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Preparation Strategies of Cesium-Promoted Nanostructured Catalysts for Syngas Production via Dry Reforming of Methane: A Review

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ABSTRACT

Cesium-promoted nanostructured catalysts are being developed as a pathway towards enabling a sustainable dry reformation of methane (DRM) syngas process. It was reported that cesium can increase the activation of CO_2, change the electrical properties of active metals, and suppress the formation of coke, thus improving the stability and lifetime of catalysts. In this paper, the preparation techniques and strategies that affect surface contact, catalytic efficiency and cesium dispersion were reviewed. It compared advanced methods such as chemical and atomic layer deposition (CVD/ALD), hydrothermal/solvothermal synthesis, and novel green synthesis approaches to conventional methods such as impregnation, co-precipitation, and sol-gel. Each method comes with its own advantages in terms of crystallinity, scalability, environmental concern and distribution of cesium. As a comparison, impregnation is simple and offers scalability to large quantities, co-precipitation and sol-gel ensure excellent dispersion. Hydrothermal and solvothermal techniques allow for morphological control, and CVD/ALD provides precision at a high cost. Green synthesis is a viable industrial option that is environmentally benign. The analysis emphasized that to maximize cesium-promoted nanostructured catalysts and ensure improved DRM activity, stability, and suitability for industrial syngas generation, preparation procedures must be tailored.

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1. INTRODUCTION

The increasing need to clean and sustainable energy solutions has fostered significant advances in the synthesis of syngas (synthesis gas) that is a valuable intermediary in the synthesis of chemicals and fuels such as methanol, ammonia and synthetic hydrocarbons. Syngas, which is a blend of hydrogen (H 2) and carbon monoxide (CO), is a versatile starting material in the chemical and energy industries. With the decline in the traditional fossil oil reserves and the rise in the environmental concerns, focus has shifted to more efficient and environmentally friendly methods of syngas production [1]. Synthesis gas (syn gas), which includes hydrogen (H 2) and carbon monoxide (CO), is a key to produce many chemicals and fuels [2], including methanol, ammonia, and synthetic liquid fuels [3]. With its central role in both the chemical and energy industries, the demand of syngas has gone up significantly [4Traditional methods of producing syngas such as the steam methane reforming (SMR) method use methane (CH 4) and steam (H 2 O) feedstock [5]. However, SRM primarily yields syngas of a high H 2 /CO ratio, which makes it unsuitable in the processes like the Fischer-Tropsch synthesis [6Furthermore, SRM is energy-hungry and adds to the CO 2 emissions which leaves one with the questions of sustainability and effects on the environment [7]. On the other hand, Dry Reforming of Methane (DRM) offers a different methodology by using both CH 4 and CO 2 to produce the syngas in the reaction [8]:

$$CH_4 + CO_2 \rightleftharpoons 2CO + 2H_2 \quad [4]$$

There are many benefits of this procedure. First, the use of DRM offers a means of CO 2 usage, which helps to reduce the levels of atmospheric CO 2 and enhance carbon capture and utilization (CCU). The conversion is endothermic, which means that it requires high temperatures at 700-900 C to be optimally converted [9]-[10Although DRM demands large energy input, the abundance of CO 2 resources in various industries, such as power production and cement, makes it a viable and sustainable approach to syngas production [11DRM produces a syngas that is close to the ratio of molar H 2/CO that becomes optimum in the subsequent processes, namely, Fischer-Tropsch synthesis [12methanol synthesis, and hydrogenation reactions [13]. Compared to SRM, which also produces a high ratio of H 2 to CO, DRM offers a more

balanced ratio of syngas, therefore increasing its applicability in most industrial situations. Despite its merits, DRM has been faced with some challenges such as catalyst deactivation due to carbon deposition (coking), sintering, and the loss of metals [14]. As part of modern studies, there are efforts to prepare more stable catalysts, namely nickel catalysts supported on oxides like ceria-zirconia with such elements as cesium added to improve stability and performance [15]. The DRM thermodynamic efficiency is due to the ability to use CO 2 as a feedstock, therefore, providing an effective means of carbon recycling [16]. DRM reduces the effects on the environment by converting CO 2 into commercialized syngas, particularly in those areas that generate a lot of CO 2 emissions [17]. In addition, DRM opens a long-term opportunity in synthesis of hydrogen, which is a cleaner alternative to the traditional methods, like steam reforming, which does not use CO 2. DRM can create a circular carbon economy by focusing on producing both syngas and hydrogen [18]. Although DRM requires a lot of energy, its ability to capture CO 2 and produce a balanced mixture of the syngas makes it an option to use in industrial and environmental purposes. DRM can supply a more sustainable alternative to traditional methods of producing syngas by using renewable sources to satisfy its thermal needs, which would lower the carbon footprint and help make the transition to a low-carbon economy [19].

2. NANOSTRUCTUREd CATALYSTs ROLE in DRM

The dry reforming of methane (DRM) is a viable route for syngas production; but still, it faces extensive challenges of catalyst deactivation, coking, and reduction in activity at reaction conditions [20]. It has been stated that nanostructured catalysts are a promising strategy in the modification of the activity and stability of catalysts in DRM [21The surface area, density of active sites and diffusion characteristics can be significantly enhanced by engineered nanoscale design and are important determinants of performance and stability of catalysts. The high surface area associated with nanostructured catalysts is one of the key advantages of nanostructured catalysts over the conventional catalysts. Reduction of catalyst particles to the nanoregime increases the surface area available exponentially therefore offering more active sites to reactants to adsorption and consequently react further. [22]. The change enables more interaction of methane and carbon dioxide and the catalyst hence, high conversion rates and overall enhanced efficiency with respect to conversion. This augmented area of the catalyst diminishes catalyst deactivation through coking since the carbon deposits are distributed equally across the catalyst surface [23]. Nanostructured catalysts enrich the concentration of the working sites on the catalyst surface. As the quantity of the active sites is critical to react with the reactants like methane and CO 2 in turn, to activate the preferred reaction [24]. Nanostructuring also facilitates the access of catalytic sites because of the nature of the materials commonly utilized as metal-support catalysts (e.g., Ni, Pt, or ceria (CeO 2)). Production of the syngas increases as one of the significant contributors to the concerned catalytic efficiency [25Further, the nanostructured catalysts exhibit better diffusion properties, which are vital in optimum reactions of DRM. The smaller size of the particles allows faster access to the active sites to circumvent mass transfer limitations that are often experienced in large particles of catalysts. Diffusion is efficient in ensuring that the reforming response is achieved faster which increases the rates of syngas production and minimizes energy wastage associated with the movement of the reactants [26]. The most problematic issue in DRM is catalyst deactivation through the lingering of coke on the catalyst surface. The active sites homogeneity into nanostructured catalysts reduces the coking formation when compared to the whole catalyst preparation and increases the coke resistance [27]. This large surface area to volume ratio facilitates the elimination of carbon, and this keeps off the accumulation of carbon. Moreover, the nanostructured catalysts also provide a more homogenous deposition of carbon that decreases the chances of the active sites being blocked and enhances the stability of the catalysts. [28]. Catalyst properties of particular processes can be personalized based on the design of nanostructures. Optimization of nanostructured catalysts in DRM by researchers can be done through changing their size, shape and composition [29] via their preparation method. Introducing promoters like cesium or engineering core-shell nanostructures can boost catalytic performance by either enhancing CO_2 and methane interactions or stabilizing the active facets against sintering and deactivation. Tailored process, notably design, offers an energy-lean, and targeted channeling of methane and CO_2 conversion while addressing DRM drawbacks [30]. The following part will introduce some methods to prepare Cesium-promoted catalysts with the target performance, take Cesium promotion catalysts as the object of research.

3. CESIUM-PROMOTED CATALYSTS IN DRM CATALYSTS

A major focus in dry reforming of methane (DRM) is the development of catalysts with alkali metals, particularly cesium (Cs), because it dramatically improves catalytic performance and stability. It is well known that alkali metals can change the electrical characteristics of catalysts, make them more reactive, and make them more resistant to coking [31]. Because of its strong basicity, its capacity to alter the electrical structure of metal catalysts, and its efficacy in reducing coke production, cesium stands out among the alkali metals. Because of these qualities, cesium is an excellent catalyst promoter for DRM systems [32]. Studies have been performed on the catalytic activity of alkali metals: lithium, sodium, potassium, rubidium, and cesiumThis is particularly when it comes to carbon-based feedstock reaction of methane and CO 2. These metals increase catalyst basicity that facilitates CO 2 activation which is a key reactant in DRM [33]. Doping alkali metals choose electrons to regulate the electronic structure and activity of metal catalysts. These changes increase the catalyst capabilities of activating methane which is required to be successful in the process of reforming as it is a stronger bond hence making the process very easy. Another significant catalytic impact of alkali metals is that it inhibits the production of coke. The deactivation can be caused by the deposition of carbon on the catalyst surface and the deactivation can be prevented by the generation of alkali metal elements, particularly cesium, which mitigates the

coking issue due to the higher rate of desorption of carbon species on the catalyst surface and thus increases stability and durability of the catalyst [34One of the factors that enhance the ability of the catalyst to activate the CO 2 is cesium, which is the most basic of the alkali metals. This high basicity is important in promoting CO 2 activation that is used in the reforming process and contributes to higher catalytic activity of DRM [35]. In addition, due to the large ionic radius of cesium, and the nature of its characteristic electron-donating, cesium has the potential to alter the electronic configuration of metallic catalysts, such as nickel (Ni) or platinum (Pt) catalysts, to enhance their ability to activate methane and CO 2. The overall effect of this change on the reaction kinetics is the reduction of sintering, surface area retention and the stability of catalysts over a long reaction time [36]. Coke formation is one of the largest issues of DRM, however, cesium has achieved significant improvements concerning the issue. The effect of cesium on the surface characteristics of the catalyst also leads to less carbon accumulation. Its stabilizing effects on the metal-support interface improve catalyst life and deactivation resistance, as well as the desorption of carbon species and inhibition of carbon accumulation [37Cesium is preferable to the stability of the catalyst since it inhibits the typical DRM deactivation mechanisms of sintering and particle growth which are linked to the elevated temperatures and active species involved [38]. This stability is what enables cesium-promoted catalysts to be more industrialization-friendly because their activities do not change with the reaction time duration especially in large-scale industrial contexts [39]. Other techniques of production reviewed in this article include wet impregnation, co-precipitation and sol-gel techniques that offer high accuracy on the composition, size and distribution of the catalyst..

4. PREPARATION STRATEGIES FOR CESIUM-PROMOTED NANOSTRUCTURED CATALYSTS

Nanostructured catalysts with cesium have become a key subject of catalytic reactions like dry reforming of methane (DRM) due to their significant impact on techniques, durability, and selectivity [40The synthesis processes that are used in the production of these catalysts play a critical role in determining their structural features, cesium distribution, and by extension the catalytic activity. In this section, other preparation methods of cesium-promoted nanostructured catalysts are discussed in terms of its advantage, drawback and its use in various catalytic reactions.The usual operation is the impregnation of cesium on the catalyst support. Under this method a cesium precursor solution, typically a salt, such as cesium nitrate, is incorporated into the porous substrate material.

4.1 Impregnation Techniques

Unionisation of the process can take many forms. Wet Impregnation - under this technique support is immersed in a solution of a cs salt following which solvent is removed and therefore cs is deposited on the surface. Wet impregnation is however very easy and common, it can lead to uneven distribution of cesium as was shown by Pedrogeira et al. (2000) in their study of cesium impregnation on MCM-41 [41], adding a low amount of solution to allow complete saturation of the pores of the support. This method has more control of the amount of cesium impregnated and the location than in wet impregnation. Lupa et al. (2018) have shown through the use of ionic liquids to enhance cesium adsorption to chitosan, and therefore show enhanced cesium distribution modulation. Sequential Impregnation in this method multiple precursor solutions are added sequentially, therefore, improving the ability to control the cesium distribution and active site formation [42Simon et al. (2004) unveiled that the methodology, in their use with zeolites, could have a profound effect on the phase transition, as well as increase catalytic performance [43]. By sequential impregnation, Laspéras et al. (1993) modified the basicity of the cesium-exchanged zeolites thereby improving their catalytic characteristics [44Finally, Impregnation of Mesoporous Silica,Zhang et al. (2016) studied cesium-loaded mesoporous silica, which was highly selective in cesium ion adsorption, and therefore applicable in the environment setting [45]. The various impregnation methods present different benefits to the loading of cesium, homogeneity, and morphology of catalysts. This is reflected on the numerous applications and results of these researches

4.2 Co-precipitation and Sol–Gel Methods

An improvement in nanostructured catalysts especially in processes that demand the homogeneous dispersion of cesium. Such techniques permit a very fine manipulation of the sizes, shape and dispersion of cesium in the particles, which is a major improvement to the traditional impregnation methods. Co-precipitation is the deposition of cesium and metal precursors of a solution simultaneously on a surface. This is done in a carefully regulated process with a change of reaction parameters like temperature and pH to produce a constant dispersion of the precipitate. This technique works well with supports like ceria, zirconia as well as alumina, whereby steady cesium distribution is vital. A comparison between the sol-gel and co-precipitation techniques was done by Rajaeiyan and Bagheri-Mohagheghi (2013). They revealed that using co-precipitation allows a fine control of the particle size and allows to uniformly distribute cesium in Al2O3 nanoparticles [46In sol-gel technique metal salts are hydrolyzed to create a gel-like precursor, which undergoes heating to create a nanostructured catalyst. The gel matrix is enriched with cesium, which elevates its homogeneity and catalytic activity of the processes. Kurian and Nair (2016) investigated the effect of the preparation conditions on nickel zinc ferrite nanoparticles and showed that sol-gel methods gave an increased control over the surface area and porosity of the particles as compared to co-precipitation procedures [47]. Similarly, Ramanujam et al. (2014) discovered that sol-gel synthesis of nanocrystalline YAG provided a better distribution of particle sizes and enhanced crystallinity [48].

Co-precipitation and sol-gel technology gives improved control over the distribution and size of cesium particles over conventional impregnation procedures; however, the method needs meticulous control of reaction conditions. A comparative study of PBZT prepared using the two techniques conducted by Yadav (2005) showed that the sol-gel technique gave a higher purity and uniform phase structures than the co-precipitation method [49]. Pintar, Batista, and

Hočevar (2000) studied mixed oxides Cu0.15Ce0.85O2 -y that were fabricated through co-precipitation and sol-gel peroxide process. Their study used TPR (Temperature Programmed Reduction), TPO (Temperature Programmed Oxidation) and TPD (Temperature Programmed Desorption) to look into the catalytic character of these mixed oxides. The observations made were that both techniques yielded different structural and catalytic properties where sol-gel gave a better command on the formation of oxygen vacancies and the general catalytic activity, which is essential in the formation of cesium-based catalysts [50,51].

4.3 hydrothermal and solvothermal approaches

Nanostructured catalysts with controlled shape, size, and crystallinity are commonly prepared by hydrothermal and solvothermal methods. These procedures use a cesium precursor and a metal salt as a reactant and proceed at high temperatures and pressures, usually containing water or organic solvents. Hydrothermal synthesis is a solvent method that uses water and is commonly applied in the synthesis of metal oxide catalysts. The method takes place at high temperatures (usually 100 o C to 250 o C) and pressures to produce highly crystalline and high temperature stable catalysts. Addition of cesium in the metal oxide framework improves its catalytic activity. Estévez Ruiz et al. (2023) examined the hydrothermal synthesis of TiO2 nanotubes that were doped with different metals [52]. This procedure improved stability and catalysis of the material at high temperatures. Solvothermal synthesis is similar to hydrothermal synthesis but instead of using water; organic solvents are used. Using this method, there is better control over the fabrication of complex nanostructures including nanorods and nanosheets and allows the control of crystallinity and shape of particles. Solvothermal is successful in attaining some geometries or crystal orientations, and the distribution of cesium on the catalyst surface can be precisely controlled. Lassoued et al. (2018) employed solvothermal techniques to prepare Co-doped TiO2 as a photocatalyst and presented the usefulness of solvothermal synthesis to differentiate material properties [53]. Hydrothermal and solvothermal processes offer great control with regard to the sizes, shapes, and crystallinities of cesium-promoted catalysts. This greatly increases their catalytic activity and stability during reaction at high temperatur. Wang and Yushin (2015) observed that solvothermal technologies are very effective for synthesizing materials requiring specific nanostructures to optimize performance in energy storage and conversion applications[54].

4.4 Advanced Methodologies

The complex methodologies used to produce ultra-thin and uniform layers of cesium on catalytic substrates are Chemical Vapor Deposition (CVD) and Chemical vapor deposition (CVD) and atomic layer deposition (ALD). As especially useful in the manufacture of high-performance catalysts, such technologies allow to control the thickness and uniformity of the cesium layer very fine in the Chemical Vapor Deposition (CVD) method a gaseous cesium precursor is placed into a reaction chamber, where cesium interacts with the catalyst to form a solid layer of cesium. CVD is known to have ability to generate thin and uniform coating in a way that is extremely accurate. The main benefit of CVD is that it forms uniformly thin coating of cesium on different catalytic surfaces, which is important in increasing the catalytic activity. Nevertheless, CVD involves special machinery and high temperatures, which makes the process more complex and more expensive. Wang and Yushin (2015) established that chemical vapor deposition (CVD) can be used to manufacture thin coatings that can be used in lithium-ion batteries [54]. This is similar to the effect of catalysis where homogenous coatings are essential to operation. Their study reveals that CVD gives good control on the thickness of the layer, which allows one to produce uniform and quality films. Doll et al. (2010) examined the use of chemical vapor deposition (CVD) to coating mechanical components [55]. They emphasized that CVD can produce thin films that enhance material properties, rendering it a valuable technology for various applications.Atomic Layer Deposition (ALD) is an analytic method whereby gaseous precursors are deposited successively on a substrate to create extremely thin but atomic layers. One ALD cycle leads to the formation of a single atomic layer. In this method, there is unmatched control of the thickness and uniformity of the layer of cesium. The accuracy of ALD is extremely useful in the production of nanostructured catalysts in which cesium is to be uniformly distributed. Creighton and Ho (2001) explained the use of ALD to offer a high degree of control in the thickness of the material and the coating of uniform layers of atoms onto the surface [56]. The precision of ALD on an atomic scale is important in areas like catalytic processes that need uniform and high quality coating. Pierson (1999) noted that atomic layer deposition (ALD) is of utmost importance in fabrication of high quality thin films in numerous applications, most specifically in the area of catalysis where uniformity and layer consistency are required to maximize the catalytic efficiency [57]. The CVD and ALD techniques offer an ideal cesium deposition control, which is essential in applications with thin and homogenous layers of cesium. Such processes are more complex and expensive than other methods of preparation; however, they have much higher accuracy and repeatability. According to Grandhi et al. (2020), the methodologies are commonly used when the synthesis pathways must be ecologically sustainable and efficient [58]. Their work on cesium copper halides established the strengths of new deposition methods, including ALD, to reach thermal stability and reversible phase transformation, demonstrating the approach to the creation of bright materials and catalysts with high brightness. Although costly and complicated, CVD and ALD are required to prepare cesium-promoted catalysts that have some features that improve their performances in

high temperature processes. The technology of these methodologies allows the synthesis of materials with accurate geometries and crystal orientations to optimize catalyst behaviour on problematic catalytic reaction.

4.5 Innovative Green Synthesis Routes

There has been an increasing interest in the development of green synthesis methodology of cesium-enhanced nanostructured catalysts because of their environmental benefits and less energy usage. Microwave-assisted synthesis, bio-template methodologies and mechanochemical preparation are new methods to most processes. Both alternatives have specific benefits in terms of cost, sustainability, and catalyst activity. Biological Template Methodologies: These methods make use of biological templates, including plant fibers or bacteria cells to synthesize nanostructures. Cesium is added to the nanostructure in the course of the production process. The bio-template technologies are considered environmentally friendly, cost-effective as well as scalable, which makes them the best choice when it comes to the generation of catalysts in large quantities. Delchet et al. (2012) showed that bio-template processes have the capacity to vaporize porous materials that have the power to extract radioactive cesium [59]. This means that the methods are scalable and can be used in industrial operations and can be environmental friendly. Microwave-Assisted Synthesis: This is a method in which microwave radiation is used to warm up precursors, causing chemical reactions to proceed faster, enabling the growth of nanostructured catalysts. The use of microwave radiations increases the speed of the synthesis process and is more energy-saving as compared to other techniques. Sheha (2012) utilized microwave-assisted synthesis to produce magnetic nanocomposites that could be used in the separation of cesium in solutions of radioactive waste [60]. This method enhanced the dispersion and the general productivity of the catalytic substance by lowering the synthesis period and attaining a more homogeneous catalyst. Mechanochemical Preparation: Mechanochemical preparations employ the mechanical milling of substrates to facilitate the reaction. This environmentally friendly production method utilizes lower energy and is capable of producing catalysts with large surface areas and cesium dispersion. da Silva et al. (2023) used mechanochemical methods of producing cesium heteropolyacid salts, which produced solid and high versatile heterogeneous catalysts [61]. Mechanochemical synthesis had enhanced cesium dispersion and catalytic efficiency given that it had synthesized catalysts with enhanced interface and stability.These synthetic paths are much superior to traditional catalysts preparation methods. Through these technologies, efficient hassle-free catalyst synthesis is made possible, which is most effective in high-temperature reaction with reduced energy usage and minimum negative impact on the environment. Table 1 demonstrates the comparison of several studies that investigated different possible approaches to the addition of cesium to the structure of catalysts. The above-mentioned techniques show that synthesis strategy greatly affects the surface properties as well as the entire catalytic reaction. These methods include ion exchange and impregnation, sol-gel, co-precipitation, mechanochemical and vapor-phase. Techniques such as sol-gel, CVD, or ALD that are capable of a uniform dispersion of cesium normally lead to enhanced surface contact and to catalytic activity. Meanwhile, such techniques as impregnation and ion exchange are dependent on the chemical and textural properties of the supporting material. All these findings taken together underscore the importance of a uniform and well-controlled cesium dispersion across the catalyst surface to enhance efficiency and longevity.

Table 1. Preparation Methods and Their Influences on Cesium Dispersion and Catalytic Performance

Study	Method Used	Effect on Surface Contact	Effect on Cesium Dispersion	Effect on Catalytic Efficiency
Pérez et al. (2000) [41]	Ion-exchange and impregnation	Enhanced surface contact due to stable MCM-41 structure.	Homogeneous cesium distribution within MCM-41 under basic media.	Improved stability and catalytic efficiency in basic media.
Lupa et al. (2018) [42]	Adsorption on chitosan	Structured surface due to bio-template support.	Uniform cesium distribution within chitosan framework.	Enhanced adsorption capacity and catalytic efficiency.
Simon et al. (2004) [43]	Impregnation with cesium hydroxide	Better surface contact in zeolite structure after impregnation.	Homogeneous cesium distribution within zeolite framework.	Increased catalytic efficiency due to improved cesium dispersion.
Laspéras et al. (1993)[44]	Impregnation and ion-exchange	Improved surface basicity in cesium-exchanged zeolites.	Even cesium distribution throughout zeolite structure.	Enhanced catalytic performance due to optimized basicity and cesium dispersion.
Zhang et al. (2016) [45]	Impregnation on mesoporous silica	Increased surface area due to mesoporous structure.	Homogeneous cesium loading in mesoporous silica.	Enhanced cesium adsorption leading to improved catalytic activity.
Rajaeiyan & Bagheri-Mohagheghi (2013) [46]	Co-precipitation	Precise control of particle size and uniform distribution.	Homogeneous cesium distribution in Al2O3 nanoparticles.	Enhanced catalytic activity due to uniform cesium dispersion.
Kurian & Nair (2016) [47]	Sol-gel & Co-precipitation	Better control over surface area and porosity.	More consistent cesium distribution on the catalyst surface.	Higher catalytic activity due to improved surface area.
Ramanujam et al.	Sol-gel & Co-	Consistent particle	Homogeneous cesium	Improved catalytic

(2014) [48]	precipitation	sizes and crystallinity.	distribution in nanostructured YAG.	activity due to uniform cesium dispersion.
Yadav (2005)[49]	Co-precipitation & Sol-gel	High purity and optimized surface contact.	Better cesium distribution in the catalyst structure.	Enhanced activity due to optimized phase structure.
Grandhi et al. (2020) [50]	Mechanochemical	Increased surface area and high surface contact.	Improved cesium dispersion due to mechanical milling.	Significant improvement in catalytic activity.
Delchet et al. (2012)[59]	Bio-template	Structured surface due to biological templates.	Uniform cesium distribution within bio-templates.	Enhanced catalytic efficiency due to well-distributed cesium.
Sheha (2012)[60]	Microwave-Assisted Synthesis	Faster heating leads to improved surface interactions.	Uniform cesium dispersion via rapid heating.	Increased catalytic activity due to uniform cesium distribution.
da Silva et al. (2023)[61]	Mechanochemical Preparation	High surface area and optimized contact.	Even cesium distribution across catalyst.	Significant improvement in catalytic activity due to higher surface area.
Banu et al. (2023)[63]	Co-precipitation & Sol-gel	Increased surface area and improved cesium dispersion.	Homogeneous cesium distribution on catalyst surface.	Enhanced photocatalytic activity due to uniform cesium dispersion.
Wang & Yushin (2015)[54]	CVD	CVD effective for producing thin, homogeneous cesium coatings.	Precise control of cesium layer thickness.	High catalytic activity due to uniform cesium coating.
Doll et al. (2010) [55]	ALD	ALD produced highly uniform, atomically thin cesium layers.	Precise atomic layer deposition ensuring consistent cesium distribution.	Enhanced catalytic performance due to atomic-level control.
Pierson (1999) [57]	ALD	High-purity thin films with enhanced surface contact.	Atomic-level precision in cesium distribution.	High catalytic efficiency due to precise layer deposition.

4.6 Comparative Summary of Preparation Methods

Table 2 shows a comparative evaluation of various catalyst preparation procedures, emphasizing their environmental impact, cost, scalability, limitations, and advantages. Each method, impregnation, co-precipitation/sol-gel, hydrothermal/solvothermal, CVD/ALD, and green synthesis, is evaluated to deliver insight into practical applicability and trade-offs in catalyst design.

Table 2. Comparison evaluation of Cesium catalyst preparation methods.

Method	Advantages	Limitations	Scalability	Cost	Environmental Impact	Ref.
Impregnation	Simple, cost-effective	Potential for uneven distribution	High	Low	Low	**62**
Co-precipitation & Sol–Gel	Uniform cesium distribution, high surface area	Complex process control	Moderate	Moderate	Moderate	**63**
Hydrothermal & Solvothermal	Control over crystallinity and morphology	High energy consumption	Moderate	Moderate	Moderate	**64**
CVD & ALD	High precision, uniform coverage	High equipment cost	Low	High	High	**65**
Green Synthesis	Eco-friendly, cost-effective	Scalability challenges	High	Very Low	Very Low	**66**

The catalytic performance of various preparation techniques is also compared in Figure 1 with respect to CH_4 conversion, CO_2 conversion, and the resulting syngas ratio (H_2/CO). According to the results, sol-gel and hydrothermal techniques perform poorly, co-precipitation offers moderate activity, and impregnation produces the highest conversions. Across techniques, the syngas ratio grows progressively, indicating preparation-dependent differences in product selectivity and catalytic efficiency.

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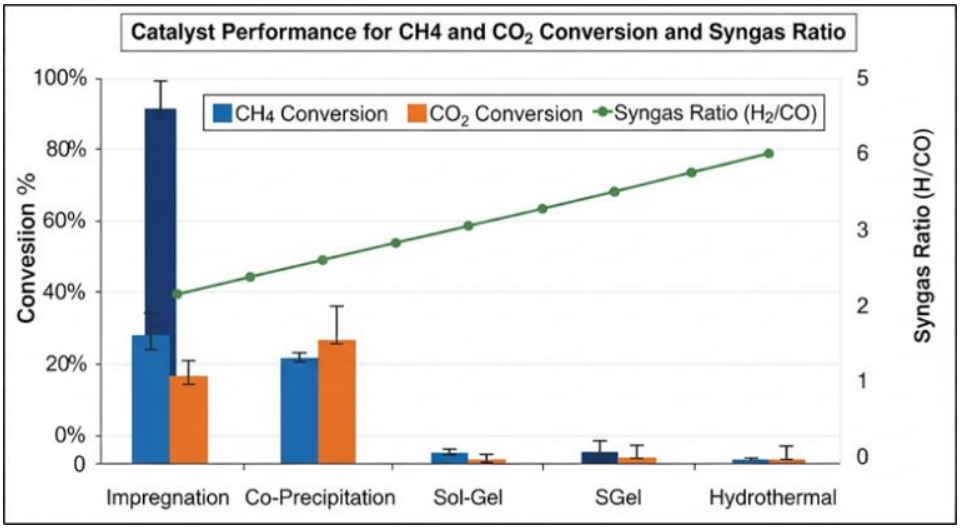

Figure 1. Impact of catalyst synthesis techniques on CH_4/CO_2 conversion and syngas ratio.

5. CONCLUSIONS

Preparation methods are also a major determinant of the effectiveness of cesium-promoted nanostructured catalysts in catalyzing the dry reforming of methane. Nanostructuring increases accessibility of active sites and diffusion rate, whereas cesium increases CO 2 adsorption and electron transfer. Yet, the way the catalyst is prepared makes the difference in the efficacy of such traits. The impregnation technique is an economical and scalable technique, but often results in uneven cesium distribution. Co-precipitation and sol-gel methods are more effective in controlling particle size and dispersion, but these methods have serious prerequisites. Hydrothermal and solvothermal processes enable the shape and the crystallinity to be controlled carefully due to their ability to enhance the structural stability. CVD and ALD offer a high level of consistency and nanoscale resolution, however, it requires a lot of equipment and money. A visionary strategy, novel green synthesis methods, such as bio-templating, microwave assisted and mechanochemical techniques, put forward green synthesis strategies alongside the possibility of scale. In general, the cost-scalability-cesium-distribution-catalytic-endurance balance is influenced by the choice of the preparation technique. The combination of cesium promotion and the latest nanostructuring and sustainable synthesis methods can offer a promising path to strong catalysts capable of facilitating DRM as a low-carbon, economically viable, and efficient process of producing syngas.

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