reactant. In PEALD, highly reactive species are generated by plasma, using gases such as oxygen and nitrogen with purity above 99.999%, allowing film growth at near-room temperatures. This feature makes PEALD suitable for coatings on heat-sensitive substrates, such as polymers. However, the conformality of films obtained by PEALD is usually lower than that of ThALD [17–19,24,25]. Considering the relevance of this field, this study analyzes Scopus-indexed documents using the Bibliometrix R tool. The aim is to map the most impactful publications, identify research gaps, and highlight advances in the application of core-shell catalysts and ALD in SOFC.

Materials and Methods

The technological prospecting was conducted by collecting academic data from the Scopus database and using the Bibliometrix tool for analysis. The main indicators extracted from the processed data are organized in Table 1, which synthesizes the results obtained. The survey was conducted in March 2025, encompassing scientific publications from 2010 to 2025. The year 2010 was adopted as the starting point as it corresponds to the publication of the most relevant identified article, with this criterion maintained up to the year of research.

Three different keyword combinations were applied to the title, abstract, and keyword fields of the records:

- “Solid Oxide Fuel Cell” AND “Atomic Layer Deposition”,
- “Solid Oxide Fuel Cell” AND “core-shell”,
- “Atomic Layer Deposition” AND “core-shell”.

These searches yielded 118, 113, and 498 documents, respectively, all of which were subjected to bibliometric analysis.

No studies were identified addressing ALD, core-shell catalysts, and SOFC simultaneously. This absence highlights a significant gap in the scientific literature, demonstrating that the integration of these topics has not yet been consolidated. This

Table 1. Main information on the data generated by bibliometrix.

Description	"Solid Oxide Fuel Cell" AND "Atomic layer deposition"	"Solid Oxide Fuel Cell" AND "core-shell"	"Atomic layer deposition" AND "core-shell"
Time interval	2010–2025	2010–2025	2010–2025
Sources	51	51	175
Documents	118	113	498
Annual growth rate	-7.06%	-8.83%	-2.67%
Authors	309	468	2026
Single-authored documents	1	0	2
International co-authorship	33.05%	37.17%	26.51%
Co-authors per document	6.15	6.21	6.44
Author keywords – DE	235	313	1063
References	4041	5083	21721
Average document age	7.41	6.89	7.42
Average citations per document	29.67	28.42	40.22

scenario highlights the relevance and opportunity for research that combines these technologies, given the potential of their integration for developing innovative and efficient solutions for SOFC.

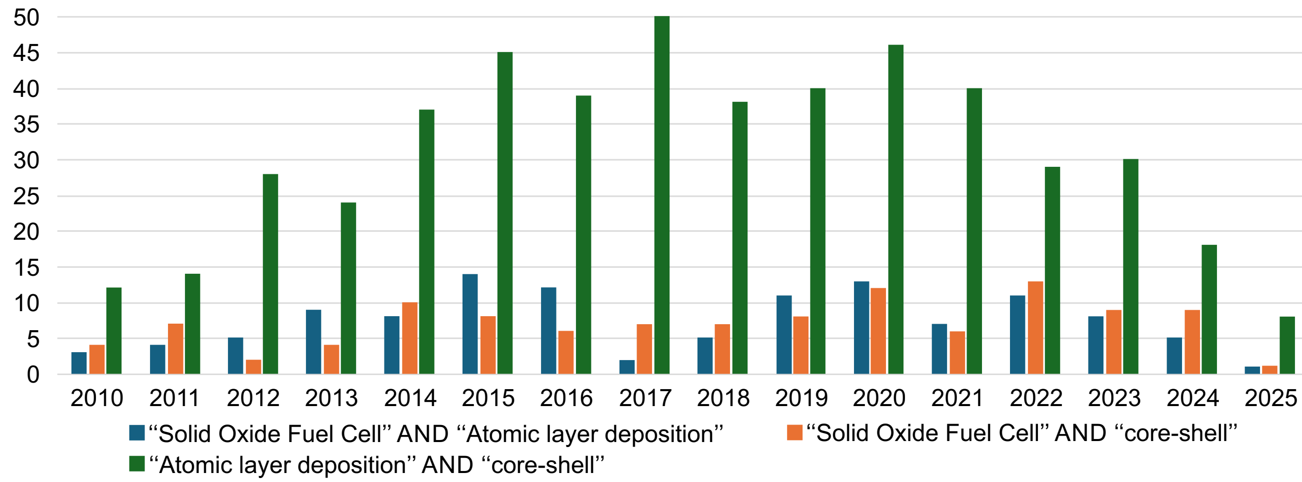
Results and Discussion

Figure 1 shows the annual evolution of scientific production between 2010 and 2025 related to the topics "Solid Oxide Fuel Cell," "core-shell," and "Atomic Layer Deposition," considering different combinations of these terms. Among the analyzed sets, it is observed that the association between "Atomic Layer Deposition" and "core-shell" presents the highest number of publications throughout the period, reaching its peak in 2017 with 50 articles. This high and relatively constant volume over the years indicates an already consolidated interest in research on core-shell structures obtained through ALD, whether by the formation of these structures during the process or by the direct deposition of materials already configured in this format. This interest is likely due to the broad applicability of these structures in various technological areas, beyond solid oxide fuel cells.

In contrast, the combinations that directly involve SOFCs show a significantly lower volume of publications. The combination of "Solid Oxide Fuel Cell" and "Atomic Layer Deposition" exhibits an irregular trend, with two notable peaks of activity recorded in 2015 and 2020, corresponding to 14 and 13 publications, respectively. From 2022 onward, however, there is a sharp decline in this number, reaching only one article published in 2025. Similarly, the combination of "Solid Oxide Fuel Cell" and "core-shell" also shows a modest evolution, with the most expressive values observed in 2020 (12) and 2022 (13).

Figure 2 highlights the countries with the highest number of scientific publications related to the different combinations of the terms "Solid Oxide Fuel Cell," "Atomic Layer Deposition," and "core-shell." The data show a significant

Figure 1. Annual evolution of the number of scientific publications between 2010 and 2025, considering the combinations between the terms "Solid Oxide Fuel Cell," "Atomic Layer Deposition," and "core-shell."



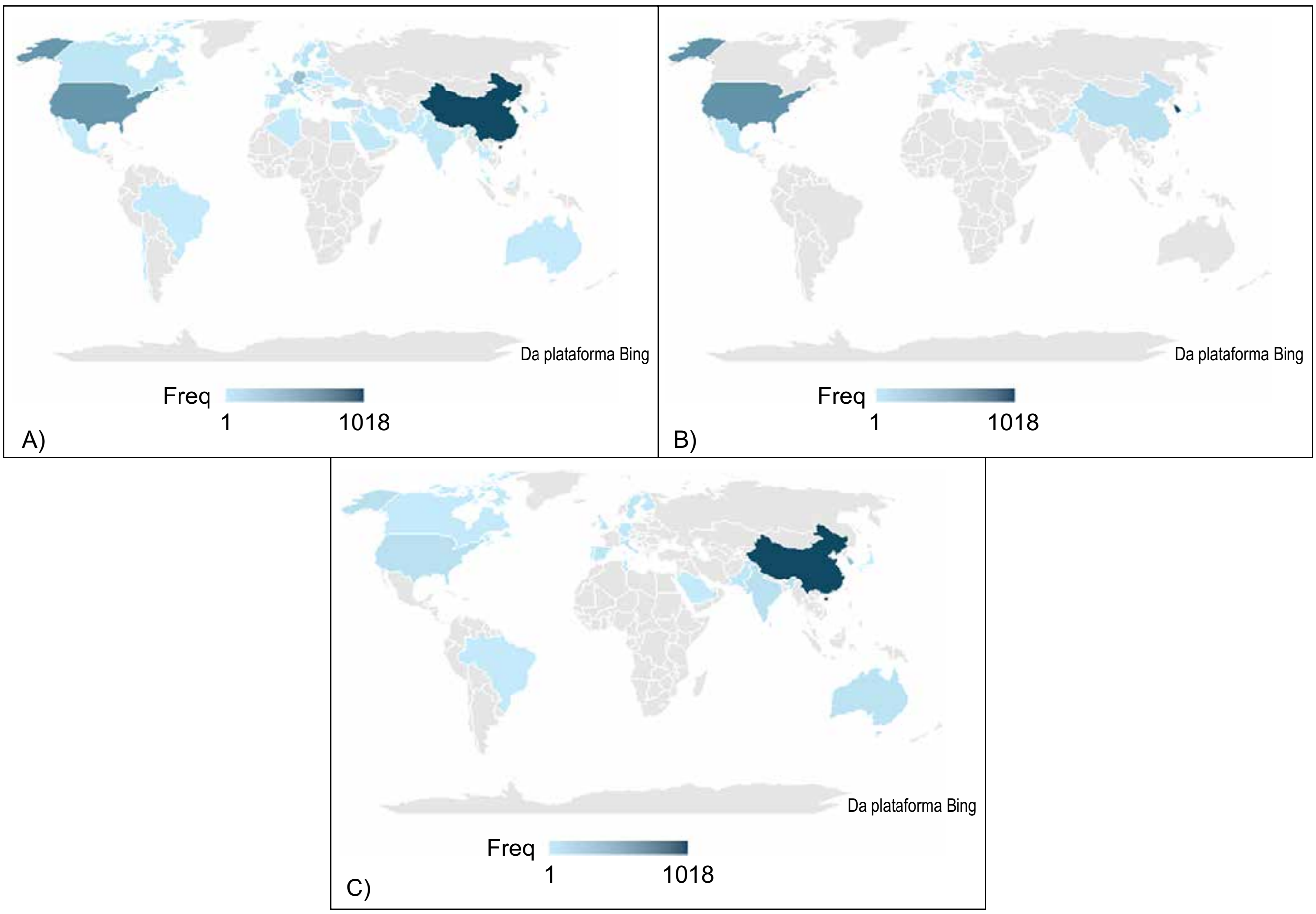
concentration of production in Asia and North America, with China, South Korea, and the United States occupying prominent positions. In the analysis of the combination between "Atomic Layer Deposition" and "core-shell" [Figure 2A], the highest absolute volumes among the four analyzed categories are noted. China leads with 1018 publications, followed by the United States (523) and South Korea (490). This distribution suggests that, regardless of the application system, there is already a consolidated interest in these countries in exploring the ALD technique for fabricating core-shell structures, as demonstrated by the quantitative expressiveness of the publications.

In the case of the combination between "Solid Oxide Fuel Cell" and "Atomic Layer Deposition" (Figure 2B), South Korea appears in the lead, accounting for 403 publications. Next are the United States, with 218, and China, with 28. These numbers indicate that studies involving the application of ALD in solid oxide fuel cells have gained greater prominence in the South Korean context, as revealed by the volume of identified works. When observing the combination of "Solid Oxide Fuel Cell" and "core-shell" (Figure 2C), China takes the lead, with 397 publications. South Korea comes in second, with 100, followed by the United States, with 28. These data point to greater activity by Chinese institutions in investigations exploring the use of core-shell structures in the context of SOFCs.

The analysis of Brazilian participation in the thematic combinations reveals that the country is present only once in the association between "Atomic Layer Deposition" and "core-shell," and in four instances in the combination between "Solid Oxide Fuel Cell" and "core-shell." On the other hand, there are no records of national publications relating to "Solid Oxide Fuel Cell" and "Atomic Layer Deposition." This scenario highlights a relevant gap in Brazil's scientific production on the topic, while also signaling a strategic opportunity for the formation of new research groups and for strengthening the national presence in this field.

The pattern observed in the three categories suggests a higher density of publications in countries with significant activity in science and technology, particularly in research areas related to advanced materials and alternative energy sources. The consistent presence of China, South Korea, and the United States in the different sets, associated with the absolute values of publications, justifies identifying these countries as the primary centers of scientific production on the addressed topics. Overall, the data identified in the four categories indicate a greater concentration of publications

Figure 2. Geographic distribution of scientific production by country, according to different combinations of research terms: A) “Atomic Layer Deposition” AND “core-shell”; B) “Solid Oxide Fuel Cell” AND “Atomic Layer Deposition”; C) “Solid Oxide Fuel Cell” AND “core-shell.”



in countries with prominent roles in science and technology, especially in areas focused on materials and alternative energy sources. The constant presence of China, South Korea, and the United States in various combinations, along with the high absolute numbers of publications, confirms the importance of these countries as the main centers of scientific production related to the topics in question. Other countries, such as Germany, France, India, Australia, and Singapore, occasionally make significant contributions in specific areas within the research field.

Table 2 presents the five institutions with the highest number of publications for each combination of the terms “Solid Oxide Fuel Cell,” “Atomic Layer Deposition,” and “core-shell,” revealing significant patterns in the institutional distribution of scientific production.

In the combination of “Solid Oxide Fuel Cell” and “Atomic Layer Deposition,” Seoul National University occupies first place, with 94 publications. Next are Seoul National University of Science and Technology, with 60 publications, and Stanford University, with 53. Completing the group are Korea University (43) and West Virginia University (38). In this group, there is a notable concentration in South Korean institutions, which account for three of the top five positions and more than half of the total articles, evidencing South Korea’s leadership in ALD applications in SOFC.

In the case of the combination of “Solid Oxide Fuel Cell” and “core-shell,” the five most

Table 2. The five central institutions with the highest number of publications.

"Solid Oxide Fuel Cell" AND "Atomic Layer Deposition"			"Solid Oxide Fuel Cell" AND "core-shell"			"Atomic Layer Deposition" AND "core-shell"		
Affiliation	**Country**	**Articles**	**Affiliation**	**Country**	**Articles**	**Affiliation**	**Country**	**Articles**
Seoul National University	South Korea	94	Hubei University	China	44	Fudan University	China	120
Seoul National University of Science and Technology	South Korea	60	Huazhong University of Science and Technology	China	28	University of North Carolina at Chapel Hill	United States	84
Stanford University	United States	53	Shenzhen University	China	23	Hanyang University	South Korea	81
Korea University	South Korea	43	Tianjin University	China	18	Inha University	South Korea	70
West Virginia University	United States	38	University of Science and Technology of China	China	18	Nanyang Technological University	Singapore	43

productive institutions are all located in China. Leadership is attributed to Hubei University, with 44 publications, followed by Huazhong University of Science and Technology (28), Shenzhen University (23), Tianjin University (18), and the University of Science and Technology of China (18). The geographic concentration of the data reveals a strong institutional focus of the Chinese scientific community on the study of core-shell structures applied to solid oxide fuel cells.

For the combination of "Atomic Layer Deposition" and "core-shell," Fudan University (China) leads with 120 publications. Next are the University of North Carolina at Chapel Hill (United States), with 84, and three Asian institutions: Hanyang University (South Korea), with 81, Inha University (South Korea), with 70, and Nanyang Technological University (Singapore), with 43. This combination presents a more balanced institutional distribution between North America and Asia, indicating a relatively more diversified scientific interest in this field.

The institutional analysis reveals a pronounced concentration of scientific production in Asian universities, particularly those in South Korea and China. Institutions in North America and Singapore are also present, reflecting the leadership of the most productive countries and the strategic role of research centers that stand out in advancing technologies such as ALD, SOFC, and core-shell structures. "Solid Oxide Fuel Cell" AND "Atomic Layer Deposition""Solid Oxide Fuel Cell" AND "core-shell""Atomic Layer Deposition" AND "core-shell"

Table 3 brings together the five most productive authors in each of the analyzed term combinations. The data reveal significant variations in individual productivity, depending on the thematic focus, highlighting the prominence of certain researchers in specific areas.

In the combination "Solid Oxide Fuel Cell" with "Atomic Layer Deposition," author AN J leads with 29 publications, followed by CHA SW (23), JI S (17), LEE S (17), and PRINZ FB (17). These results indicate production concentrated in a small number of authors, with a clear highlight for AN J, whose contribution significantly surpasses that of the others.

In the combination of "Solid Oxide Fuel Cell" and "core-shell," a different scenario is observed.

Table 3. Distribution of the five primary authors.

"Solid Oxide Fuel Cell" AND "Atomic Layer Deposition"		"Solid Oxide Fuel Cell" AND "core-shell"		"Atomic Layer Deposition" AND "core-shell"	
Author	**Articles**	**Author**	**Articles**	**Author**	**Articles**
AN J	29	LI J	10	LU H-L	18
CHA SW	23	ZHU B	9	LEE C	15
JI S	17	CHI B	6	WANG X	15
LEE S	17	JIA L	6	KIM H	14
PRINZ FB	17	LIU W	6	KIM SS	12

LI J appears at the top with 10 publications, followed by ZHU B (9), CHI B (6), JIA L (6), and LIU W (6). In this case, the values are lower and relatively balanced among the authors, which suggests a more dispersed distribution of scientific production and a possibly less consolidated stage of the topic.

When considering the combination between "Atomic Layer Deposition" and "core-shell," LU H-L leads with 16 publications, followed by LEE C (15), WANG X (15), KIM H (14), and KIM SS (12). The data show a distribution concentrated among authors with similar productivity, indicating the active involvement of several research groups in this thematic area.

Overall, the data reveal variations in productivity among authors depending on the thematic combination analyzed. In some approaches, there is a greater balance among researchers, while in others, specific authors stand out. This scenario may reflect different levels of maturity and specialization within the research field.

Challenges and Opportunities

No publications were found addressing the simultaneous use of core-shell catalysts, and ALD applied to SOFC. However, relevant studies addressing these themes separately were identified. The combinations among "Solid Oxide Fuel Cell" and "Atomic Layer Deposition," "Solid Oxide Fuel Cell" and "core-shell," and "Atomic Layer Deposition" and "core-shell" provide important insights for identifying challenges and opportunities regarding their possible integration.

Literature indicates that both core-shell structures and ALD are widely applied in other technological contexts. However, their joint application in SOFC still presents significant gaps. From the data analysis, several challenges stand out: the limited number of studies addressing the convergence of the three themes, the operational instability of certain structures, restricted access to specific ALD equipment, and difficulties in thermal compatibility among materials used.

On the other hand, the results also indicate promising opportunities, such as the potential for increasing catalytic activity in anodes and cathodes, mitigating structural degradation, enabling operation at intermediate temperatures, and compatibility with alternative fuels, as well as the ability of ALD to form ultrathin, selective, and uniform layers.

Additionally, core-shell structures may contribute to improving the thermal and chemical stability of materials. The presence of international co-authorship in the publications further suggests a favorable environment for global collaborations.

Thus, despite the absence of studies integrating these three elements, the technical and bibliometric indicators analyzed point to a promising research field. Recognizing current limitations, along with identified opportunities, suggests that this line of investigation has the potential to generate significant contributions to the development of more efficient energy technologies, especially in the context of transitioning to sustainable sources.

Conclusion

The bibliometric analysis carried out in this study, based on data from the Scopus database and processed with Bibliometrix R, enabled a detailed mapping of the scientific output between 2010 and 2025, focusing on the combinations among the terms "Solid Oxide Fuel Cell," "Atomic Layer Deposition," and "core-shell." The results indicate that while the association between ALD and core-shell structures shows the highest volume of publications and a more regular evolution over time, combinations directly involving SOFC still represent less developed niches, reflected in a lower frequency of studies during the analyzed period.

The combination of "Atomic Layer Deposition" and "core-shell" stood out for both the highest absolute number of publications and the temporal stability observed, indicating a consolidated field with applications spanning several knowledge areas. In contrast, approaches directly involving SOFC showed lower quantitative expressiveness, with more pronounced variations in publication numbers and no clear growth pattern.

No publications were found that simultaneously integrate core-shell catalysts and ALD in SOFC. However, analyses based on isolated studies of these approaches allowed identifying technical and operational challenges, as well as revealing promising opportunities for developing advanced solutions in the SOFC context. These results indicate that integrating these technologies represents both a significant gap and an opportunity for progress in the field.

Geographically, scientific research is concentrated in Asian and North American countries, notably China, South Korea, and the United States. These same countries gather the most productive institutions, reinforcing their central role in investigations related to ALD, SOFC, and core-shell structures. The analysis of authors and institutions shows a thematic distribution consistent with the different focuses of the term combinations, highlighting specific leaderships according to each research line.

Although no studies integrating ALD, core-shell catalysts, and SOFC simultaneously were found, the results indicate the presence of active collaborative networks, high-quality publications, and promising indicators in the individual analyses of these combinations. In this scenario, the gradual approximation of these approaches may pave the way for an innovative and strategic research line, with the potential to make significant contributions to improving SOFC. The integration of these topics presents a significant opportunity for the development of more efficient and durable energy technologies that align with the demands of the global energy transition.

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