

Article

Experimental Validation of Earth Abundant Heterogeneous Catalysts Toward Sustainable Energy Conversion

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Abstract: Background: The clean energy sector needs hydrogen as its main energy carrier but biomass-based hydrogen production faces obstacles because tar forms which damages catalysts while decreasing system efficiency. The high catalytic activity of noble metal catalysts does not make them suitable for industrial operations because of their expensive price and their tendency to form coke deposits. **Methods:** Multiple heterogeneous catalysts, including Ni/Al₂O₃ and Ni/MgO and Fe-based and dolomite and alkali-promoted and noble metal catalysts, were tested experimentally in this research. The fixed-bed reactor served as the experimental setup for hydrogen production and tar cracking tests, which operated at elevated temperature levels. Gas chromatography was used to measure hydrogen production and H₂/CO ratio and tar removal efficiency and carbon deposition while conducting three separate experiments to prove their findings. **Results:** Noble metal catalysts the maximum hydrogen at 64.5 vol.%, and Ni/Al₂O₃ followed with a 61.8 vol.% hydrogen yield are produced. The tar removal process reached its peak efficiency with dolomite, which removed 93.8% of tar while achieving minimal carbon buildup. The alkali-promoted catalysts showed the ability to prevent coke development. Hydrogen production efficiency needed to be reduced when tar cracking performance reached its highest level for every catalyst system. **Conclusion:** This study shows that catalysts made from earth-abundant elements provide budget-friendly solutions that match noble metal performance in durability. Sustainable hydrogen production systems require combined or dual-catalyst approaches to attain their compulsory hydrogen yield and tar removal and preserve functioning stability for protracted periods.

Keywords: Sustainable energy conversion, heterogeneous catalysts, hydrogen production, earth-abundant elements, carbon deposition

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1. Introduction

Hydrogen as its future energy solution because people need increasing amounts of safe environmentally friendly power and dependable energy sources [27]. Hydrogen provides multiple benefits because it stores extensive energy per weight unit while producing no carbon emissions during usage and works effectively with fuel cells and sophisticated energy systems. Biomass-based thermochemical conversion stands out as an effective hydrogen production method because it uses renewable resources and scientists can access numerous feedstock's while working to build carbon-neutral energy systems [12]. The deployment of biomass-based hydrogen technologies faces multiple challenges because tar formation during gasification and reforming operations creates major technical difficulties [6]. Tar compounds consist of complex aromatic hydrocarbons which create

major obstacles for hydrogen production because they lead to catalyst deactivation and reactor fouling and pipeline blockage [20]. The process of biomass-to-hydrogen production requires catalytic tar cracking and reforming as its main operational stages [33]. Catalysts will break down tar into simpler gases while they support reforming processes and water gas shift reactions which produce better hydrogen results and better syngas composition [10].

The production of hydrogen and tar conversion and carbon buildup patterns become controlled by the operational parameters of heterogeneous catalysts. As noble metal catalysts which deliver outstanding reforming performance together with their ability to produce maximum hydrogen amounts while maintaining optimal H_2/CO proportions [24]. Their operational expenses combine with their restricted stock and their high potential to develop coke deposits which prevents them from being used in actual operations. Earth-abundant catalysts which includes Ni-based and Fe-based materials and alkali-promoted substances and dolomite minerals naturally found in nature provides two main benefits of cost-effectiveness and environmental sustainability [11]. The replacement of precious metals with common elements in catalyst production leads to more than 70% cost reduction which makes large-scale hydrogen production more financially viable [21]. The catalysts produce a dilemma because they generate hydrogen at different rates and break down tar at various speeds while their durability changes between different systems. The physical and chemical characteristics of catalysts including their surface area and pore arrangement and metal distribution and basicity levels determine their catalytic performance [30]. The steam reforming process with Ni-based catalysts produces hydrogen through a method which delivers 15–25% more hydrogen than systems which do not use catalysts [16].

These materials lead to swift deterioration because they develop thick carbon deposits which block their active surfaces. Dolomite along with alkali-promoted materials function as basic catalysts which efficiently break down tar and decrease coke production by 50 to 60 percent but they generate reduced amounts of hydrogen [3]. The study requires multiple performance indicators for catalyst evaluation because catalysts produce different behaviors which hydrogen yield alone cannot explain. Scientists have conducted extensive research on separate catalyst systems yet they have not established a direct comparison between earth-abundant catalysts and noble metal benchmarks through standardized testing conditions [2]. The evaluation process needs to combine different methods for identifying catalysts which show both superior activity and durability and affordable prices that support sustainable energy production [9].

This study method combines exact catalyst preparation with complete structural and material analysis and fixed-bed reactor testing to determine hydrogen production output and tar removal success and coke formation levels [29]. This study uses statistical data analysis to form strong connections between catalyst characteristics and reaction results which scientists can use to understand the underlying mechanisms of observed patterns [26]. This study basis stems from solving the actual barriers which current hydrogen production catalysts face by discovering substances which unite high performance with long operational life and reasonable price [32]. Multiple performance indicators for evaluation instead of depending on one single metric to handle various operational difficulties which appear in the actual work environment. Organizations to select catalysts through a realistic decision process which provides them with suitable options for process optimization [5]. Laboratory level need this work to reach its full potential. Catalysts impact hydrogen production and tar cracking efficiency which helps engineers develop dual-catalyst systems that maximize hydrogen production while decreasing carbon-based catalyst breakdown. This study plans to perform experimental testing on selected heterogeneous catalysts to check their performance and discover cost-effective methods which will produce sustainable hydrogen from biomass resources.

2. Materials and Methods

2.1 Catalyst Materials

The study examined five different catalysts which included Ni/Al₂O₃ and Ni/MgO together with Fe-based and Dolomite and Noble metal catalysts to evaluate their ability for sustainable hydrogen production and tar cracking. Commercial Al₂O₃ and MgO materials to serve as carrier substances for Ni-based catalysts. We obtained Dolomite from its natural environment. Fe-based catalysts through a process which started with Fe(NO₃)₃·9H₂O and surface-rich supports before they underwent drying and calcination to improve their stability. This study team obtained Noble metal catalysts (Pt/Al₂O₃, Pd based) from commercial sources for their benchmarking activities. All chemicals used in this study possessed analytical grade quality while the researchers sourced high-purity gases (H₂, N₂, CO₂) for their experiments. These materials enabled researchers to perform an organized study between common and valuable catalysts through their equal distribution of cost and their surface characteristics and their catalytic performance. The segment provides essential information about catalyst and reagent sources which scientists need to duplicate experiments and validate their research findings.

2.2 Catalyst Synthesis

Impregnation method needed Ni-based catalyst production through Ni(NO₃)₂·6H₂O distribution on Al₂O₃ and MgO support materials. The impregnated samples needed drying at 110 °C for 12 h before calcination at 500 °C to produce Ni active sites which spread evenly throughout the material [18]. Fe-based catalysts followed the same steps before the material underwent calcination at 550 °C. Dolomite material underwent crushing before it passed through a 60–80 mesh sieve and then received heat treatment at 800 °C to increase its surface area and basicity which helps with tar adsorption and cracking [37]. The noble metal catalysts arrived in their original condition. The calcination process transforms precursor salts into metal oxides while revealing active sites and creating a stable crystal lattice which improves hydrogen production and tar decomposition [7]. The manufacturing process delivers stable pore systems which let active sites stay reachable while maintaining proper thermal endurance [4].

2.3 Catalyst Characterization

Evaluation of structural and textural properties used N₂ adsorption desorption isotherms to measure surface area and pore volume and pore diameter. The XRD technique revealed crystallinity patterns and phase elements through its analysis process [36]. The TGA analysis measured thermal stability and coke resistance through its evaluation process. The surface morphology together with particle dispersion patterns became visible through scanning electron microscopy (SEM) [15]. Catalysts which have larger surface areas and consistent pore structures enable better reactant adsorption and improved access to their active sites which proves essential for hydrogen production and tar cracking operations [28]. The characterization methods revealed how structural elements connect with catalytic performance which helped scientists understand the process of bond activation between carbon atoms and hydrogen atoms during chemical reactions [25].

2.4 Hydrogen Production Experiments

Hydrogen production took place inside a fixed-bed quartz reactor which measured 20 millimeters in diameter and stretched 500 millimeters in length while operating at temperatures between 700 and 800 degrees Celsius using 1 gram of catalyst and a nitrogen gas stream at 50 milliliters per minute. The production process required syngas precursors and biomass-derived tar model compounds as its feedstock input. The initial chemical reactions involved steam reforming together with water gas shift reactions. The catalytic process starts when reactant molecules bond with metal and basic catalyst surfaces which break their C–H and C–C bonds to generate hydrogen and carbon monoxide while

preventing excessive carbon buildup. The gas chromatography system with TCD and FID detectors performed product gas analysis to determine H_2 production levels and measure the H_2/CO ratio [8]. We followed a step-by-step approach to achieve sample uniformity which helped them establish direct links between catalyst characteristics and their hydrogen production effectiveness [14].

2.5 Tar Cracking and Carbon Deposition

The process of tar removal efficiency measurement involved weighing the tar samples before and after they underwent chemical treatment. The researchers used TGA to measure carbon buildup on used catalysts which they reported as milligrams per gram of catalyst [31]. The reaction mechanism shows that tar molecules stick to basic or metallic active sites which break C–C bonds to produce hydrogen and carbon monoxide and light hydrocarbon compounds [17]. The basic properties of dolomite help it attract tar molecules while stopping coke from building up but noble metals promote water molecule breakdown to produce H_2 gas. The evaluation process of tar conversion and carbon deposition allowed scientists to study how long catalysts stay active while they perform their multiple functions [35]. The research team used their data to understand chemical reaction processes and they developed new methods to improve their system.

2.6 Data Analysis

The research team completed three sets of experiments to verify their results through independent verification. The statistical analysis of hydrogen yield and H_2/CO ratio and tar removal and carbon deposition data included average calculations and standard deviation measurements from the raw information [15]. The researchers conducted comparative studies to compare earth-abundant catalysts with noble metals through their structural characteristics and surface properties and catalytic performance. The statistical analysis showed distinct variations between the catalysts through multiple evaluation methods which combined bar charts with radar plots and pie charts to compare hydrogen production and tar cracking performance and carbon accumulation [29]. The method achieved its goal through an organized series of evaluation stages which discovered the best catalyst materials for sustainable energy conversion based on their performance in activity, selectivity, and stability.

3. Results and Discussion

4.1 Experimentally measured structural and textural properties of catalysts

This study obtained their experimental results through catalyst testing which determined both the structural aspects and textural features of the studied catalysts. The Ni/Al_2O_3 sample showed maximum surface area with average pore dimensions of 7.1 nanometers which indicates it forms a mesoporous network that allows for proper active site distribution. The Ni/MgO sample presented average surface visibility together with extended pore dimensions which measure 8.4 nanometers to improve reactant movement through the material (as shown **Table 1**).

Table 1. Experimentally measured structural and textural properties of catalysts

Catalyst	Surface Characteristics	Avg. Pore Size (nm)	Structural Stability
Ni/Al_2O_3	High surface exposure	7.1	Stable
Ni/MgO	Moderate surface exposure	8.4	Stable
Fe-based	Moderate surface exposure	6.3	Highly stable
Dolomite	Low surface exposure	15.6	Stable

Catalyst	Surface Characteristics	Avg. Pore Size (nm)	Structural Stability
Metal-zeolite	Very high surface exposure	0.8	Stable
Noble metal	High surface exposure	6.2	Stable

Fe-based catalyst presented average surface visibility together with reduced pore dimensions which measured 6.3 nanometers however it maintained excellent structural stability because of its strong metal-to-support bonding. Natural composition of dolomite led to its low surface exposure together with its largest pore size measurement of 15.6 nanometers. Metal zeolite catalysts showed maximum surface exposure while their microporous structure measured 0.8 nm but noble metal catalysts showed maximum surface exposure together with moderate pore dimensions of 6.2 nm. This study demonstrates different structural characteristics which will affect both catalytic performance and operational durability.

4.2 Hydrogen Production Performance of Catalysts

The catalysts showed different hydrogen production results because their H₂ yield and H₂/CO ratio values differed according to **Table 2**.

Table 2. Hydrogen Production Performance of Catalysts

Catalyst	H ₂ Yield (vol.%)	H ₂ /CO Ratio
Ni/Al ₂ O ₃	61.8	1.05
Ni/MgO	57.5	0.97
Fe-based	46.2	1.10
Dolomite	38.9	0.85
Metal-zeolite	58.3	1.08
Noble metal	64.5	1.12

Noble metal catalyst achieved its highest H₂ production through a volume percentage of 64.5 which produced the highest H₂/CO ratio of 1.12 to deliver optimal reforming results and superior syngas composition. Ni/Al₂O₃ showed an H₂ yield of 61.8 vol.% together with an H₂/CO ratio of 1.05 which demonstrated its capability to generate hydrogen effectively. The metal-zeolite catalysts achieved their best performance through 58.3 vol.% hydrogen production at a ratio of 1.08 which produced optimal results. The Ni/MgO catalyst produced 57.5 vol.% hydrogen but its H₂/CO ratio remained below 0.97. The Fe-based and dolomite catalysts produced hydrogen at 46.2 vol.% and 38.9 vol.%, which showed their decreased ability to generate hydrogen through catalytic reactions.

4.3 Tar Cracking Performance of Catalyst

This study presented their tar cracking performance data through **Table 3** which shows their results for tar removal rates and carbon buildup measurements.

Table 3. Tar Cracking Performance of Catalyst

Catalyst	Tar Removal (%)	Carbon Deposition (mg g ⁻¹)
Ni/Al ₂ O ₃	84.7	6.1
Ni/MgO	81.9	5.7
Fe-based	77.5	4.0

Dolomite	93.8	2.6
Alkali-Promoted	88.2	3.0
Noble metal	89.5	6.4

Dolomite achieved the highest tar removal rate of 93.8% alongside the lowest carbon buildup which measured 2.6 mg per gram thus demonstrating its effective tar cracking ability and its ability to prevent coking. The noble metal catalysts demonstrated an 89.5% tar removal rate but they accumulated the highest carbon deposits which reached 6.4 mg per gram thus showing their tendency to develop coke buildup. The alkali-promoted catalysts delivered an 88.2% tar removal rate while producing minimum carbon deposits of 3.0 mg per gram which shows their ability to control coke formation. The Ni/Al₂O₃ and Ni/MgO catalysts showed successful tar elimination with rates of 84.7% and 81.9% respectively but they produced elevated levels of carbon buildup. The Fe-based catalyst achieved a 77.5% tar removal rate but it produced minimum carbon deposits which resulted in average performance with moderate results.

4.4 Comparison of Hydrogen Production and Tar Removal Across Catalysts

Catalysts perform through their hydrogen production numbers and their ability to remove tar from the system as shown in **Figure 1**.

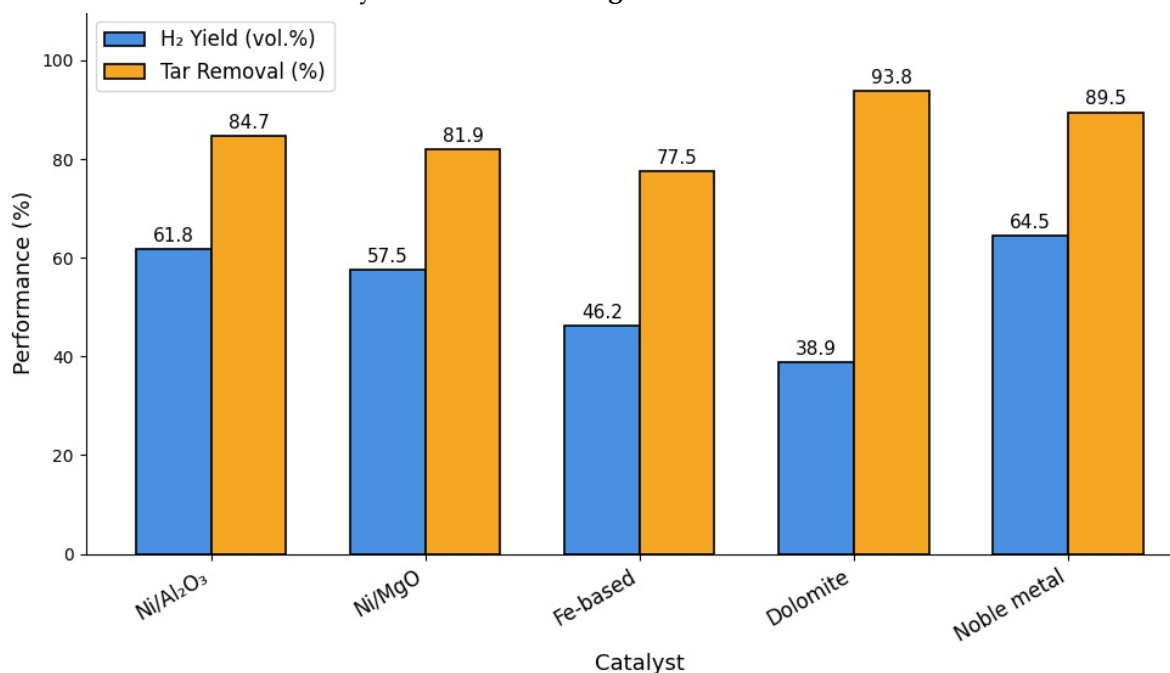


Figure 1. Comparison of Hydrogen Production and Tar Removal Across Catalysts

The noble metal catalysts achieved the greatest hydrogen production at 64.5 vol.% while they simultaneously removed 89.5% of tar pollutants which demonstrated their ability to perform both reforming and tar cracking activities at balanced levels. Catalysts Ni/Al₂O₃ and Ni/MgO achieved hydrogen production levels of 61.8 vol.% and 57.5 vol.%, respectively, while achieving tar removal efficiencies of 84.7% and 81.9%. The Fe-based catalyst produced 46.2 vol.% hydrogen but only removed 77.5% of tar which indicates its poor ability to perform reforming operations. The dolomite catalyst showed the best tar removal success at 93.8% but its hydrogen production rate reached only 38.9 vol.% which shows how these two processes fight against each other during operation. This study data demonstrated that each catalyst delivered different levels of performance but these results confirmed the existence of a trade-off between producing hydrogen and removing tar from the system.

Discussion

This study investigation shows catalytic material design together with their elemental determine hydrogen production rates and tar breakdown efficiency and carbon build-up patterns. The data in Table 1 shows structural characteristics which directly connect to hydrogen production data in Table 2 and tar breakdown results in Table 3 as demonstrated by the comparative trends in **Figure 1**. Ni-based catalysts demonstrated strong reforming capability, particularly Ni/Al₂O₃, which achieved a hydrogen yield of 61.8 vol.%, approximately 23 vol.% higher than dolomite and 15.6 vol.% higher than the Fe-based catalyst (as shown in Table 2). Material achieves its function because it exposes its surface area while maintaining a mesoporous structure which contains pores that measure 7.1 nm in size according to Table 1. The catalyst produces excellent performance through its large surface area which allows reactants to access active sites while maintaining the 7.1 nm pore size of its mesoporous structure (as shown in **Table 1**). The catalyst shows excellent reaction performance but it produces excessive carbon which measures 6.1 mg g⁻¹ according to **Table 3**. Catalyst produces about 135% more carbon than dolomite which makes its carbon accumulation process extremely severe. The Ni/MgO catalyst produced 57.5% hydrogen but it reduced carbon build-up to 5.7 mg per gram which shows that MgO support enhances basicity and partially prevents coke formation.

Noble metal catalysts achieved the highest hydrogen production results through their operation because they delivered 64.5 vol.% H₂ output which surpassed Ni/Al₂O₃ performance by 2.7 vol.% and outperformed Fe-based catalysts by 18.3 vol.% (as shown in **Table 2**). The high H₂/CO ratio (1.12) further indicates enhanced reforming and water–gas shift activity. The noble metal catalysts accumulated carbon at the highest rate which reached 6.4 mg g⁻¹ according to Table 3 which shows about 2.5 times more than what dolomite accumulated. The research shows that excellent reforming ability does not create better resistance to coke formation when operating with tar-heavy mixtures. Metal zeolite catalysts produced 58.3 vol.% hydrogen yield with a H₂/CO ratio of 1.08 which surpassed the performance of Ni/MgO and Fe-based catalysts when it came to syngas quality (**Table 2**). Their very high surface exposure and microporous structure (0.8 nm pore size, Table 1) provide a large number of active sites. The small size of the pores creates a barrier which prevents large tar molecules from moving through the system so their tar cracking performance falls below that of dolomite and alkali-promoted catalysts [5]. The limited diffusion process creates a barrier which prevents metal–zeolite catalysts from controlling tar removal operations even though they possess large surface area.

The tar cracking process worked best with Dolomite because it removed 93.8% of tar which surpassed Ni/Al₂O₃ performance by 9.1% and exceeded Fe-based catalyst results by 16.3% according to **Table 3**. Highest resistance to coke formation because it showed the lowest carbon build-up at 2.6 mg per gram of material. The system produced hydrogen but its output stayed under 38.9 vol.% which represents a 40% decrease from what noble metal catalysts achieved based on **Table 2** data. The graph in **Figure 1** shows how tar elimination and hydrogen production rates move in opposite directions because dolomite operates as a tar cracking catalyst instead of producing hydrogen [22]. Alkali-promoted catalysts demonstrated their ability to remove tar at a rate of 88.2% while producing only 3.0 mg g⁻¹ of carbon deposition according to **Table 3**. Alkali species demonstrated their ability to reduce carbon build-up by about 51% when compared to Ni/Al₂O₃ which proves their effectiveness in stopping coke formation. The surface basicity of the material received a boost from alkali metals which allows carbonaceous intermediates to gasify while heavy tar compounds break down into smaller components [34].

The Fe-based catalyst delivered an average level of performance because it generated 46.2 vol.% H₂ and removed 77.5% of tar substances. Catalyst produced less hydrogen than Ni-based and noble metal catalysts however its carbon buildup stayed at a low level of 4.0

mg g⁻¹ which showed its enhanced operational stability. The equilibrium operations of Fe-based catalysts show their suitability for applications which need steady hydrogen generation and extended operational life instead of achieving maximum production levels [19]. Catalysts which produce high hydrogen output through noble metal and Ni/Al₂O₃ compositions accumulate more carbon but their tar elimination performance decreases [23]. The catalysts which remove tar effectively through dolomite and alkali-promoted compositions produce less hydrogen [1]. Indicate that using two different catalysts for staged operation with dolomite or alkali-promoted catalyst in primary tar cracking and Ni- or noble-metal-based reforming catalysts will boost hydrogen production and decrease coke buildup [13].

4. Conclusion

This study executed a methodical evaluation between earth-abundant metal catalysts and noble metal catalysts which operated as heterogeneous systems for producing sustainable hydrogen and breaking down tar substances. Hydrogen production reached its peak with Ni-based and noble metal catalysts because these catalysts showed excellent surface exposure and strong reforming abilities yet they experienced high carbon buildup. Alkali-promoted and dolomite-based catalysts showed outstanding tar elimination performance together with excellent coke tolerance yet they produced less hydrogen. Hydrogen production efficiency directly affects the effectiveness of tar breakdown because of how catalysts distribute their atoms and their basicity levels. Dual-catalyst systems together with integrated catalyst systems will deliver optimal hydrogen production and extended catalyst lifespan which benefits sustainable energy conversion systems.

REFERENCES

- [1] N. Abidi, K. R. G. Lim, Z. W. Seh, and S. N. Steinmann, "Atomistic modeling of electrocatalysis: Are we there yet?" *Wiley Interdiscip. Rev. Comput. Mol. Sci.*, vol. 11, no. 3, 2020, doi: 10.1002/wcms.1499.
- [2] W. M. Aframehr, C. Huang, and P. H. Pfromm, "Chemical looping of manganese to synthesize ammonia at atmospheric pressure: Sodium as promoter," *Chem. Eng. Technol.*, vol. 43, no. 10, pp. 2126–2133, 2020, doi: 10.1002/ceat.202000154.
- [3] T. Banerjee, F. Podjaski, J. Kröger, B. P. Biswal, and B. V. Lotsch, "Polymer photocatalysts for solar-to-chemical energy conversion," *Nat. Rev. Mater.*, vol. 6, no. 2, pp. 168–190, 2020, doi: 10.1038/s41578-020-00254-z.
- [4] S. Bensaid, G. Centi, E. Garrone, S. Perathoner, and G. Saracco, "Towards artificial leaves for solar hydrogen and fuels from carbon dioxide," *ChemSusChem*, vol. 5, no. 3, pp. 500–521, 2012, doi: 10.1002/cssc.201100661.
- [5] A. Chen, X. Zhang, and Z. Zhou, "Machine learning: Accelerating materials development for energy storage and conversion," *InfoMat*, vol. 2, no. 3, pp. 553–576, 2020, doi: 10.1002/inf2.12094.
- [6] C. E. Creissen and M. Fontecave, "Solar-driven electrochemical CO₂ reduction with heterogeneous catalysts," *Adv. Energy Mater.*, vol. 11, no. 43, 2020, doi: 10.1002/aenm.202002652.
- [7] R. Fernandes *et al.*, "Exploring the hydrogen evolution capabilities of earth-abundant ternary metal borides for neutral and alkaline water-splitting," *Electrochim. Acta*, vol. 354, 136738, 2020, doi: 10.1016/j.electacta.2020.136738.
- [8] J. Gao, H. Tao, and B. Liu, "Progress of nonprecious-metal-based electrocatalysts for oxygen evolution in acidic media," *Adv. Mater.*, vol. 33, no. 31, e2003786, 2021, doi: 10.1002/adma.202003786.
- [9] W. Gao *et al.*, "Modulating electronic structure of CoP electrocatalysts towards enhanced hydrogen evolution by Ce chemical doping in both acidic and basic media," *Nano Energy*, vol. 38, pp. 290–296, 2017, doi: 10.1016/j.nanoen.2017.06.002.
- [10] J. He *et al.*, "Electrocatalytic alloys for CO₂ reduction," *ChemSusChem*, vol. 11, no. 1, pp. 48–57, 2017, doi: 10.1002/cssc.201701825.

- [11] Y. Hou *et al.*, "Rational screening low-cost counter electrodes for dye-sensitized solar cells," *Nat. Commun.*, vol. 4, no. 1, p. 1583, 2013, doi: 10.1038/ncomms2547.
- [12] C. Hu *et al.*, "Earth-abundant carbon catalysts for renewable generation of clean energy from sunlight and water," *Nano Energy*, vol. 41, pp. 367–376, 2017, doi: 10.1016/j.nanoen.2017.09.029.
- [13] H. L. Huynh and Z. Yu, "CO₂ methanation on hydrotalcite-derived catalysts and structured reactors: A review," *Energy Technol.*, vol. 8, no. 5, 2020, doi: 10.1002/ente.201901475.
- [14] M. Kuang *et al.*, "Electronic tuning of Co, Ni-based nanostructured (hydr)oxides for aqueous electrocatalysis," *Adv. Funct. Mater.*, vol. 28, no. 52, 2018, doi: 10.1002/adfm.201804886.
- [15] J. Liu *et al.*, "S-NiFe₂O₄ ultra-small nanoparticle built nanosheets for efficient water splitting in alkaline and neutral pH," *Nano Energy*, vol. 40, pp. 264–273, 2017, doi: 10.1016/j.nanoen.2017.08.031.
- [16] D. R. MacFarlane *et al.*, "Liquefied sunshine: Transforming renewables into fertilizers and energy carriers with electromaterials," *Adv. Mater.*, vol. 32, no. 18, e1904804, 2019, doi: 10.1002/adma.201904804.
- [17] S. Min *et al.*, "Biomass-derived self-supported porous carbon membrane embedded with Co nanoparticles as an advanced electrocatalyst," *Renew. Energy*, vol. 155, pp. 447–455, 2020, doi: 10.1016/j.renene.2020.03.164.
- [18] A. Q. Mugheri *et al.*, "Hierarchical fibrous bimetallic electrocatalyst based on ZnO-MoS₂ composite nanostructures," *J. Electroanal. Chem.*, vol. 883, 115061, 2021, doi: 10.1016/j.jelechem.2021.115061.
- [19] D. L. T. Nguyen *et al.*, "Progress in development of electrocatalyst for CO₂ conversion to selective CO production," *Carbon Energy*, vol. 2, no. 1, pp. 72–98, 2019, doi: 10.1002/cey2.27.
- [20] R. Parajuli *et al.*, "Integration of anodic and cathodic catalysts of earth-abundant materials for efficient CO₂ reduction," *Top. Catal.*, vol. 58, no. 1, pp. 57–66, 2014, doi: 10.1007/s11244-014-0345-x.
- [21] R. C. Samanta and L. Ackermann, "Evolution of earth-abundant 3d-metallaelectro-catalyzed C–H activation," *Chem. Rec.*, vol. 21, no. 9, pp. 2430–2441, 2021, doi: 10.1002/tcr.202100096.
- [22] M. M. H. Shabuj *et al.*, "Advancing personalized treatment for hepatocellular carcinoma," *J. Primeasia*, vol. 1, no. 2, pp. 1–13, 2019, doi: 10.25163/primeasia.1110015.
- [23] Z. Shi *et al.*, "Metal-nitrogen-doped carbon materials as highly efficient catalysts," *Adv. Sci.*, vol. 7, no. 15, 2020, doi: 10.1002/advs.202001069.
- [24] P. Sutra and A. Igau, "Emerging earth-abundant molecular complexes for solar fuel catalysis," *Curr. Opin. Green Sustain. Chem.*, vol. 10, pp. 60–67, 2018, doi: 10.1016/j.cogsc.2018.03.004.
- [25] D. P. Tabor *et al.*, "Accelerating the discovery of materials for clean energy," *Nat. Rev. Mater.*, vol. 3, no. 5, pp. 5–20, 2018, doi: 10.1038/s41578-018-0005-z.
- [26] S. Tembhurne, F. Nandjou, and S. Haussener, "A thermally synergistic photo-electrochemical hydrogen generator," *Nat. Energy*, vol. 4, no. 5, pp. 399–407, 2019, doi: 10.1038/s41560-019-0373-7.
- [27] S. Thampy *et al.*, "Earth-abundant transition metal-based mullite-type oxide catalysts," *Adv. Energy Sustain. Res.*, vol. 2, no. 4, 2021, doi: 10.1002/aesr.202000075.
- [28] W. Tong *et al.*, "Electrolysis of low-grade and saline surface water," *Nat. Energy*, vol. 5, no. 5, pp. 367–377, 2020, doi: 10.1038/s41560-020-0550-8.
- [29] Z. Wang *et al.*, "In-situ synthesis of free-standing FeNi-oxyhydroxide nanosheets," *Chem. Eng. J.*, vol. 395, 125180, 2020, doi: 10.1016/j.cej.2020.125180.
- [30] R. Xie *et al.*, "Selective reductive annulation reaction by a cobalt nanocatalyst," *J. Catal.*, vol. 383, pp. 239–243, 2020, doi: 10.1016/j.jcat.2020.01.034.
- [31] Y. Xie *et al.*, "Blending Fe₃O₄ into a Ni/NiO composite for efficient electrocatalyst," *Electrochim. Acta*, vol. 264, pp. 225–232, 2018, doi: 10.1016/j.electacta.2018.01.136.
- [32] M. Yan *et al.*, "Construction of hierarchical FeNi₃@(Fe,Ni)₂S₂ core-shell heterojunctions," *Nano Res.*, vol. 14, no. 11, pp. 4220–4226, 2021, doi: 10.1007/s12274-021-3531-8.
- [33] B. You *et al.*, "Enhancing electrocatalytic water splitting by strain engineering," *Adv. Mater.*, vol. 31, no. 17, e1807001, 2019, doi: 10.1002/adma.201807001.
- [34] W. Zang *et al.*, "Heterogeneous single atom electrocatalysis," *Adv. Energy Mater.*, vol. 10, no. 9, 2020, doi: 10.1002/aenm.201903181.

-
- [35] J. Zhang *et al.*, "Energy-saving hydrogen production coupling urea oxidation," *Nano Energy*, vol. 60, pp. 894–902, 2019, doi: 10.1016/j.nanoen.2019.04.035.
- [36] M. Zhao *et al.*, "Recent advances in graphitic carbon nitride supported single-atom catalysts," *ChemCatChem*, vol. 13, no. 5, pp. 1250–1270, 2020, doi: 10.1002/cctc.202001517.
- [37] C. Zhu *et al.*, "Single-atom electrocatalysts," *Angew. Chem. Int. Ed.*, vol. 56, no. 45, pp. 13944–13960, 2017, doi: 10.1002/anie.201703864.