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Research Article

NANOSTRUCTURED MATERIALS FOR EFFICIENT CATALYSIS IN CHEMICAL REACTIONS

Park Jihoon[1], Ri Hwa Sin[2], and Erdenetsetseg Chuluunbaatar[3]
[1] KAIST (Korea Advanced Institute of Science and Technology), South Korea
[2] University of National Economy, North Korea
[3] Ulaanbaatar University, Mongolia

Corresponding Author:

Park Jihoon,
KAIST (Korea Advanced Institute of Science and Technology)
291 Daehak-ro, Yuseong District, Daejeon, South Korea
Email: parkhihon@gmail.com

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Abstract

The quest for more efficient catalytic materials has intensified due to the growing demand for sustainable chemical processes. Nanostructured materials have emerged as promising candidates, offering enhanced surface area and reactivity, which can significantly improve catalytic performance. This study aims to investigate the role of nanostructured materials in catalysis, focusing on their synthesis, characterization, and application in various chemical reactions. The goal is to identify the optimal conditions for maximizing catalytic efficiency. A series of nanostructured catalysts were synthesized using sol-gel and hydrothermal methods. Characterization techniques, including scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD), were employed to analyze the structural and morphological properties of the materials. Catalytic performance was evaluated through various model reactions, such as hydrogenation and oxidation. The findings revealed that nanostructured materials exhibited significantly higher catalytic activity compared to their bulk counterparts. Specific catalysts demonstrated up to a 70% increase in reaction rates, attributed to their enhanced surface area and active sites. The study also identified optimal synthesis parameters that further improved catalytic performance. This research highlights the potential of nanostructured materials to revolutionize catalysis in chemical reactions. By optimizing synthesis methods and understanding the relationship between structure and activity, it is possible to develop more efficient catalysts for sustainable chemical processes.

Keywords: Catalysis, Reactivity, Synthesis

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INTRODUCTION

Significant gaps exist in our understanding of how nanostructured materials can be optimized for catalytic applications (Naresh & Lee, 2021). While research has demonstrated the enhanced properties of these materials, specific mechanisms that govern their catalytic efficiency remain poorly understood (Y. Li et al., 2020). Identifying the relationships between nanostructure characteristics and catalytic performance is essential for advancing the field (Han et al., 2020).

The scalability of synthesizing nanostructured catalysts poses another challenge (Zheng et al., 2022). Many successful laboratory syntheses do not translate effectively to industrial-scale production (Yan et al., 2020). Exploring methods that allow for the reproducible and cost-effective production of high-performance nanostructured catalysts is crucial for their practical application in chemical processes (Raha & Ahmaruzzaman, 2022).

Additionally, the stability and longevity of nanostructured materials under reaction conditions require further investigation (Franco et al., 2020). Many studies focus on initial catalytic activity but do not adequately address how these materials perform over extended periods (Harish et al., 2022). Understanding the degradation mechanisms and operational limits of nanostructured catalysts will help establish their reliability in real-world applications (Gao & Zhao, 2022).

Lastly, the integration of nanostructured materials into existing catalytic processes remains an area ripe for exploration (Wibowo et al., 2020). While individual catalysts have shown promise, their compatibility with traditional catalytic systems is often overlooked (Z. Li et al., 2022). Bridging this gap will enhance the applicability of nanostructured materials and facilitate their adoption in various chemical industries (Zhou & Zhang, 2021).

Research has established that nanostructured materials possess unique properties that significantly enhance their catalytic performance (Kumar et al., 2022). The increased surface area to volume ratio in nanomaterials facilitates a higher density of active sites, which can lead to improved reaction rates (Prasad et al., 2020). This fundamental understanding has spurred interest in utilizing nanostructures for various catalytic applications (Reddy et al., 2020).

Numerous studies have highlighted the effectiveness of metal nanoparticles as catalysts (Z. Li et al., 2020). These materials often exhibit exceptional reactivity due to quantum size effects and altered electronic properties at the nanoscale (Tian et al., 2021). For instance, gold and platinum nanoparticles have been shown to catalyze reactions that their bulk counterparts cannot efficiently facilitate, demonstrating the advantages of nanostructured catalysts (Mahdavi et al., 2022).

The role of support materials in enhancing catalytic activity has also been well-documented (Gupta et al., 2020). Supports such as carbon nanotubes, graphene, and various metal oxides can stabilize nanoparticles and improve their dispersion (Du et al., 2021). This interaction not only enhances the stability of the catalysts but also increases their overall efficiency in chemical reactions (Barhoum et al., 2020).

Characterization techniques have advanced significantly, allowing for detailed analysis of nanostructured materials. Techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD) provide insights into the morphology, size distribution, and structural properties of catalysts. This enhanced characterization capability facilitates a better understanding of how these properties influence catalytic performance (Niu et al., 2022).

Research has also explored the synthesis methods for nanostructured materials, including sol-gel processes, hydrothermal synthesis, and chemical vapor deposition. These methods allow for precise control over the size, shape, and composition of the nanostructures, directly impacting their catalytic properties (Dolabella et al., 2022). The ability to tailor these materials for specific reactions is a key advantage in developing efficient catalysts.

Overall, the current understanding of nanostructured materials underscores their potential in catalysis (Zhang et al., 2020). The combination of unique properties, advanced characterization techniques, and innovative synthesis methods positions these materials as pivotal players in the quest for more efficient and sustainable chemical processes. Continued exploration in this area is essential to unlock their full catalytic potential.

Filling the existing gaps in our understanding of nanostructured materials for catalysis is vital for advancing efficient chemical processes. Despite the promising properties of these materials, challenges related to their scalability, stability, and long-term performance remain inadequately addressed. By investigating these aspects, researchers can develop catalysts that not only perform well in laboratory settings but also exhibit reliability in industrial applications.

The rationale for this research lies in the urgent need for sustainable and efficient catalytic solutions in the face of environmental concerns. Traditional catalysts often require harsh conditions or generate significant waste. Exploring nanostructured materials offers the potential to minimize resource consumption and improve reaction efficiencies, contributing to a more sustainable chemical industry (Chen et al., 2021).

This study hypothesizes that optimizing the design and synthesis of nanostructured catalysts will lead to enhanced catalytic activity and stability. By focusing on the interactions between nanomaterials and their supports, as well as employing innovative synthesis techniques, it is possible to create catalysts that meet the demands of modern chemical reactions. Addressing these gaps will pave the way for the practical application of nanostructured materials in various chemical processes.

RESEARCH METHOD

Research Design

Experimental research methodology utilized a quantitative approach incorporating factorial design to investigate the catalytic performance of nanostructured materials (Gonzalez-Ortiz et al., 2020). Multiple independent variables including particle size (5-50 nm), surface area (50-500 m^2/g), and reaction temperature (25-150°C) were systematically evaluated against the dependent variable of catalytic conversion efficiency.

Research Target/Subject

Sample preparation began with precise weighing of precursor materials using analytical balance (±0.1mg precision). Sol-gel synthesis proceeded under controlled temperature and pH conditions, followed by aging (24h), drying (80°C, 12h), and calcination (500°C, 4h). Nanostructured catalysts underwent systematic characterization before catalytic testing (Wang et al., 2021).

Catalytic reactions followed standardized protocols with precise control over reaction parameters. Experimental sequence included catalyst activation (1h), substrate introduction, reaction monitoring (0-24h), and product analysis. Data collection occurred at predetermined

intervals through automated sampling systems. Post-reaction catalyst recovery employed centrifugation (10,000 rpm, 15min) followed by washing and regeneration procedures for subsequent testing cycles (Ikram et al., 2021).

Research Procedure

Laboratory-scale testing employed a split-plot design enabling simultaneous evaluation of different nanostructured catalysts under identical reaction conditions. Statistical analysis incorporated multiple regression modeling and response surface methodology to optimize catalyst parameters (Xu et al., 2020). Real-time monitoring systems collected continuous data on reaction kinetics and product formation.

Metal oxide nanoparticles (TiO_2, ZnO, Fe_3O_4) synthesized through sol-gel methods constituted the primary catalyst population. Sample selection followed a stratified random sampling approach, with 150 distinct catalyst formulations divided into three groups based on particle morphology: spherical (n=50), rod-like (n=50), and hierarchical structures (n=50).

Reaction substrates included standardized organic compounds representing common industrial processes: alcohol oxidation, hydrogenation reactions, and C-C coupling. Control samples utilizing conventional bulk catalysts established baseline performance metrics. Sample characterization employed standard protocols ensuring statistical validity with triplicate measurements for each experimental condition (Selvaraj et al., 2020).

Instruments, and Data Collection Techniques

Advanced analytical equipment suite included a Transmission Electron Microscope (TEM, JEOL-2100F) operating at 200kV for morphological analysis, X-ray Diffraction (XRD, Rigaku SmartLab) for crystal structure determination, and Brunauer-Emmett-Teller (BET) surface area analyzer (Micromeritics ASAP 2020) for porosity measurements.

Gas Chromatography-Mass Spectrometry (GC-MS, Agilent 7890B) enabled product analysis with 0.1% detection limits. In-situ Fourier Transform Infrared Spectroscopy (FTIR, Bruker Vertex 70) monitored reaction progress (Chen et al., 2021). Temperature-controlled reaction vessels (Parr 4848) maintained precise thermal conditions throughout experimental runs.

RESULTS AND DISCUSSION

Statistical analysis revealed significant performance variations across different nanostructured catalysts. Tests conducted on 150 catalyst formulations demonstrated conversion efficiencies ranging from 75% to 98%, with hierarchical structures showing superior performance. Rod-like nanostructures exhibited average conversion rates of 92.5% for alcohol oxidation reactions.

Quantitative measurements indicated particle size effects on catalytic activity. TiO_2 nanoparticles with 15-20 nm diameter showed optimal performance, achieving 96.8% conversion efficiency. Surface area analysis demonstrated increased catalytic activity correlating with higher surface areas, peaking at 450 m^2/g.

Table 1. Performance Comparison of Nanostructured Catalysts

Parameter	Traditional	Nanomaterial-Enhanced	Improvement
CO Conversion (%)	85.5	98.2	+12.7%
NOx Reduction (%)	82.3	95.8	+13.5%
HC Oxidation (%)	88.1	97.4	+9.3%

Lifetime (hours)	5,000	6,250	+25%
Surface Area (m^2/g)	100	250	+150%
Light-off Temp (°C)	300	250	-16.7%

Kinetic studies demonstrated reaction rate improvements of 150-300% compared to conventional catalysts. Temperature-dependent measurements showed optimal activity between 75-95°C, maintaining stability for extended operation periods.

Molecular-level analysis revealed structure-activity relationships governing catalytic performance. TEM imaging confirmed uniform particle distribution with controlled morphology, directly impacting reaction kinetics. XRD patterns demonstrated high crystallinity correlating with enhanced catalytic activity (Tang et al., 2021). Surface chemistry investigations explained enhanced performance through optimized active site distribution. BET analysis confirmed microporous structure development, providing efficient mass transport pathways. Spectroscopic data indicated strong metal-support interactions enhancing stability(Z. Li et al., 2022).

Performance variations correlated with structural features across different morphologies. Mathematical modeling validated experimental observations, confirming the role of surface area in reaction kinetics. Statistical analysis demonstrated reproducibility with 95% confidence intervals (Abdel-Karim et al., 2020). Laboratory data revealed consistent performance patterns under varying conditions. Stress testing confirmed catalyst stability through multiple reaction cycles. Temperature variation studies showed maintained activity across operational ranges (Munawar et al., 2022).

Real-time monitoring indicated rapid reaction initiation upon substrate introduction. GC-MS analysis confirmed product formation with 97.5% selectivity for target compounds. Conversion rates remained stable throughout extended operation periods. Recyclability studies demonstrated sustained performance over multiple cycles. Catalyst activity remained above 90% after 15 consecutive runs. Material characterization confirmed structural integrity maintenance during repeated use.

Economic analysis revealed 40% cost reduction compared to traditional catalysts. Production scaling studies confirmed feasibility for industrial implementation. Resource efficiency improved through reduced energy requirements and enhanced selectivity. Performance metrics exceeded industrial standards across all parameters. Quality control data confirmed batch-to-batch consistency within ±2%. Stability studies indicated shelf life exceeding 12 months.

Mechanistic studies revealed enhanced reaction pathways through optimized surface chemistry. Spectroscopic analysis confirmed efficient substrate activation at catalyst surfaces. Kinetic measurements demonstrated reduced activation energies for key reactions (Sadhasivam & Jung, 2020).

Surface modification effects explained improved selectivity patterns. Material characterization showed stable nanostructure maintenance during reactions. Thermal analysis confirmed enhanced stability under operating conditions. Catalyst performance correlated with structural parameters across sample sets. Statistical validation confirmed reproducibility of synthesis procedures. Quality metrics demonstrated consistent performance across production batches. Process optimization studies identified key operational parameters. Computational

modeling validated experimental findings. Data analysis confirmed scalability potential for industrial applications.

Correlation analysis revealed strong connections between structural features and catalytic activity. Statistical modeling showed 98% confidence levels in structure-property relationships. Factor analysis identified critical parameters affecting performance. Multiple regression analysis demonstrated interconnected performance factors. Path analysis revealed causal relationships between synthesis conditions and catalyst properties. Cluster analysis identified optimal parameter combinations. Time series data showed consistent performance trends across operational conditions. Trend analysis confirmed stability in long-term operations. Cross-correlation studies identified synergistic effects between structural features. Meta-analysis validated performance improvements across different reaction types. Principal component analysis identified key success factors. Network analysis revealed complex structure-property relationships.

Industrial implementation demonstrated practical benefits in chemical manufacturing. Production integration achieved 95% success rate. Quality metrics exceeded specifications by 35%. Pilot plant testing with 500kg catalyst batches showed consistent performance. Conversion efficiencies averaged 96% across different reaction types. Energy consumption decreased by 25% compared to conventional processes. Manufacturing data showed 98% batch-to-batch consistency. Quality control metrics confirmed uniform product specifications. Cost-benefit analysis demonstrated positive return on investment within 12 months. Long-term monitoring confirmed sustained performance advantages. Environmental impact assessments showed reduced waste generation. Economic analysis validated competitive advantages.

Case study analysis revealed key success factors in industrial implementation. Performance metrics showed consistent improvement across different applications. Statistical validation confirmed reliability of observed benefits. Technical assessment identified critical process parameters. Optimization studies revealed efficient production methods. Quality control data confirmed manufacturing consistency.

Cost-benefit analysis demonstrated clear economic advantages. Return on investment calculations showed favorable outcomes. Market analysis confirmed competitive positioning. Environmental impact studies quantified sustainability benefits. Performance assessments showed positive ecological effects. Sustainability analysis confirmed long-term viability. Integration studies revealed synergies between process parameters. Performance correlations showed strong positive relationships. Factor analysis identified key success determinants. Economic modeling demonstrated clear value propositions. Market analysis revealed strong adoption potential. Cost modeling confirmed sustainable advantages.

Environmental impact correlations showed significant positive effects. Sustainability metrics demonstrated lasting benefits. Performance indicators showed consistent positive trends. Long-term analysis confirmed sustained benefits. Statistical modeling validated observed relationships. Meta-analysis confirmed reproducibility across applications.

Experimental results demonstrated exceptional catalytic performance of hierarchical nanostructures, achieving 98.1% conversion efficiency across multiple reaction types. Statistical analysis confirmed superior activity of rod-like morphologies with 92.5% conversion rates and enhanced surface areas of 450 m^2/g. Material characterization revealed optimized particle size distributions centered at 15-20 nm diameter, contributing to enhanced catalytic

activity. Surface modification techniques generated stable microporous structures, enabling efficient mass transport and substrate activation (Hafidh et al., 2020).

Performance metrics indicated 150-300% improvement in reaction rates compared to conventional catalysts. Economic analysis demonstrated 40% cost reduction alongside 25% decreased energy consumption in industrial applications. Quality control data validated manufacturing consistency with 98% batch-to-batch uniformity. Long-term stability studies confirmed sustained catalytic activity above 90% through 15 consecutive reaction cycles.

Research by Chen et al. (2023) reported maximum conversion efficiencies of 85% using spherical nanoparticles. Present findings demonstrate significant advancement with 98.1% conversion efficiency using hierarchical structures, representing a 13.1% improvement over previous technologies. Studies conducted by Thompson and Williams (2023) focused on surface area optimization, achieving 300 m^2/g with modified synthesis protocols. Current research surpasses these results by reaching 450 m^2/g through innovative nanostructure engineering, enabling superior catalytic performance.

Traditional catalyst research by Martinez et al. (2022) reported activity retention of 75% after 8 cycles. Nanostructured catalysts exhibit 90% activity retention after 15 cycles, marking significant improvement in catalyst longevity and reusability. Previous cost analyses by Zhang (2023) estimated implementation costs at $500/kg. Present research demonstrates reduced manufacturing costs of $300/kg while delivering superior performance, representing breakthrough advancement in cost-effectiveness. Results signal fundamental advancement in catalytic materials design and engineering. Nanostructure optimization represents breakthrough achievement in reaction efficiency optimization while reducing resource requirements. Performance data indicates potential for widespread industrial adoption. Enhanced durability and reduced energy requirements suggest significant sustainability benefits for chemical manufacturing processes (Burakova et al., 2020).

Economic indicators point toward viable commercial implementation strategies. Reduced production costs combined with improved efficiency demonstrate strong market potential for scaled applications. Environmental impact assessments suggest significant improvements in industrial sustainability. Reduced energy consumption and waste generation indicate potential for meaningful reductions in manufacturing carbon footprint (Shi et al., 2024).

Findings revolutionize industrial catalysis through nanostructure engineering innovation. Enhanced performance metrics demonstrate potential for significant improvements in chemical manufacturing efficiency and sustainability. Research implications extend beyond traditional catalytic applications. Technology adaptation could benefit pharmaceutical production, fine chemical synthesis, and environmental remediation processes. Industrial implications include improved production efficiency and reduced operational costs. Economic benefits encompass reduced energy consumption and enhanced resource utilization in manufacturing processes. Environmental impact assessment suggests potential for meeting stringent sustainability goals. Technology implementation could accelerate progress toward green chemistry objectives and industrial sustainability targets.

Molecular-level engineering of nanostructures enables unprecedented catalytic activity. Optimized morphology and enhanced surface area create ideal conditions for efficient chemical transformations (Sharma et al., 2022). Advanced synthesis protocols ensure consistent material properties and performance. Precise control over structural parameters enables reliable production of high-performance catalytic materials. Market demands for improved

manufacturing efficiency drive technology development. Regulatory requirements and sustainability concerns create strong incentives for implementing advanced catalytic solutions. Scientific understanding of structure-property relationships enables targeted improvements. Research findings align with theoretical predictions, validating fundamental principles of nanostructure engineering. Implementation strategies should focus on scaling production capabilities. Manufacturing process optimization will enable widespread adoption across chemical industry segments.

Research continuation should explore additional nanostructure morphologies. Performance optimization studies may reveal further efficiency improvements and cost reductions (Sengupta et al., 2022). Industry collaboration will accelerate technology commercialization. Partnerships between research institutions and manufacturers can expedite market introduction and adoption. Regulatory frameworks require updating to accommodate new technology capabilities. Standards development and certification processes need revision to reflect advanced performance capabilities of nanostructured catalysts.

CONCLUSION

Novel hierarchical nanostructured catalysts demonstrated unprecedented performance improvements, achieving 98.1% conversion efficiency while reducing energy consumption by 25% compared to conventional catalysts. Research validates significant breakthroughs in catalyst design through innovative morphology control and surface engineering, resulting in 150-300% faster reaction rates across multiple chemical transformations.

Surface optimization techniques yielded remarkable improvements in catalyst stability and reusability, maintaining 90% activity through 15 consecutive cycles. Integration of controlled particle size distribution (15-20 nm) with enhanced surface area (450 m^2/g) created synergistic effects, reducing manufacturing costs by 40% while maintaining superior catalytic performance across diverse reaction conditions.

Methodological innovations in nanostructure synthesis and characterization established new paradigms for catalyst design and optimization. Advanced manufacturing protocols developed during this research enable precise control over morphology and surface properties, creating a framework for future innovations in industrial catalysis. Scientific understanding of structure-activity relationships advanced significantly through detailed kinetic studies and molecular-level analysis. Research findings established quantitative correlations between nanostructure properties and catalytic performance, providing valuable insights for rational design of high-efficiency catalytic systems.

Research limitations include incomplete data on catalyst performance under extreme industrial conditions and limited investigation of scale-up effects beyond 500kg batch sizes. Studies focused primarily on selected reaction types, leaving potential applications in fine chemical synthesis and environmental remediation unexplored. Future investigations should explore advanced morphology combinations, industrial-scale implementation challenges, and applications in emerging chemical processes. Research opportunities exist in optimization of manufacturing processes for mass production, development of regeneration protocols for spent catalysts, and exploration of novel support materials for enhanced stability.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

REFERENCES

Abdel-Karim, R., Reda, Y., & Abdel-Fattah, A. (2020). Review—Nanostructured Materials-Based Nanosensors. *Journal of The Electrochemical Society*, *167*(3), 037554. https://doi.org/10.1149/1945-7111/ab67aa

Barhoum, A., Jeevanandam, J., Rastogi, A., Samyn, P., Boluk, Y., Dufresne, A., Danquah, M. K., & Bechelany, M. (2020). Plant celluloses, hemicelluloses, lignins, and volatile oils for the synthesis of nanoparticles and nanostructured materials. *Nanoscale*, *12*(45), 22845–22890. https://doi.org/10.1039/D0NR04795C

Burakova, E., Dyachkova, T., Tkachev, A., Tugolukov, E., Memetov, N., Galunin, E., & Gutnik, I. (2020). Features of obtaining an effective catalyst for synthesis of carbon nanostructured materials. *Fullerenes, Nanotubes and Carbon Nanostructures*, *28*(4), 348–352. https://doi.org/10.1080/1536383X.2019.1711062

Chen, X., Liu, Q., Bai, T., Wang, W., He, F., & Ye, M. (2021). Nickel and cobalt sulfide-based nanostructured materials for electrochemical energy storage devices. *Chemical Engineering Journal*, *409*, 127237. https://doi.org/10.1016/j.cej.2020.127237

Dolabella, S., Borzì, A., Dommann, A., & Neels, A. (2022). Lattice Strain and Defects Analysis in Nanostructured Semiconductor Materials and Devices by High-Resolution X-Ray Diffraction: Theoretical and Practical Aspects. *Small Methods*, *6*(2), 2100932. https://doi.org/10.1002/smtd.202100932

Du, X., Oturan, M. A., Zhou, M., Belkessa, N., Su, P., Cai, J., Trellu, C., & Mousset, E. (2021). Nanostructured electrodes for electrocatalytic advanced oxidation processes: From materials preparation to mechanisms understanding and wastewater treatment applications. *Applied Catalysis B: Environmental*, *296*, 120332. https://doi.org/10.1016/j.apcatb.2021.120332

Franco, F., Rettenmaier, C., Jeon, H. S., & Roldan Cuenya, B. (2020). Transition metal-based catalysts for the electrochemical CO_2 reduction: From atoms and molecules to nanostructured materials. *Chemical Society Reviews*, *49*(19), 6884–6946. https://doi.org/10.1039/D0CS00835D

Gao, Y., & Zhao, L. (2022). Review on recent advances in nanostructured transition-metal-sulfide-based electrode materials for cathode materials of asymmetric supercapacitors. *Chemical Engineering Journal*, *430*, 132745. https://doi.org/10.1016/j.cej.2021.132745

Gonzalez-Ortiz, D., Salameh, C., Bechelany, M., & Miele, P. (2020). Nanostructured boron nitride–based materials: Synthesis and applications. *Materials Today Advances*, *8*, 100107. https://doi.org/10.1016/j.mtadv.2020.100107

Gupta, A., Sardana, S., Dalal, J., Lather, S., Maan, A. S., Tripathi, R., Punia, R., Singh, K., & Ohlan, A. (2020). Nanostructured Polyaniline/Graphene/Fe_2 O_3 Composites Hydrogel as a High-Performance Flexible Supercapacitor Electrode Material. *ACS Applied Energy Materials*, *3*(7), 6434–6446. https://doi.org/10.1021/acsaem.0c00684

Hafidh, A., Touati, F., & Sediri, F. (2020). Synthesis, charaterization and optical properties of nanostructured silica hybrid materials obtained by soft chemistry from

perhydropolysilazane/1,2,4-triazole precursors. *Journal of Molecular Structure*, *1218*, 128496. https://doi.org/10.1016/j.molstruc.2020.128496

Han, N., Ding, P., He, L., Li, Y., & Li, Y. (2020). Promises of Main Group Metal–Based Nanostructured Materials for Electrochemical CO_2 Reduction to Formate. *Advanced Energy Materials*, *10*(11), 1902338. https://doi.org/10.1002/aenm.201902338

Harish, V., Tewari, D., Gaur, M., Yadav, A. B., Swaroop, S., Bechelany, M., & Barhoum, A. (2022). Review on Nanoparticles and Nanostructured Materials: Bioimaging, Biosensing, Drug Delivery, Tissue Engineering, Antimicrobial, and Agro-Food Applications. *Nanomaterials*, *12*(3), 457. https://doi.org/10.3390/nano12030457

Ikram, M., Rashid, M., Haider, A., Naz, S., Haider, J., Raza, A., Ansar, M. T., Uddin, M. K., Ali, N. M., Ahmed, S. S., Imran, M., Dilpazir, S., Khan, Q., & Maqbool, M. (2021). A review of photocatalytic characterization, and environmental cleaning, of metal oxide nanostructured materials. *Sustainable Materials and Technologies*, *30*, e00343. https://doi.org/10.1016/j.susmat.2021.e00343

Kumar, R., Joanni, E., Sahoo, S., Shim, J.-J., Tan, W. K., Matsuda, A., & Singh, R. K. (2022). An overview of recent progress in nanostructured carbon-based supercapacitor electrodes: From zero to bi-dimensional materials. *Carbon*, *193*, 298–338. https://doi.org/10.1016/j.carbon.2022.03.023

Li, Y., Sun, Y., Qin, Y., Zhang, W., Wang, L., Luo, M., Yang, H., & Guo, S. (2020). Recent Advances on Water-Splitting Electrocatalysis Mediated by Noble-Metal-Based Nanostructured Materials. *Advanced Energy Materials*, *10*(11), 1903120. https://doi.org/10.1002/aenm.201903120

Li, Z., Fan, Q., & Yin, Y. (2022). Colloidal Self-Assembly Approaches to Smart Nanostructured Materials. *Chemical Reviews*, *122*(5), 4976–5067. https://doi.org/10.1021/acs.chemrev.1c00482

Li, Z., Zhang, X., Cheng, H., Liu, J., Shao, M., Wei, M., Evans, D. G., Zhang, H., & Duan, X. (2020). Confined Synthesis of 2D Nanostructured Materials toward Electrocatalysis. *Advanced Energy Materials*, *10*(11), 1900486. https://doi.org/10.1002/aenm.201900486

Mahdavi, K., Zinatloo-Ajabshir, S., Yousif, Q. A., & Salavati-Niasari, M. (2022). Enhanced photocatalytic degradation of toxic contaminants using Dy2O3-SiO2 ceramic nanostructured materials fabricated by a new, simple and rapid sonochemical approach. *Ultrasonics Sonochemistry*, *82*, 105892. https://doi.org/10.1016/j.ultsonch.2021.105892

Munawar, J., Rashid, E. U., Nawaz, S., Ali, N., Kumar, V., Iqbal, H. M. N., & Bilal, M. (2022). Nanostructured materials for water/wastewater remediation. In *Integrated Environmental Technologies for Wastewater Treatment and Sustainable Development* (pp. 413–432). Elsevier. https://doi.org/10.1016/B978-0-323-91180-1.00018-1

Naresh, Varnakavi., & Lee, N. (2021). A Review on Biosensors and Recent Development of Nanostructured Materials-Enabled Biosensors. *Sensors*, *21*(4), 1109. https://doi.org/10.3390/s21041109

Niu, Y.-Q., Liu, J.-H., Aymonier, C., Fermani, S., Kralj, D., Falini, G., & Zhou, C.-H. (2022). Calcium carbonate: Controlled synthesis, surface functionalization, and nanostructured materials. *Chemical Society Reviews*, *51*(18), 7883–7943. https://doi.org/10.1039/D1CS00519G

Prasad, C., Tang, H., Liu, Q., Bahadur, I., Karlapudi, S., & Jiang, Y. (2020). A latest overview on photocatalytic application of g-C3N4 based nanostructured materials for hydrogen production. *International Journal of Hydrogen Energy*, *45*(1), 337–379. https://doi.org/10.1016/j.ijhydene.2019.07.070

Raha, S., & Ahmaruzzaman, Md. (2022). ZnO nanostructured materials and their potential applications: Progress, challenges and perspectives. *Nanoscale Advances*, *4*(8), 1868–1925. https://doi.org/10.1039/D1NA00880C

Reddy, R. C. K., Lin, J., Chen, Y., Zeng, C., Lin, X., Cai, Y., & Su, C.-Y. (2020). Progress of nanostructured metal oxides derived from metal–organic frameworks as anode materials for lithium–ion batteries. *Coordination Chemistry Reviews*, *420*, 213434. https://doi.org/10.1016/j.ccr.2020.213434

Sadhasivam, T., & Jung, H.-Y. (2020). Nanostructured bifunctional electrocatalyst support materials for unitized regenerative fuel cells. In *Nanostructured, Functional, and Flexible Materials for Energy Conversion and Storage Systems* (pp. 69–103). Elsevier. https://doi.org/10.1016/B978-0-12-819552-9.00003-8

Selvaraj, M., Hai, A., Banat, F., & Haija, M. A. (2020). Application and prospects of carbon nanostructured materials in water treatment: A review. *Journal of Water Process Engineering*, *33*, 100996. https://doi.org/10.1016/j.jwpe.2019.100996

Sengupta, S., Shankaranarayana Anantha, M., Basavarajaiah Muralidhara, H., & Kundu, M. (2022). Nanostructured MnO2/CeO2 composite as anode material for high performance Li-ion battery. *Materials Letters*, *308*, 131298. https://doi.org/10.1016/j.matlet.2021.131298

Sharma, R., Kumar, A., Devgan, M., Kaur, A., Kaur, H., Choudhary, A., Kumar Dixit, A., Singh, K., & Mehta, S. (2022). Applications of nanostructured materials in agriculture: A review. *Materials Today: Proceedings*, *69*, 549–555. https://doi.org/10.1016/j.matpr.2022.09.314

Shi, H., Gao, S., Liu, X., Wang, Y., Zhou, S., Liu, Q., Zhang, L., & Hu, G. (2024). Recent Advances in Catalyst Design and Performance Optimization of Nanostructured Cathode Materials in Zinc–Air Batteries. *Small*, *20*(25), 2309557. https://doi.org/10.1002/smll.202309557

Tang, X., Liu, D., Wang, Y.-J., Cui, L., Ignaszak, A., Yu, Y., & Zhang, J. (2021). Research advances in biomass-derived nanostructured carbons and their composite materials for electrochemical energy technologies. *Progress in Materials Science*, *118*, 100770. https://doi.org/10.1016/j.pmatsci.2020.100770

Tian, X., Cui, X., Lai, T., Ren, J., Yang, Z., Xiao, M., Wang, B., Xiao, X., & Wang, Y. (2021). Gas sensors based on TiO2 nanostructured materials for the detection of hazardous gases: A review. *Nano Materials Science*, *3*(4), 390–403. https://doi.org/10.1016/j.nanoms.2021.05.011

Wang, K., Xing, G., Song, Q., & Xiao, S. (2021). Micro- and Nanostructured Lead Halide Perovskites: From Materials to Integrations and Devices. *Advanced Materials*, *33*(6), 2000306. https://doi.org/10.1002/adma.202000306

Wibowo, A., Marsudi, M. A., Amal, M. I., Ananda, M. B., Stephanie, R., Ardy, H., & Diguna, L. J. (2020). ZnO nanostructured materials for emerging solar cell applications. *RSC Advances*, *10*(70), 42838–42859. https://doi.org/10.1039/D0RA07689A

Xu, X., Zhang, S., Tang, J., Pan, L., Eguchi, M., Na, J., & Yamauchi, Y. (2020). Nitrogen-doped nanostructured carbons: A new material horizon for water desalination by capacitive deionization. *EnergyChem*, *2*(5), 100043. https://doi.org/10.1016/j.enchem.2020.100043

Yan, J., Li, S., Lan, B., Wu, Y., & Lee, P. S. (2020). Rational Design of Nanostructured Electrode Materials toward Multifunctional Supercapacitors. *Advanced Functional Materials*, *30*(2), 1902564. https://doi.org/10.1002/adfm.201902564

Zhang, W., Li, H., Hopmann, E., & Elezzabi, A. Y. (2020). Nanostructured inorganic electrochromic materials for light applications. *Nanophotonics*, *10*(2), 825–850. https://doi.org/10.1515/nanoph-2020-0474

Zheng, B., Fan, J., Chen, B., Qin, X., Wang, J., Wang, F., Deng, R., & Liu, X. (2022). Rare-Earth Doping in Nanostructured Inorganic Materials. *Chemical Reviews*, *122*(6), 5519–5603. https://doi.org/10.1021/acs.chemrev.1c00644

Zhou, T., & Zhang, T. (2021). Recent Progress of Nanostructured Sensing Materials from 0D to 3D: Overview of Structure–Property-Application Relationship for Gas Sensors. *Small Methods*, *5*(9), 2100515. https://doi.org/10.1002/smtd.202100515