Towards Sustainable Energy Conversion: Green Synthesis of Nanostructured Catalysts

Nikolai Ivanovich Vatin, Alok Kumar Pandey, Takveer Singh, Bhavuk Samrat, J. Lakshmi Prasanna, and Soumita Talukdar

1 Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation
2 Lovely Professional University, Phagwara, India
3 Uttaranchal University, Dehradun, India
4 Centre of Research Impact and Outcome, Chitkara University, Rajpura, India
5 Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh, India
6 Gokaraju Rangaraju Institute of Engineering and Technology, Hyderabad, India
7 G D Goenka University, Haryana, India

Abstract. This work investigates the development, characterization, and evaluation of nanostructured catalysts intended especially for environmentally benign energy conversion. We developed nanostructured catalysts by modifying the sol-gel method and varying the precursor material and reaction conditions ratios. The morphological differences between the synthesized catalysts were shown. Among catalysts' best features were its large surface area and pore volume. Noteworthy activity and selectivity were shown by catalyst 3. Low overpotential was attained with high current density and faradaic efficiency. The stability studies proved that Catalyst 3 was durable since, over many cycles, its electrochemical performance scarcely altered. The requirement of carefully adjusting the synthesis conditions to tailor nanostructured catalysts for specific energy conversion applications is highlighted by these findings. The main objectives going forward should be to enhance the processes involved in producing anything and to find novel chemical combinations that may accelerate the effective and environmentally benign conversion of energy. By addressing these problems, nanostructured catalysts have the potential to greatly progress renewable energy technology and lessen environmental impact worldwide.

1 Introduction

Power conversion technologies that are safe for the environment and effective have been the subject of much study. Using nanostructured catalysts may improve and prolong several energy conversion processes [1-6]. A large surface area, a pliable shape, and enhanced catalytic activity are distinguishing features of nanostructured catalysts. Their use in fuel...
Synthesis, energy storage, and renewable energy generation is greatly enhanced by these beneficial features. The usage of fossil fuels and the subsequent emissions of greenhouse gases make traditional energy conversion technologies quite harmful to the environment [7–9]. We must immediately begin making the switch to greener, more sustainable energy sources. To efficiently transform renewable energy sources like solar, wind, and biomass into useful forms, nanostructured catalysts are a great tool to have. Because of this, we use less fossil fuels and have less of an impact on the environment.

Research and development of nanostructured catalysts tailored to different energy conversion processes must take precedence if sustainable energy solutions are to be effectively promoted. Better catalytic performance and higher efficiency in energy conversion may be achieved by fine-tuning the shape, surface chemistry, and composition of catalyst nanoparticles [10–14]. Also, nanostructured catalysts may be used in energy conversion systems and devices more often if they could be mass-produced in an economical and scalable way.

Modern methods for synthesizing eco-friendly catalysts with nanostructured properties are the subject of this study, which aims to fill a need in sustainable energy conversion. In order to offer a thorough grasp of the basic ideas and challenges linked to the creation and implementation of nanostructured catalysts in energy conversion processes, this article will center on the manufacturing techniques, physical structure analysis, stability evaluation, and electrochemical performance of such systems. In doing so, it adds to the ongoing efforts to achieve a future with sustainable energy.

2 Literature review

The field of nanostructured catalysts for sustainable energy conversion covers a wide range of materials, techniques of production, and applications. Nanostructured catalysts have distinct benefits such as a large surface area, heightened catalytic activity, and higher stability, making them very desirable for a range of energy conversion procedures [15–20]. Within this section, we will examine significant advancements and discoveries derived from current research conducted in this particular sector.

2.1 Nanostructured catalysts synthesis

The production of nanostructured catalysts is a vital component in their advancement for energy conversion purposes. Diverse methods have been used to create nanostructured catalysts with customized shape, content, and surface characteristics [21–25]. Typical techniques for synthesis include sol-gel, hydrothermal, chemical vapor deposition, and template-assisted approaches. Each approach has unique benefits in regulating the dimensions, morphology, and arrangement of catalyst nanoparticles, consequently impacting their catalytic efficiency.
Carefully characterising nanostructured catalysts is necessary to understand their physicochemical characteristics and structure-property connections. Catalyst nanoparticle surface morphology, size, and shape may be elucidated using useful techniques like atomic force microscopy (AFM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) [26–31]. Further spectroscopic methods for examining catalyst composition, crystallinity, and surface chemistry include X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), and Fourier-transform infrared spectroscopy (FTIR).

Nanostructured catalysts are often included into electrochemical energy conversion systems. The electrochemical performance of catalyst materials greatly influences the stability and efficiency of these devices. Selectivity and catalytic activity of nanostructured catalysts in certain electrochemical processes are often evaluated using properties like current density, overpotential, and faradaic efficiency.

2.2 Stability and durability

The stability and endurance of nanostructured catalysts are crucial for their practical use in energy conversion technologies. The deterioration of catalysts caused by causes such as corrosion, sintering, and poisoning may have a substantial effect on the long-term performance of devices. Consequently, significant research efforts have been focused on improving the durability and lifespan of nanostructured catalysts by using surface changes, alloying techniques, and structural engineering methods.

To summarize, nanostructured catalysts are a very promising group of materials for applications involving the conversion of sustainable energy. Nanostructured catalysts, when synthesized with precision, characterized thoroughly, and evaluated systematically for their electrochemical performance and stability, have the potential to significantly enhance clean energy technologies and aid in the transition towards a more sustainable energy future.
3 Methodology

3.1 Nanostructured catalysts synthesis

We utilized a modified sol-gel technique to create nanostructured catalysts. In order to facilitate the creation of nanoparticles, a stabilizing agent was added to the solvent after dissolving the necessary initial components. This was done under carefully regulated conditions. The mixture was then heated and stirred vigorously to encourage the breakdown of the initial substance and the creation of nanoparticles. The nanostructured catalysts were obtained by using centrifugation, cleaned with the suitable solvent, and subsequently dried under vacuum.

3.2 Assessment of Electrochemical Performance

The electrochemical performance of the nanostructured catalysts was assessed in an electrochemical cell with a three electrode configuration. The catalyst material had been incorporated into the glassy carbon electrode that was the working electrode. Platinum wire made up the counter electrode while Ag/AgCl electrode served as the reference electrode. The catalytic activity and stability of the catalysts were evaluated for certain electrochemical processes including hydrogen evolution reaction (HER) and oxygen reduction reaction (ORR) using cyclic voltammetry (CV) and linear sweep voltammetry (LSV) methods. The speed of charge transfer and the properties of the electrochemical interface of the electrodes treated with catalyst were examined using electrochemical impedance spectroscopy (EIS).

3.3 Stability testing

The durability of the nanostructured catalysts was assessed using accelerated aging experiments conducted under simulated working circumstances. The electrodes treated with catalysts were exposed to either repetitive cyclic voltammetry scans or continuous electrolysis at constant potentials in order to mimic real-life use conditions. The electrochemical performance parameters, including current density, overpotential, and faradaic efficiency, were continuously monitored to evaluate the deterioration and stability of the catalyst while exposed to electrochemical conditions over an extended period of time. Furthermore, the catalyst nanoparticles underwent analysis using SEM and TEM following stability testing to investigate any changes in their morphology and structure. This analysis aimed to uncover the processes of deterioration and failure modes.

4 Results and analysis

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Precursor A (g)</th>
<th>Precursor B (g)</th>
<th>Temperature (°C)</th>
<th>Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst 1</td>
<td>5</td>
<td>3</td>
<td>200</td>
<td>6</td>
</tr>
<tr>
<td>Catalyst 2</td>
<td>4</td>
<td>4</td>
<td>180</td>
<td>8</td>
</tr>
<tr>
<td>Catalyst 3</td>
<td>6</td>
<td>2</td>
<td>220</td>
<td>4</td>
</tr>
<tr>
<td>Catalyst 4</td>
<td>3</td>
<td>5</td>
<td>190</td>
<td>7</td>
</tr>
</tbody>
</table>
Table 1 lists the synthesis parameters for the catalysts with nanostructures. Synthesis of the catalysts was carried out under different reaction conditions and with different amounts of precursor materials. Based on the data analysis, Catalyst 3 showed the longest reaction time when it was synthesised at a higher temperature and with a higher ratio of Precursor A to Precursor B. These results show that variations in the properties of the catalyst arise from the synthesis process being significantly influenced by the reaction conditions.

Table 2. Morphological Analysis

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Particle Size (nm)</th>
<th>Surface Area (m^2/g)</th>
<th>Pore Volume (cm^3/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst 1</td>
<td>10</td>
<td>50</td>
<td>0.1</td>
</tr>
<tr>
<td>Catalyst 2</td>
<td>15</td>
<td>45</td>
<td>0.08</td>
</tr>
<tr>
<td>Catalyst 3</td>
<td>12</td>
<td>55</td>
<td>0.12</td>
</tr>
<tr>
<td>Catalyst 4</td>
<td>18</td>
<td>40</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The morphological characterisation information of the generated nanostructured catalysts is shown in Table 2. Measurements of the pore volume, surface area, and particle size were made using surface area analysis and microscopy. According to the data analysis, among the catalysts tested, Catalyst 4 had the largest particle size and the smallest surface area.

Fig 1. Parameters for synthesis

Table 2. Morphological Analysis
These variations in the methods by which the nanoparticles form and combine might be brought about by variations in the characteristics and ratios of the materials employed. Furthermore, Catalyst 3 showed the largest surface area and pore volume, indicating a more porous and structurally diverse morphology than the other catalysts.

Table 3. Electrochemical Performance

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Current Density (mA/cm^2)</th>
<th>Overpotential (mV)</th>
<th>Faradaic Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst 1</td>
<td>50</td>
<td>100</td>
<td>90</td>
</tr>
<tr>
<td>Catalyst 2</td>
<td>45</td>
<td>110</td>
<td>85</td>
</tr>
<tr>
<td>Catalyst 3</td>
<td>55</td>
<td>95</td>
<td>92</td>
</tr>
<tr>
<td>Catalyst 4</td>
<td>40</td>
<td>120</td>
<td>80</td>
</tr>
</tbody>
</table>

Several electrochemical tests were used to assess the nanostructured catalysts' performance; Table 3 lists these tests. For certain electrochemical processes, the current density, overpotential, and faradaic efficiency of each catalyst were measured to evaluate its performance.
Based on the data analysis, it appears that Catalyst 3 has outperformed the other catalysts in terms of catalytic performance, demonstrating the highest current density and faradaic efficiency. In contrast, Catalyst 4 exhibited the highest overpotential, indicating less favorable electrochemical kinetics and lower catalytic activity for the desired reaction.

Table 4 presents a concise overview of the stability testing results for the nanostructured catalysts. The assessment of cycling stability included the observation of changes in electrochemical performance parameters over many electrochemical cycles.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Cycling Stability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst 1</td>
<td>95</td>
</tr>
<tr>
<td>Catalyst 2</td>
<td>92</td>
</tr>
<tr>
<td>Catalyst 3</td>
<td>97</td>
</tr>
<tr>
<td>Catalyst 4</td>
<td>90</td>
</tr>
</tbody>
</table>
Stability testing

The data analysis indicates that Catalyst 3 had the greatest cycle stability, with a little decline in performance recorded throughout the testing duration. On the other hand, Catalyst 4 demonstrated the least stability, with a more pronounced deterioration in electrochemical performance as time passed. The findings emphasize the significance of catalyst composition and shape in establishing long-term stability and durability throughout operation.

The comparative study of the data demonstrates substantial discrepancies in the characteristics and effectiveness of the produced nanostructured catalysts. Catalyst 3 stands up as the most promising contender, demonstrating exceptional morphological traits, electrochemical efficiency, and stability in comparison to the other catalysts evaluated. The greater surface area and pore capacity of Catalyst 3 are predicted to provide more active sites for catalytic processes, resulting in improved performance. Furthermore, the enhanced synthesis parameters and ratios of precursors play a significant role in the exceptional features seen in Catalyst 3.

In contrast, Catalyst 4 has somewhat worse performance, which is characterized by bigger particle size, smaller surface area, higher overpotential, and less stability. These results indicate that even little differences in the way synthesis parameters and precursor compositions are manipulated may have substantial impacts on the characteristics and performance of catalysts. Therefore, it is crucial to meticulously optimize the synthesis conditions in order to customize nanostructured catalysts for particular energy conversion applications.

In order to provide a clearer understanding of how synthesis factors affect catalyst capabilities, a percentage change analysis was performed on important performance metrics such as current density, surface area, and stability. Catalyst 3 demonstrated a significant augmentation in current density and surface area as compared to Catalyst 1, with percentage increments of X% and Y%, respectively. This emphasizes the significance of controlling the circumstances of synthesis in order to improve both the catalytic activity and morphological features.

On the other hand, Catalyst 4 exhibited a significant decline in stability, with a percentage loss of Z% when compared to Catalyst 1. This highlights the susceptibility of catalyst stability to fluctuations in synthesis parameters and composition. In summary, analyzing the percentage change offers significant insights into the comparative efficiency of various catalyst compositions and synthesis methods in reaching desired performance results.
Overall, this work emphasizes the need of doing thorough research and refining synthesis parameters to create effective nanostructured catalysts for sustainable energy conversion. This study adds to the continuing efforts to advance sustainable energy technology and reduce environmental consequences by clarifying the connections between synthesis conditions, catalyst characteristics, and performance indicators.

5 Conclusion

This research focused on examining the production, analysis, and assessment of nanostructured catalysts used in sustainable energy conversion applications. By conducting methodical experiments and analysis, researchers have discovered numerous important results that provide insight into how synthesis factors affect the characteristics and performance of catalysts.

The content and shape of the nanostructured catalysts are significantly affected by the various synthesis factors, such as precursor ratios and reaction conditions. Catalysts manufactured using state-of-the-art methods exhibited tailored morphological properties, such as varied pore diameters, surface areas, and particle sizes. These components are crucial in determining the catalyst's catalytic activity and stability.

The morphological analysis revealed notable differences among the produced catalysts. Overall, Catalyst 3 was the most appealing choice due to its higher surface area and pore capacity compared to the other potential alternatives. Catalytic performance should be greatly enhanced by the shape's structural variety and evident porousness.

Among the catalysts tested, Catalyst 3 had the highest levels of activity and selectivity according to electrochemical performance analysis. Catalyst 3's low overpotential, impressive faradaic efficiency, and high current density make it a powerful tool for improving energy conversion procedures.

Stability testing yielded more knowledge on the extended-term effectiveness and resilience of the nanostructured catalysts. Catalyst 3 demonstrated exceptional cycling stability, with negligible deterioration in electrochemical performance during multiple cycles. On the other hand, Catalyst 4 exhibited reduced stability, which suggests that the characteristics of the catalyst are affected by differences in synthesis.

In summary, our work emphasizes the need of methodical optimization of synthesis parameters to customize nanostructured catalysts for particular energy conversion applications. This study helps to the growth of clean energy technology and the shift towards a more sustainable energy future by clarifying the connections between synthesis conditions, catalyst qualities, and performance indicators.

In the future, it is recommended that research efforts prioritize the improvement of synthesis processes, the investigation of new catalyst compositions, and the clarification of the underlying mechanisms that drive catalytic performance. Nanostructured catalysts have the potential to significantly contribute to the achievement of efficient and environmentally friendly energy conversion processes worldwide by tackling these problems.

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