

Engineering disorder in high-entropy metal oxides for advanced functional applications

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Abstract

High-entropy metal oxides (HEMOs) have emerged as a transformative class of multifunctional materials owing to their unique compositional complexity, tunable crystal structures, and remarkable physicochemical properties. Unlike conventional single-component or low-entropy oxides, HEMOs incorporate five or more metal cations in near-equimolar ratios, leading to high configurational entropy that stabilizes disordered solid-solution phases. This engineered disorder significantly influences electronic structure, defect chemistry, lattice distortion, ionic transport, and surface reactivity, thereby enabling superior performance in a wide range of advanced functional applications. Recent progress in synthesis strategies, including solid-state reactions, sol-gel processing, hydrothermal methods, spray pyrolysis, and mechanochemical approaches, has enabled precise control over morphology, phase stability, and elemental distribution in HEMOs. This review comprehensively discusses the principles of entropy stabilization and disorder engineering in high-entropy metal oxides, emphasizing the relationship between structural disorder and functional performance. Various characterization techniques used to investigate crystallographic, electronic, thermal, magnetic, and electrochemical properties are critically examined. Particular attention is given to the role of oxygen vacancies, cationic disorder, lattice strain, and multivalent states in enhancing catalytic activity, energy storage capability, ionic conductivity, magnetic behavior, and environmental remediation performance. The applications of HEMOs in electrocatalysis, photocatalysis, batteries, supercapacitors, solid oxide fuel cells, gas sensing, dielectric materials, and biomedical systems are systematically reviewed. Furthermore, current challenges associated with synthesis scalability, phase prediction, mechanistic understanding, and long-term stability are highlighted. Finally, future research directions focusing on computational design, machine learning-assisted material discovery, defect engineering, and sustainable synthesis routes are proposed to accelerate the practical implementation of HEMOs in next-generation technologies.

Keywords: high-entropy oxides, entropy engineering, defect chemistry, oxygen vacancy engineering, multivalent cations.

Engenharia da desordem em óxidos metálicos de alta entropia para aplicações funcionais avançadas

Resumo

Os óxidos metálicos de alta entropia (HEMOs, do inglês *High-Entropy Metal Oxides*) emergiram como uma classe

transformadora de materiais multifuncionais devido à sua singular complexidade composicional, estruturas cristalinas ajustáveis e notáveis propriedades físico-químicas. Diferentemente dos óxidos convencionais de componente único ou de baixa entropia, os HEMOs incorporam cinco ou mais cátions metálicos em proporções próximas às equimolares, resultando em elevada entropia configuracional que estabiliza fases de solução sólida desordenadas. Essa desordem projetada influencia significativamente a estrutura eletrônica, a química de defeitos, a distorção da rede cristalina, o transporte iônico e a reatividade superficial, possibilitando desempenho superior em uma ampla gama de aplicações funcionais avançadas. Avanços recentes nas estratégias de síntese, incluindo reações em estado sólido, processamento sol-gel, métodos hidrotérmicos, pirólise por spray e abordagens mecanoquímicas, têm permitido controle preciso da morfologia, estabilidade de fase e distribuição elementar nos HEMOs. Esta revisão discute de forma abrangente os princípios da estabilização entrópica e da engenharia da desordem em óxidos metálicos de alta entropia, enfatizando a relação entre a desordem estrutural e o desempenho funcional. Diversas técnicas de caracterização utilizadas para investigar propriedades cristalográficas, eletrônicas, térmicas, magnéticas e eletroquímicas são analisadas criticamente. É dada especial atenção ao papel das vacâncias de oxigênio, da desordem catiônica, da deformação da rede cristalina e dos estados multivalentes na melhoria da atividade catalítica, da capacidade de armazenamento de energia, da condutividade iônica, do comportamento magnético e do desempenho em remediação ambiental. As aplicações dos HEMOs em eletrocatalise, fotocatalise, baterias, supercapacitores, células a combustível de óxido sólido, sensores de gases, materiais dielétricos e sistemas biomédicos são revisadas de forma sistemática. Além disso, são destacados os desafios atuais relacionados à escalabilidade dos processos de síntese, à previsão de fases, à compreensão mecanística e à estabilidade a longo prazo. Por fim, são propostas direções futuras de pesquisa voltadas ao projeto computacional de materiais, à descoberta assistida por aprendizado de máquina, à engenharia de defeitos e ao desenvolvimento de rotas de síntese sustentáveis, com o objetivo de acelerar a implementação prática dos HEMOs em tecnologias de próxima geração.

Palavras-chave: óxidos de alta entropia, engenharia da entropia, química de defeitos, engenharia de vacâncias de oxigênio, cátions multivalentes.

1. Introduction

High-entropy metal oxides (HEMOs) have recently emerged as a transformative class of multifunctional materials owing to their unique compositional complexity, tunable crystal structures, and exceptional physicochemical properties (Islama et al., 2026; Khan et al., 2026). Unlike conventional metal oxides, which are generally composed of one or two principal metal cations, HEMOs typically contain five or more metallic elements in near-equimolar ratios. The high configurational entropy generated by this multicomponent arrangement stabilizes single-phase solid solutions and significantly influences the structural, electronic, and catalytic behavior of the materials (Haider et al., 2026). Since the pioneering concept of entropy stabilization was introduced in high-entropy alloys, researchers have extended this strategy to oxide systems to develop materials with enhanced thermal stability, defect tolerance, and functional diversity (Farooq et al., 2025).

The presence of multiple cations in HEMOs leads to severe lattice distortion, cationic disorder, oxygen vacancy formation, and modified electronic structures, which collectively contribute to improved electrochemical activity, catalytic efficiency, and optical performance (Jamila et al., 2025). These unique features make HEMOs promising candidates for a broad range of advanced applications, including energy storage devices, electrocatalysis, photocatalysis, gas sensing, environmental remediation, and biomedical technologies (Ahmad et al., 2025). In particular, the synergistic interactions among constituent elements often generate superior properties compared with conventional binary or ternary oxides. Recent studies have demonstrated the remarkable performance of HEMOs in lithium-ion batteries, supercapacitors, water splitting reactions, dye degradation, and pollutant removal systems (Zia et al., 2025).

Various synthesis approaches have been developed to fabricate HEMOs with controlled morphology, crystallinity, and defect structures. Conventional solid-state reactions, hydrothermal methods, solvothermal synthesis, sol-gel processing, combustion synthesis, and green synthesis techniques are commonly employed depending on the targeted application and desired material characteristics (Muhsim et al., 2025). Eco-friendly and sustainable synthesis routes have also gained considerable attention due to increasing environmental concerns and the need for low-cost fabrication methods. Green synthesis strategies previously explored for ZnO and other nanostructured metal oxides provide valuable insights for developing environmentally benign HEMO synthesis pathways (Jamila et al., 2025). Similarly, hydrothermal approaches have proven highly effective for tailoring nanoparticle morphology and enhancing photocatalytic activity in doped oxide systems (Khan et al., 2025).

Advanced characterization techniques play a critical role in understanding the structure-property relationships of

HEMOs. Techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), Raman spectroscopy, Brunauer–Emmett–Teller (BET) analysis, and electrochemical measurements are extensively utilized to evaluate crystallographic features, elemental distribution, surface chemistry, and functional performance (Bibi et al., 2024). Furthermore, computational approaches based on density functional theory (DFT) and machine learning have accelerated the prediction and optimization of HEMO compositions for targeted applications (Khan et al., 2025).

Despite the significant progress achieved in recent years, several challenges still hinder the large-scale commercialization and practical implementation of HEMOs. Difficulties associated with compositional control, phase purity, scalability, defect engineering, and long-term stability remain major research concerns (Ullah et al., 2025). Therefore, a comprehensive understanding of synthesis mechanisms, disorder engineering, and application-oriented design is essential for advancing this rapidly growing field.

This review comprehensively discusses the fundamentals, synthesis methods, characterization techniques, disorder engineering strategies, and functional applications of HEMOs. In addition, recent computational advances, current challenges, and future research perspectives are critically analyzed to provide a detailed understanding of the opportunities and limitations associated with these emerging materials.

2. Fundamentals of High-Entropy Metal Oxides

High-entropy metal oxides (HEMOs) have emerged as a novel class of multifunctional materials characterized by the incorporation of five or more metallic cations in near-equi-molar ratios within a single crystalline lattice (Ayub et al., 2024). Unlike conventional binary or ternary oxides, HEMOs exhibit exceptional compositional complexity, resulting in unique structural, electronic, thermal, and electrochemical properties (Gul et al., 2024). The fundamental behavior of these materials is primarily governed by entropy stabilization, lattice distortion, defect formation, and strong interactions among multiple constituent elements. These features collectively provide HEMOs with superior physicochemical performance and broad applicability in catalysis, energy storage, environmental remediation, sensing technologies, and biomedical systems (Syed et al., 2024).

The concept of entropy stabilization plays a critical role in the formation and stability of HEMOs. Thermodynamically, the stability of a material system is determined by Gibbs free energy. The materials, equipment, and methodologies used to develop the study must be systematically described. These aspects must be presented in such a way that other researchers who consult the article can reproduce it based solely on what was described in the article.

$$\Delta G = \Delta H - T\Delta S$$

where ΔG represents Gibbs free energy, ΔH denotes enthalpy, T is absolute temperature, and ΔS is entropy (Abdulaal et al., 2019). In multicomponent oxide systems, the presence of multiple cations significantly increases configurational entropy, thereby lowering Gibbs free energy and stabilizing single-phase solid solutions (Ahmad et al., 2018). The configurational entropy of mixing can be expressed as:

$$\Delta S_{config} = -R \sum_{i=1}^n x_i \ln x_i$$

where R is the universal gas constant and x_i represents the molar fraction of each component (Ahmad et al., 2017). In equimolar systems, the entropy reaches sufficiently high values to suppress phase segregation and promote structural stability even at elevated temperatures. This entropy-driven stabilization distinguishes HEMOs from conventional oxide systems and enables the development of metastable and compositionally tunable materials (Fouad et al., 2017).

The coexistence of multiple cations with varying ionic radii, oxidation states, and electronegativities introduces severe lattice distortion and structural disorder within the crystal lattice (Ahmad et al., 2015). Unlike ordered oxide structures, HEMOs possess randomly distributed cations that generate non-uniform local environments and significant strain effects. Such disorder strongly influences atomic diffusion, electron transport, phonon scattering, and surface reactivity (Ahmad et al., 2014). The atomic-scale structural complexity also promotes sluggish diffusion kinetics, which suppress grain growth and improve thermal stability under harsh operating conditions (Mohammad et al., 2010).

Defect formation is another important characteristic of HEMOs. Structural disorder often induces oxygen vacancies, cationic defects, and interstitial sites that significantly modify the functional properties of these materials (Ahmad et al., 2009). Oxygen vacancies are particularly beneficial because they enhance ionic conductivity, improve charge transfer, and provide active sites for catalytic reactions (Shah et al., 2025). Defect-rich HEMOs frequently exhibit enhanced photocatalytic and electrocatalytic performance due to improved adsorption behavior and accelerated redox kinetics. Furthermore, lattice distortion can alter bond lengths and crystal symmetry, leading to modifications in electronic structure and surface chemistry (Ahmad et al., 2023). Similar defect-assisted enhancements have been reported in doped oxide nanoparticles synthesized through hydrothermal and wet-chemical approaches for photocatalytic dye degradation applications (Ahmad; Ahmad, 2023).

The electronic and physicochemical properties of HEMOs are highly tunable because of synergistic interactions among constituent metal ions. The presence of multiple transition metals with variable oxidation states results in complex electronic band structures, enhanced redox activity, and improved charge carrier mobility (Ashraf et al., 2026). These features are advantageous for energy storage and catalytic systems where efficient electron transfer is essential. In lithium-ion batteries and supercapacitors, HEMOs demonstrate high specific capacity, excellent cycling stability, and superior conductivity compared with traditional oxides (Noureen et al., 2025). Likewise, in electrocatalytic applications such as oxygen evolution reaction (OER), hydrogen evolution reaction (HER), and oxygen reduction reaction (ORR), the presence of multiple active sites enhances catalytic efficiency and reaction kinetics (Amina et al., 2025).

HEMOs also exhibit remarkable optical and surface properties, including tunable band gaps, enhanced visible-light absorption, and reduced recombination of photogenerated electron-hole pairs (Ahmad, 2025). These characteristics significantly improve photocatalytic degradation of organic pollutants and dyes. Previous studies on Fe-doped CuO nanoparticles and Co-doped Bi₂O₃ nanostructures have demonstrated that compositional engineering and defect modulation can substantially enhance photocatalytic efficiency and electrical performance (Alsaiani et al., 2023; Aziz et al., 2023). Additionally, environmentally friendly synthesis approaches developed for ZnO nanoparticles provide valuable strategies for sustainable preparation of advanced multicomponent oxide systems (Janeen et al., 2023).

Apart from catalytic and electrochemical applications, HEMOs possess excellent thermal stability, corrosion resistance, hardness, and chemical durability due to entropy-induced phase stabilization and lattice strain effects (Aal; Ahmad, 2022). Their multifunctional behavior has further expanded their potential use in biomedical applications, including antimicrobial coatings, biosensors, bioimaging, and drug delivery systems. The successful biomedical utilization of TiO₂-based nanomaterials demonstrates the growing importance of metal oxide systems in healthcare technologies (Ahmad et al., 2021). Overall, the unique combination of entropy stabilization, structural disorder, defect engineering, and electronic tunability makes HEMOs highly promising materials for next-generation technological applications. Continued research into their structure-property relationships is expected to further accelerate the design of high-performance multifunctional oxide materials (Ahmad et al., 2018).

3. Synthesis Methods

The synthesis strategy plays a critical role in determining the structural stability, compositional homogeneity, morphology, defect concentration, and functional performance of high-entropy metal oxides (HEMOs) (Ahma; Fouad, 2017). Owing to the multicomponent nature of these materials, achieving uniform elemental distribution and phase purity remains one of the major challenges during synthesis. Various conventional and advanced fabrication techniques have therefore been developed to produce HEMOs with controlled crystallinity, particle size, porosity, and defect structures suitable for targeted applications (Ahmad et al., 2013). The choice of synthesis method significantly influences the physicochemical and electrochemical behavior of HEMOs because parameters such as temperature, precursor chemistry, reaction medium, and calcination conditions directly affect entropy stabilization and lattice formation (Bashir et al., 2023).

Among the commonly employed techniques, solid-state synthesis remains one of the most traditional and widely used approaches for preparing HEMOs (Ishraque et al., 2026). In this method, metal oxide or metal salt precursors are mixed in stoichiometric ratios followed by high-temperature calcination to promote diffusion and phase formation. Solid-state reactions are particularly advantageous for producing thermodynamically stable bulk HEMOs with high crystallinity and structural stability (Hasan et al., 2026). However, the requirement of elevated temperatures and prolonged reaction times often results in particle agglomeration, limited surface area, and non-uniform elemental distribution (Suleman et al., 2025). Despite these limitations, solid-state methods remain

effective for large-scale industrial production due to their simplicity and cost-effectiveness.

Wet-chemical synthesis approaches have gained considerable attention because they offer better control over morphology, composition, and particle size (Arshad et al., 2025). Techniques such as sol–gel processing, co-precipitation, combustion synthesis, and Pechini methods enable homogeneous mixing of multiple metal ions at the molecular level, thereby improving compositional uniformity and entropy-driven phase stabilization (Jan et al., 2025). In sol–gel synthesis, metal precursors undergo hydrolysis and condensation reactions to form interconnected gel networks that subsequently transform into oxide structures after calcination (Tanweer et al., 2025). This method provides excellent control over nanoscale morphology and porosity, making it highly suitable for catalytic and electrochemical applications (Fahim et al., 2025). Co-precipitation methods are also extensively utilized due to their simplicity, low processing temperature, and ability to produce fine nanoparticles with high surface area (Hasana et al., 2025).

Hydrothermal and solvothermal synthesis techniques are particularly important for preparing nanostructured HEMOs with controlled crystal growth and enhanced defect engineering (Hasan et al., 2025a). These methods involve chemical reactions in sealed autoclaves under high temperature and pressure conditions, enabling the formation of highly crystalline materials with tunable morphology (Hasan et al., 2025b). Hydrothermal synthesis has demonstrated remarkable effectiveness in producing defect-rich oxide nanostructures with improved photocatalytic and electrochemical performance (Jamil et al., 2025). Previous investigations on Co-doped Bi₂O₃ nanoparticles synthesized through hydrothermal methods revealed enhanced photocatalytic degradation efficiency due to improved crystallinity, defect formation, and surface activity (Hussain et al., 2023). Similarly, solvothermal approaches employing organic solvents provide additional control over nucleation kinetics, particle dispersion, and surface modification (Ihsanullah et al., 2015).

Combustion synthesis has also emerged as a rapid and energy-efficient route for preparing HEMOs (Khan et al., 2014a). In this process, exothermic redox reactions between metal nitrates and organic fuels generate high localized temperatures that facilitate rapid oxide formation. Combustion methods often produce porous and nanocrystalline materials with enhanced surface area, which are beneficial for catalytic and sensing applications. Nevertheless, difficulties associated with temperature control and phase purity may affect compositional uniformity in multicomponent systems (Khan et al., 2014b).

Recently, green and sustainable synthesis approaches have attracted growing interest due to increasing environmental concerns and the demand for eco-friendly fabrication techniques. Biological extracts derived from plants, microorganisms, and natural polymers are increasingly employed as reducing, stabilizing, and capping agents during nanoparticle synthesis. These environmentally benign approaches minimize the use of toxic chemicals and reduce energy consumption while enabling the formation of stable nanostructures with controlled morphology (Maatki et al., 2025). Green synthesis strategies previously developed for ZnO nanoparticles using plant extracts demonstrated excellent biocompatibility, enhanced photocatalytic efficiency, and reduced environmental impact, providing valuable guidance for sustainable HEMO fabrication. The integration of green chemistry principles into HEMO synthesis is therefore expected to support the development of cost-effective and environmentally sustainable multifunctional materials (Syed et al., 2024).

In addition to experimental techniques, emerging synthesis approaches such as microwave-assisted synthesis, spray pyrolysis, flame synthesis, and electrospinning have further expanded the fabrication possibilities for HEMOs (Hussain et al., 2025a). Microwave-assisted methods offer rapid heating and reduced reaction times, whereas electrospinning enables the production of one-dimensional nanofibers with high surface area and enhanced charge transport properties (Hussain et al., 2025b). Spray pyrolysis and flame-based methods are advantageous for continuous and scalable production of multicomponent oxide powders (Muhammad et al., 2026). These advanced synthesis strategies provide opportunities for tailoring HEMO architectures according to specific functional requirements.

Overall, the synthesis method strongly determines the structural and functional characteristics of HEMOs. Careful optimization of reaction conditions, precursor selection, and post-treatment processes is essential for achieving phase stability, compositional uniformity, and desirable defect structures. Future research should focus on scalable, low-cost, and environmentally sustainable synthesis routes capable of producing highly efficient HEMOs for energy, catalytic, environmental, and biomedical applications.

Table 1. Comparison of major synthesis methods used for HEMOs

Synthesis Method	Major Advantages	Limitations	Typical Applications	References
Solid-state method	Simple, cost-effective, high crystallinity	High temperature, particle agglomeration	Bulk ceramics, structural materials	Gul et al. (2025)
Sol-gel method	Excellent compositional control, nanoscale morphology	Multi-step processing	Catalysis, energy storage	Amir et al. (2025)
Co-precipitation	Low cost, uniform particle formation	Possible impurity formation	Electrochemical materials	Shaw et al. (2021)
Hydrothermal synthesis	Controlled crystal growth, high purity	Long reaction time	Photocatalysis, sensors	Hanabata et al. (2023)
Solvothermal synthesis	Tunable morphology and surface properties	Use of organic solvents	Advanced nanostructures	Wang et al. (2023)
Combustion synthesis	Rapid synthesis, porous materials	Difficult temperature control	Catalysis, gas sensing	Yavas; Turan (2026)
Green synthesis	Eco-friendly, sustainable, low toxicity	Limited scalability	Biomedical and environmental applications	Santos et al. (2024)
Microwave-assisted synthesis	Rapid heating, short processing time	Specialized equipment required	Nanomaterials and composites	Kheradmandfard et al. (2021)

Source: Authors, 2026.

4. Disorder Engineering in HEMOs

Disorder engineering has emerged as one of the most important strategies for tailoring the structural, electronic, catalytic, and electrochemical properties of high-entropy metal oxides (HEMOs). Unlike conventional oxide systems, HEMOs inherently possess significant configurational disorder due to the random distribution of multiple cations within a single lattice. This atomic-scale complexity generates lattice distortion, defect formation, oxygen vacancies, and electronic heterogeneity, all of which substantially influence the functional behavior of these materials. Controlled manipulation of such disorder provides opportunities for optimizing charge transport, catalytic activity, ionic conductivity, and surface reactivity (Meisenheimer et al., 2020).

Cationic disorder is considered a defining characteristic of HEMOs and plays a crucial role in entropy stabilization and physicochemical performance. The coexistence of multiple metallic ions with different ionic radii and oxidation states produces non-uniform local atomic environments and severe lattice strain. These structural

distortions can alter electronic band structures and surface adsorption behavior, thereby improving catalytic efficiency and electrochemical activity. Furthermore, cationic disorder suppresses long-range atomic ordering and promotes sluggish diffusion kinetics, resulting in enhanced thermal stability and resistance to phase segregation (Jiang et al., 2020).

Oxygen vacancies represent another important aspect of disorder engineering in HEMOs. The presence of oxygen-deficient sites modifies the local electronic structure and creates active centers that facilitate catalytic and electrochemical reactions. Oxygen vacancies improve charge carrier mobility, accelerate ion diffusion, and enhance adsorption of reactant molecules on the material surface. In photocatalytic systems, vacancy-rich HEMOs exhibit improved visible-light absorption and reduced electron-hole recombination rates, leading to enhanced degradation of organic pollutants. Similar effects have been reported in doped oxide nanostructures synthesized for photocatalytic dye degradation and environmental remediation applications (Gu et al., 2022).

Lattice distortion induced by atomic size mismatch among constituent elements further contributes to the multifunctionality of HEMOs. Distorted crystal lattices modify bond lengths and crystal symmetry, thereby influencing phonon transport, electrical conductivity, and redox activity. Defect engineering through controlled annealing, elemental substitution, and compositional tuning has therefore become an effective approach for enhancing HEMO performance in energy storage, electrocatalysis, and sensing technologies. The combination of entropy stabilization and defect modulation enables the development of highly robust multifunctional materials suitable for advanced technological applications (Pitchai et al., 2026).

5. Functional Applications

The exceptional structural and electronic characteristics of HEMOs have enabled their utilization in a wide range of advanced applications. Their high configurational entropy, tunable defect chemistry, and compositional flexibility provide superior catalytic, electrochemical, optical, and thermal properties compared with traditional oxide systems. Consequently, HEMOs have attracted significant attention in energy storage, catalysis, environmental remediation, sensing technologies, and biomedical engineering (Pasupathi et al., 2024).

In energy storage systems, HEMOs have demonstrated remarkable performance as electrode materials for lithium-ion batteries, sodium-ion batteries, and supercapacitors. The presence of multiple transition metals enhances redox activity and charge storage capacity, while entropy stabilization improves structural durability during repeated cycling. Defect-rich HEMOs also exhibit enhanced electrical conductivity and ion diffusion kinetics, leading to improved electrochemical performance. Their excellent cycling stability and high specific capacity make them promising alternatives to conventional electrode materials (Bao et al., 2024).

Catalysis and photocatalysis represent some of the most extensively explored applications of HEMOs. The coexistence of multiple active sites and oxygen vacancies significantly enhances catalytic reaction kinetics and surface adsorption behavior. HEMOs have been successfully applied in oxygen evolution reactions (OER), hydrogen evolution reactions (HER), oxygen reduction reactions (ORR), and water-splitting systems. In photocatalytic applications, HEMOs exhibit improved visible-light absorption and efficient charge separation, enabling rapid degradation of organic pollutants and dyes. Previous investigations on Fe-doped CuO nanoparticles and Co-doped Bi₂O₃ nanostructures demonstrated that compositional engineering and defect modulation can substantially improve photocatalytic efficiency and electrical properties (Tsubota et al., 2025).

Environmental remediation is another important application area for HEMOs. Their high surface area, tunable porosity, and defect-rich surfaces facilitate adsorption and degradation of toxic pollutants, heavy metals, and industrial dyes. HEMOs have shown excellent potential for wastewater treatment, air purification, and photocatalytic removal of hazardous organic contaminants. The enhanced catalytic activity associated with oxygen vacancies and lattice distortion further improves pollutant degradation efficiency under visible-light irradiation (Das et al., 2024).

HEMOs have also demonstrated considerable potential in sensing and electronic devices. Their tunable conductivity, defect chemistry, and large surface-to-volume ratio make them suitable for gas sensors, biosensors, humidity sensors, and electronic components. The presence of multiple cations enhances sensitivity and selectivity toward various analytes, while lattice disorder improves charge transfer processes. In addition, the thermal stability and corrosion resistance of HEMOs enable their operation under harsh environmental conditions (Naganaboina et al., 2022).

The biomedical potential of HEMOs has recently gained increasing research attention. Metal oxide nanomaterials are widely investigated for antimicrobial coatings, drug delivery systems, biosensing, and bioimaging applications.

The successful biomedical utilization of TiO₂ nanoparticles has demonstrated the importance of oxide-based nanomaterials in healthcare technologies. Furthermore, green synthesis strategies previously employed for ZnO nanoparticles provide environmentally sustainable pathways for developing biocompatible HEMOs with reduced toxicity and enhanced therapeutic efficiency (Chang et al., 2024).

6. Challenges and Future Perspectives

Despite the significant progress achieved in recent years, several challenges continue to limit the practical implementation and commercialization of HEMOs. One of the major difficulties is achieving precise compositional control and phase purity during synthesis. Because HEMOs contain multiple metallic elements with different chemical behaviors, maintaining homogeneous elemental distribution and preventing phase segregation remain challenging tasks. High-temperature processing may also lead to particle agglomeration and uncontrolled defect formation, which can adversely affect material performance.

Another critical challenge involves understanding the complex structure–property relationships in HEMOs. The simultaneous presence of lattice distortion, cationic disorder, oxygen vacancies, and multiple oxidation states generates highly complicated atomic and electronic interactions that are difficult to characterize experimentally. Advanced characterization techniques combined with computational modeling are therefore necessary to understand defect chemistry, charge transport mechanisms, and catalytic behavior in these systems.

Scalability and cost-effective manufacturing also remain important concerns for industrial applications. Many synthesis methods currently used for HEMOs involve expensive precursors, high energy consumption, or complex processing conditions. Developing low-cost, environmentally friendly, and scalable synthesis routes is therefore essential for commercial viability. Green synthesis approaches using biological extracts and sustainable processing methods may offer promising alternatives for future large-scale production.

Future research should focus on rational compositional design, defect engineering, and computational prediction of HEMO properties. The integration of machine learning, density functional theory (DFT), and high-throughput screening techniques can accelerate the discovery of optimized HEMO compositions for specific applications. Furthermore, the development of multifunctional HEMOs with combined catalytic, electronic, magnetic, and biomedical properties may open new opportunities in emerging technologies. Continued efforts toward sustainable synthesis, advanced characterization, and application-oriented design are expected to advance the field of high-entropy oxide materials significantly.

6. Conclusions

High-entropy metal oxides have emerged as an important class of advanced multifunctional materials due to their unique configurational entropy, structural disorder, and tunable physicochemical properties. The incorporation of multiple metallic cations within a single-phase lattice produces entropy stabilization, lattice distortion, oxygen vacancies, and synergistic electronic interactions that collectively enhance catalytic, electrochemical, optical, and thermal performance. Various synthesis strategies, including solid-state, wet-chemical, hydrothermal, solvothermal, combustion, and green synthesis methods, have been successfully employed to fabricate HEMOs with controlled morphology and defect structures.

The exceptional multifunctionality of HEMOs has enabled their application in energy storage systems, electrocatalysis, photocatalysis, environmental remediation, sensing technologies, and biomedical engineering. In particular, defect engineering and compositional tuning have proven highly effective for improving catalytic efficiency, conductivity, charge transfer, and pollutant degradation performance. Nevertheless, challenges associated with phase stability, compositional control, scalability, and mechanistic understanding still require further investigation.

Future advancements in HEMO research are expected to rely on sustainable synthesis approaches, advanced computational modeling, and precise defect engineering strategies. The integration of experimental and theoretical methodologies will facilitate the rational design of next-generation HEMOs with tailored functionalities for emerging technological applications. Overall, the remarkable versatility and tunability of HEMOs position them as highly promising materials for future developments in energy, environmental, electronic, and biomedical fields.

7. Authors' Contributions

Hao Sun: conceptualized and supervised the study. *Misbah Gul*: contributed to literature review, data collection,

and manuscript drafting. *Sakina*: assisted in the preparation of sections related to synthesis strategies and applications. *Ali Khan*: contributed to disorder engineering analysis and figure preparation. *Zainab Liaqat*: participated in manuscript writing and reference management. *Seeqal Aleena*: assisted in data interpretation and formatting of the manuscript. *Aqsa Ali*: contributed to proofreading, editing, and final revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

Not applicable.

10. References

- Aal, A., & Ahmad, N. (2022). A study of the impact of iron content on the thermal response of the sPP/Fe composites. *Engineering, Technology & Applied Science Research*, 12(3), 8555-8558. <https://doi.org/10.48084/etasr.4884>
- Ahmad, M., Rasool, S., Khitab, F., Ahmad, N., Ahmad, F., Khan, A. S., & Jamila, N. (2025). Nickel-impregnated ZnO catalysts: A promising catalyst for efficient methylene blue dye degradation via photocatalysis and sonocatalysis. *Journal of Environmental Science and Pollution Research*, 32, 23054-23067.
- Ahmad, F., Ahmad, N., Al-Khazaal, A. Z., & Alenezi, I. (2018). Remediation of sulfidic wastewater by aeration in the presence of ultrasonic vibration. *Engineering, Technology & Applied Science Research*, 4(8), 2919-2922.
- Ahmad, F., Maitra, S., & Ahmad, N. (2017). Treatment of sulfidic wastewater using iron salts. *Arabian Journal of Science and Engineering*, 42, 1455-1462. <https://doi.org/10.1007/s13369-016-2315-z>
- Ahmad, N., Ahmad, F., Khan, I., & Khan, A. D. (2015). Studies on the oxidative removal of sodium thiosulfate from aqueous solution. *Arabian Journal of Science and Engineering*, 40, 289-293. <https://doi.org/10.1007/s13369-014-1473-0>
- Ahmad, F., Fouad, E., & Ahmad, N. (2014). Removal of lead from wastewater by adsorption using Saudi Arabian clay. *International Journal of Chemical and Environmental Engineering*, 5(2), 65-68.
- Ahmad, N., Maitra, S., Dutta, B. K., & Ahmad, F. (2009). Remediation of sulfidic wastewater by catalytic oxidation using hydrogen peroxide. *Journal of Environmental Sciences*, 21(12), 1735-1740. [https://doi.org/10.1016/S1001-0742\(08\)62481-X](https://doi.org/10.1016/S1001-0742(08)62481-X)
- Ahmad, F., Ahmad, N., Al-Khazaal, A. A. Z. (2024). Machine learning-assisted prediction and optimization of exergy efficiency and destruction of cumene plant under uncertainty. *Engineering Technology & Applied Science Research*, 14(1), 12892-12899. <https://doi.org/10.48084/etasr.6654>
- Ahmad, N., & Ahmad, F. (2023). The effect of iron content on the thermodynamic properties of syndiotactic polypropylene/iron composites. *Engineering, Technology & Applied Science Research*, 13(5), 11785-11788. <https://doi.org/10.48084/etasr.6241>
- Ahmad, N. (2025). Effect of iron loading on quiescent crystallization of syndiotactic polypropylene/iron composites. *Engineering Technology & Applied Science Research*, 15(1), 20185-20189. <https://doi.org/10.48084/etasr.9421>
- Ahmad, N., Ahmad, F., & Alenezi, I. (2021). Influence of starch content on thermal and rheological properties of syndiotactic polypropylene/starch composites. *Engineering, Technology & Applied Science Research*, 11(3), 7228-7232. <https://doi.org/10.48084/etasr.4161>
- Ahmad, N., Fouad, E., & Ahmad, F. (2018). Effect of shear flow on crystallization of syndiotactic polypropylene/clay composites. *Engineering, Technology & Applied Science Research*, 8(4), 3108-3112.
- Ahmad, N., & Fouad, E. (2017). Influence of clay contents on rheology of syndiotactic polypropylene/clay composites. *Arabian Journal of Science and Engineering*, 42, 1537-1543. <https://doi.org/10.1007/s13369-016-2389-7>
- Ahmad, N., Di Girolamo, R., Auriemma, F., De Rosa, C., & Grizzuti, N. (2013). Relations between stereoregularity

- and melt viscoelasticity of syndiotactic polypropylene. *Macromolecules*, 46(19), 7940-7946. <https://doi.org/10.1021/ma401469a>
- Al-Khazaal, A. Z., Ahmad, F., & Ahmad, N. (2019). Laboratory scale studies on removal of thiosulfate from wastewater by catalytic oxidation. *Technology & Applied Science Research*, 9(2), 4053-4056.
- Alsaiani, M., Roghani, K., Liaqat, S., Alkorbi, A. S., Sharif, F., Irfan, M., Rizk, M. A., Uroos, M., Ahmad, N., & Muhammad, N. (2023). Effect of ionic liquids on mechanical, physical, and antifungal properties and biocompatibility of a soft denture lining material. *ACS Omega*, 8(30), 27300-27311. <https://doi.org/10.1021/acsomega.3c02677>
- Amina, K. H., Alrefae, S. H., Elhadi, M., Abduvalieva, D., Abiyev, A. S., Akhter, N., Ahmad, N., Tirth, V., Algahtani, A., Hadia, N. M. A., & Zaman, A. (2025). First-principles investigation of structural, electronic, mechanical and optical properties of tl based semiconducting perovskites TlVX3 (X = Br, I) for reflective coating applications. *Journal of Inorganic and Organometallic Polymers and Materials*, 35, 6479-6490. <https://doi.org/10.1007/s10904-025-03670-2>
- Amir, J., Muhammad, S., Kashif, M., Khan, A. A., Gul, M., Sun, H., Shah, M., Azizi, S., & Maaza, M. (2025). Synthesis, characterization and dielectric properties evaluation of NiO-Co₃O₄ nanocomposite. *Journal of the Iranian Chemical Society* 22, 63-72. <https://doi.org/10.1007/s13738-024-03129-0>
- Arshad, S. A., Ali, U. N., Taqvi, S. A. A., Kazmi, B., Khalid, A., Ahmer, M., Ahmad, F., & Ahmad, N. (2025). Towards sustainable methanol production: energy, exergy, economics, and environmental evaluation of Thar coal gasification. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-025-06451-6>
- Ashraf, L., Waseem, S., Khalil, M., Ahmad, N., Ahmad, P., Kebaili, I., & Saleem, M. (2026). Brief investigations on Cu_xTa_{2-x}O₅ for thermoelectric and optical response using density functional and experimental techniques. *CPB - Chinese Physics B*, 35(2), 027801. <https://doi.org/10.1088/1674-1056/adee89>
- Ayub, Z., Liaqat, S., Alamoudi, A. J., Alshamrani, M., Rizg, W. Y., Shaik, R. A., Ahmad, N., Feroz, S., & Muhammad, N. (2024). Effect of nystatin coated copper oxide (CuO) particles on mechanical, thermal, and antifungal properties of polymethyl methacrylate (PMMA)-based denture materials. *Advances in Materials Science and Engineering*. <https://doi.org/10.1155/2024/5530338>
- Aziz, S., Javed, R., Nowak, A., Liaqat, S., Khan, Z. U. H., Ahmad, N., Dulski, M., Matus, K., Ahmad, P., & Muhammad, N. (2023). Effects of TiO₂, Ag-TiO₂, and Cu-TiO₂ nanoparticles on mechanical and anticariogenic properties of conventional pit and fissure sealants. *Open Nano*, 14(3), 100185. <https://doi.org/10.1016/j.onano.2023.100185>
- Bao, W., Shen, H., Zhang, Y., Qian, C., Zeng, G., Jing, K., Cui, D., Xia, J., Liu, H., Guo, C., Yu, F., Sun, K., & Li, J. (2024). High-entropy oxides for energy storage and conversion. *Journal of Materials Chemistry A*, 12(35), 23179-23201. <https://doi.org/10.1039/D4TA04156A>
- Bashir, F., Muhammad, N., Alshamrani, M., Uroos, M., Salawi, A., Safhi, Y. A., Alsalhi, N. A. A., Sabei, F. Y., & Madkhali, O. A. (2023). Synthesis and characterization of cosmetic grade ionic liquids and their application as skin whitening agents. *Journal of Pharmaceutical Innovation*, 18, 2277-2286. <https://doi.org/10.1007/s12247-023-09790-x>
- Bibi, A., Zaman, M. I., Niaz, A., Bibi, S., Gul, S., Ahmad, N., & Osman, H. E. (2024). Kinetics of silver ion encapsulation as nanoparticles using Vaccinium oxycoccos plant extract for the efficient sensing of Cr(III) ions and its biological assessment. *Chemical Engineering Journal*. <https://doi.org/10.1016/j.cej.2024.158185>
- Chang, L., Jing, H., Liu, C., Qiu, C., & Ling, X. (2024). High-entropy materials for prospective biomedical applications: challenges and opportunities. *Advanced Science*, 11(42), 2406521. <https://doi.org/10.1002/advs.202406521>
- Das, S., Chowdhury, S., & Tiwary, C. S. (2024). High-entropy-based nano-materials for sustainable environmental applications. *Nanoscale*, 16(17), 8256-8272. <https://doi.org/10.1039/D4NR00474D>
- Fahim, K. E., De Silva, L. C., Shezan, S. A., Islam, M. A., Hassan, M. S., Yassin, H., & Ahmad, N. (2025). Techno-economic feasibility analysis of grid-connected hybrid PV power system in Brunei. *Journal of Energy Engineering*, 122(10), 3985-3997. <http://dx.doi.org/10.32604/ee.2025.066484>
- Fouad, E., Ahmad, F., & Ahmad, N. (2017). Optimization of chromium extraction from aqueous solutions by emulsion liquid membrane. *Desalination and Water Treatment*, 65, 428-434.

<https://doi.org/10.5004/dwt.2017.20287>

- Farooq, A., Zafar, F., Hassan, S. U., Nazir, M. S., Ali, Z., Ahmad, N., & Ahmad, F. (2025). Rational design of metal-organic framework hybrids via metal and ligand engineering for enhanced oxygen evolution reaction catalysis. *Energy & Fuels*, 39(50), 23796-23804. <https://doi.org/10.1021/acs.energyfuels.5c04018>
- Gu, Y., Bao, A., Wang, X., Chen, Y., Dong, L., Liu, X., Pan, H., Li, Y., & Qi, X. (2022). Engineering the oxygen vacancies of rocksalt-type high-entropy oxides for enhanced electrocatalysis. *Nanoscale*, 14(2), 515-524.
- Gul, S., Khan, M. A., Liaqat, S., Ahmad, N., & Muhammad, N. (2024). Assessment of chlorohexidine-coated cotton filler addition on resin-based fissure sealants' mechanical, water sorption, and antibacterial properties. *European Journal of Materials*, 4(1), 2336225. <https://doi.org/10.1080/26889277.2024.2336225>
- Gul, M., Kashif, M., Muhammad, S., Azizi, S., & Sun, H. (2025). Various methods of synthesis and applications of gold-based nanomaterials: A detailed review. *Crystal Growth & Design*, 25(7), 2227-2266. <https://doi.org/10.1021/acs.cgd.4c01687>
- Haider, W., Ullah, Q., Amir, M. A., Ahmad, N., Farid, M., Rahman, A., & Shezan, S. A. (2026a). Heterojunction-driven photo-oxidation for pathogen and dye synergistic degradation in decentralized wastewater systems. *Environmental Science: Water Research & Technology*, 6. <https://doi.org/10.1039/D6EW00043F>
- Hanabata, S., Kusada, K., Yamamoto, T., Toriyama, T., Matsumura, S., Kawaguchi, S., Kubota, Y., Nishida, Y., Haneda, M., & Kitagawa, H. (2023). Denary high-entropy oxide nanoparticles synthesized by a continuous supercritical hydrothermal flow process. *Journal of the American Chemical Society*, 146(1), 181-186. <https://doi.org/10.1021/jacs.3c07351>
- Hasan, M. N., Ishraque, M. F., Shezan, S. A., Kamwa, I., Ahmad, K., Alrwaili, A., Alruwaili, M., Amin, N., Ahmad, N. (2026). Hydrogen and fuel cells as the cornerstones of the universal energy transfer – A comprehensive review. *International Journal of Hydrogen Energy*, 209, 153486. <https://doi.org/10.1016/j.ijhydene.2026.153486>
- Hasan, M. N., Ishraque, M. F., Ahmed, M. S., Imam, F. T., Shezan, S. A., & Ahmad, N. (2025). An innovative method for enhanced energy management in hybrid power systems: Dual predator optimization (DPO). *Arabian Journal for Science and Engineering*, 51, 7269-7292. <https://doi.org/10.1007/s13369-025-10254-2>
- Hasan, M. N., Rahman, M. A., Ishraque, M. F., Ahmad, K., Shezan, S. A., Ahmed, M. S., Ahmad, N., & Ahmad, F. (2025). An improved energy management strategy for hybrid power systems using dual predator optimization. *Journal of Sustainable Development of Energy, Water and Environment Systems*, 13(5), 1130586. <https://doi.org/10.13044/j.sdewes.d13.0586>
- Hasana, M. N., Ishraque, M. F., Shezan, S. A., Kamwa, I., & Ahmad, N. (2025). Novel twin fang algorithm for advanced optimization of energy coordination in hybrid power systems. *Engineering Science and Technology, an International Journal*, 70, 102165. <https://doi.org/10.1016/j.jestch.2025.102165>
- Hussain, S., Khan, A. D., Rashid, M., Ahmad, N., & Khan, H. A. (2023). Design and numerical characterization of high-performance all-perovskite multi-junction solar cells. *Optiks*, 277, 170714. <https://doi.org/10.1016/j.ijleo.2023.170714>
- Hussain, T., Kamran, M. F., Popa, I-L., Ahmad, N., Alshammari, H. O., Jamel, L., & Mahariq, I. (2025). Exact solutions of einstein's field equations via homothetic symmetries of non-static plane symmetric space time. *Open Physics*, 23(1). <https://doi.org/10.1515/phys-2025-0238>
- Ihsanullah, S. S., Ayaz, M., Ahmad, I., Ali, M., Atieh, M. A., Ahmad, I., Ahmad, N. (2015). Collection and utilization of potential spirogyra algal specie for biodiesel production in Khyber Pakhtunkhwa, Pakistan. *Journal of Pure and Applied Microbiology*, 9, 79-85.
- Ishraque, M. D., Shezan, S. A., Kamwa, I., Li, Y., Shafiullah, G. M., Ahmad, N., Ahmad, F. (2026). Novel intelligent model following controller and PQ droop controller operated nuclear-PV-biogas hybrid microgrid and EV charging station. *Computers and Electrical Engineering*, 129(Part A), 110756. <https://doi.org/10.1016/j.compeleceng.2025.110756>
- Kashif, M., Sharif, T., Khan, S., Shahzad, N., Amir, J., Gul, M., Shahid, K., Qarni, A., Shah, A., Matinise, N. (2026). Synthesis strategies and multifaceted applications of molybdenum - based nanomaterials: A comprehensive review. *Scientifica*, 1. <https://doi.org/10.1155/sci5/1764400>
- Khan, S., Rahman, S. U., Shah, A., Akhtar, N., Hussain, Z., Ahmad, N., Kamika, I., Azizi, S., & Maaza, M. (2026). MXene-based membranes for advanced desalination: Properties, engineering strategies, and emerging

- applications. *Desalination*, 624, 119860. <https://doi.org/10.1016/j.desal.2026.119860>
- Khan, N. A., Ahmad, N., Ahmad, F., Alsayer, I. A., Altuwair, I. A., Ahmad, S. A., Zaheer, R., & Khan, R. (2025). Copper recovery from scrap electrical cables based on an environmentally sustainable gravity separation technique. *Engineering, Technology & Applied Science Research*, 15(2), 20891-20897. <https://doi.org/10.48084/etasr.9779>
- Khan, H., Ullah, S., Khan, A. S., Nasrullah, A., Rehman, A., Khan, P., Gilani, M. A., Kanan, S., Samara, F., & Ahmad, N. (2025). Amine-based deep eutectic solvents for the extraction of eriochrome black t from aqueous media: experimental and density functional theory studies. *Journal of Molecular Liquids*. <https://doi.org/10.1016/j.molliq.2025.128496>
- Khan, A. D., Khan, S. D., Khan, R. U., Ahmad, N., Ali, A., Khalil, A., & Khan, F. A. (2014). Generation of multiple fano resonances in plasmonic split nanoring dimer. *Plasmonics*, 5, 1091-1102. <https://doi.org/10.1007/s11468-014-9719-y>
- Khan, A. D., Khan, S. D., Khanand, R. U., Ahmad, N. (2014). Excitation of multiple fano-like resonances induced by higher order plasmon modes in three-layered bimetallic nanoshell dimer. *Plasmonics*, 9, 461-475. <https://doi.org/10.1007/s11468-013-9644-5>
- Kheradmandfard, M., Minouei, H., Tsvetkov, N., Vayghan, A. K., Kashani-Bozorg, S. F., Kim, G., Hong, S. I., & Kim, D-E. (2021). Ultrafast green microwave-assisted synthesis of high-entropy oxide nanoparticles for Li-ion battery applications. *Materials Chemistry and Physics*, 262, 124265. <https://doi.org/10.1016/j.matchemphys.2021.124265>
- Jabeen, H., Muhammad, N., Siddique, U., Sabir, M., Ahmad, N., & Liaqat, S. (2023). Effect of TiO₂ decorated cellulosic materials addition on mechanical and biological properties of dental adhesive composites. *Cellulose Chemistry and Technology*, 57(5-6), 541-549.
- Jamil, S., Khalil, U. K., Jamil, S., Ahmad, N., Ahmad, F., & Khan, A. D. (2025). Dynamic plasmonic control in bowtie nanostructure: The role of gap variation and polarization orientation. *Plasmonics*, 1-10. <https://doi.org/10.1007/s11468-025-02916-6>
- Jamila, N., Ullah, R., Khitab, F., Ahmad, N., Ahmad, F., Afridi, M. S., Kanwal, F., & Khan, N. (2025b). Visible-light-sensitive highly-efficient photocatalytic degradation of hazardous contaminant fast yellow AB in industrial wastewater using zinc ferrite nano-photocatalyst: Synthesis, characterization and removal performance. *Spectroscopy Letters*. <https://doi.org/10.1080/00387010.2025.2602841>
- Jan, W., Khan, A. D., Iftikhar, F. J., Abbasi, M. Z., Ali, G., Iwuoha, E., Shahzad, S., Ahmad, F., Ahmad, N. (2025). Electrolyte design for lithium-sulfur batteries: Progress and challenges. *Renewable and Sustainable Energy Reviews*, 221, 115916. <https://doi.org/10.1016/j.rser.2025.115916>
- Jiang, B., Bridges, C. A., Unicic, R. R., Pitike, K. C., Cooper, V. R., Zhang, Y., Lin, D-Y., & Page, K. (2020). Probing the local site disorder and distortion in pyrochlore high-entropy oxides. *Journal of the American Chemical Society*, 143(11), 4193-4204. <https://doi.org/10.1021/jacs.0c10739>
- Maatki, C., Bilal, M., Ahmad, N., Ahmad, F., Alshammari, B., Kriaa, K., & Kolsi, L. (2025). Numerical study of three-dimensional unsteady viscous fluid flow across parallel rotating discs with an upward fluctuation and thermal radiation. *Journal of Radiation Research and Applied Sciences*, 18(2), 101577. <https://doi.org/10.1016/j.jrras.2025.101577>
- Meisenheimer, P., & Heron, J. T. (2020). Oxides and the high entropy regime: A new mix for engineering physical properties. *MRS Advances*, 5(64), 3419-3436. <https://doi.org/10.1557/adv.2020.295>
- Mohammad, M., Maitra, S., Ahmad, N., Bustam, A., Sen, T. K., & Dutta, B. K. (2010). Metal ion removal from aqueous solution using physic seed hull. *Journal of Hazardous Materials*, 179(1-3), 363-372. <https://doi.org/10.1016/j.jhazmat.2010.03.014>
- Muhsin, R. M. M., Manan, T. S. B. A., Bidai, J., Mangat, M. S. A., Hanafiah, Z. M., Gohari, A., Ahmad, N., Ahmad, F., Beddu, S., Kamal, N. L. M., Mohamad, D., Aldala'in, S. A. H., Mustafa, M. R. U., Mohtar, W. H. M. W. S., Isa, M. H., Yusoff, M. S., & Aziz, H. A. (2025). Polycyclic aromatic hydrocarbons (PAHs) occurrences in water bodies, extraction techniques, detection methods, and standardized guidelines for PAHs in aqueous solutions. *Science of The Total Environment*, 972, 179123. <https://doi.org/10.1016/j.scitotenv.2025.179123>
- Naganaboina, V. R., Anandkumar, M., Deshpande, A. S., & Singh, S. G. (2022). Single-phase high-entropy oxide-based chemiresistor: Toward selective and sensitive detection of methane gas for real-time applications.

- Sensors and Actuators B: Chemical*, 357, 131426. <https://doi.org/10.1016/j.snb.2022.131426>
- Noureen, S., Ahmad, Z., Sirajuddin, M., Ahmed, A., Haider, A., Mahmood, S., Ayub, K., Yousuf, S., Ihsan-ul-haq, I., Nisar, S., Ismail, M. A., Ahmad, N., & Tariq, M. (2025). Synthesis, physicochemical characterization, exploration of biological potential and DFT study of di- and tri-organotin(IV) carboxylate derivatives. *Journal of Organometallic Chemistry*, 1039, 123802. <https://doi.org/10.1016/j.jorgchem.2025.123802>
- Pasupathi, A., & Subramaniam, Y. (2024). A novel strategy for rapid synthesis of nanostructured high-entropy metal oxides through thermal plasma for supercapacitor applications. *Energy & Fuels*, 38(6), 5534-5544. <https://doi.org/10.1021/acs.energyfuels.3c04730>
- Pitchai, C., Vedanarayanan, M., & Chen, C-M. (2026). Entropy engineering in multimetallic hydroxides and oxides: a new paradigm for electrocatalytic oxygen evolution. *Nanoscale Horizons*. <https://doi.org/10.1039/D6NH00108D>
- Santos, J. R. D., Raimundo, R. A., Oliveira, J. F. G. A., Hortencio, J. S., Loureiro, F. J. A., Macedo, D. A., Morales, M. A., Gualandi, I., Tonelli, D., & Gomes, U. U. (2024). Eco-friendly high entropy oxide rock-salt type structure for oxygen evolution reaction obtained by green synthesis. *Journal of Electroanalytical Chemistry*, 961, 118191. <https://doi.org/10.1016/j.jelechem.2024.118191>
- Shah, S. A., Nazir, M. S., Mustafa, F., Irfan, S., Ahmad, N., Ahmad, F., Ali, Z., & Hassan, S. U. (2025). Sustainable oxidative desulfurization of fuel via lignin-derived heterogeneous catalysis: Optimized by Box-Behnken design for high efficiency under mild conditions. *International Journal of Biological Macromolecules*, 310, 143404. <https://doi.org/10.1016/j.ijbiomac.2025.143404>
- Shaw, S., Gangwar, A., Sharma, A., Alla, S. K., Kavita, S., Vasundhara, M., Meena, S. S., Maiti, P., Prasad, N. K. (2021). Structural and magnetic properties of nanocrystalline equi-atomic spinel high-entropy oxide (AlCoFeMnNi)₃O₄ synthesised by microwave assisted co-precipitation technique. *Journal of Alloys and Compounds*, 878, 160269. <https://doi.org/10.1016/j.jallcom.2021.160269>
- Suleman, F., Muhbat, S., Uddin, F., Hashmi, S., Borhan, A., Ahmad, F., & Ahmad, N. (2025). Influence of co-pyrolysis temperature on the characteristics of diesel-like fuel produced from waste frying and engine oils. *Journal of Analytical and Applied Pyrolysis*, 193(Part 1), 107352.
- Syed, N. H., Haq, I., Ahmad, F., Khan, N. A., Habib, M., Ahmad, N., & Rind, I. K. (2024). A low-cost wastewater reclamation unit comprising a lamella settler for reducing fresh water usage in carwash stations. *Engineering, Technology & Applied Science Research*, 14(5), 16221-16228. <https://doi.org/10.48084/etasr.8066>
- Syed, N. H., Khan, N. A., Ahmad, N., Khan, M., Ahmad, F., Humayun, F., Haq, S., Alsayer, I. A., Altuwair, I. A. (2024). A CFD Analysis to Investigate the effect of inserts on the overall heat transfer coefficient in a concentric tube heat exchanger. *Engineering Technology & Applied Science Research*, 14(6), 18077-18085. <https://doi.org/10.48084/etasr.8891>
- Tanweer, A., Taqvi, S. A. A., Kazmi, B., Khatoon, A., Taha, M., Nadir, M., Ahmad, F., Ahmad, N. (2025). Advancing algae-based bioenergy: Techno-economic assessment of hydrogen and biochar production from algal biomass. *Biomass & Bioenergy*, 200, 108039. <https://doi.org/10.1016/j.biombioe.2025.108039>
- Tsubota, H., Jitianu, A., & Kawamura, G. (2025). Recent advances in high-entropy oxides for photocatalytic applications. *ACS Materials Letters*, 7(3), 1042-1056. <https://doi.org/10.1021/acsmaterialslett.4c02323>
- Ullah, K., Abrar, M., Uddin, S., Ahmad, M., Ali, A., Ahmad, P., Alrefae, S. H., Ahmad, N., Iqbal, N., Rahman, A., Tirth, V., Algahtani, A., & Zaman, A. (2025). Structural, optical, and dielectric properties of Sr²⁺ substituted Ba_{1-x}Sr_x(Co_{1/2}W_{1/2})O₃ ceramics for wireless applications. *Ceramics International*, 5, 5923-5929. <https://doi.org/10.1016/j.ceramint.2024.12.039>
- Wang, D., Dua, C., He, H., Wang, Z., Zheng, R., Sun, H., Liu, Y., & Liu, C. (2023). Microwave solvothermal synthesis of component-tunable high-entropy oxides as high-efficient and stable electrocatalysts for oxygen evolution reaction. *Journal of Colloid and Interface Science*, 646, 89-97. <https://doi.org/10.1016/j.jcis.2023.05.043>
- Yavas, U. C., & Turan, A. (2026). Solution combustion synthesis and characterization of (CoCrFeMnNi)₃O₄ high-entropy oxide using different fuels. *ACS Omega*, 11(13), 20763-20776. <https://doi.org/10.1021/acsomega.5c12933>
- Zia, R., Nazir, M. S., Rouf, H., Ahmad, N., Ahmad, F., Ali, Z., & Hassan, S. U. (2025). Modified lignin etched sulphur-doped graphitic carbon nitride for electrochemical sensing of cypermethrin in drinking water:

Experimental and theoretical insights. *International Journal of Biological Macromolecules*, 6(321), 146503.
<https://doi.org/10.1016/j.ijbiomac.2025.146503>

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