

SnO₂-based nanocomposites as advanced anode materials for Lithium-ion batteries: Mechanisms, challenges, and design strategies

Ibraheem¹, Azmat Ali Khan², Shah Zeb², Esha Noor³, Jalal Amir⁴ & Ajmal Shah⁵

¹ Laboratory of Advanced Technologies in Energy and Sustainability, Institute of Physics, Federal University of Mato Grosso do Sul, Campo Grande, MS 79070-900, Brazil

² Department of Chemistry, Abdul Wali Khan University, Mardan, Mardan 23200, KP, Pakistan

³ Lahore College for Women University Lahore, Pakistan

⁴ Department of Physics, Abdul Wali Khan University, Mardan, Mardan 23200, KP, Pakistan

⁵ School of Chemistry, Xian Jiaotong University, 710049, Xian, People's Republic of China

Correspondence: Ajmal Shah, School of Chemistry, Xian Jiaotong University, 710049, Xian, People's Republic of China. Email: ajmal.chem@awku.edu.pk

Submitted: March 24, 2026

DOI: 10.14295/bjs.v5i11.915

Accepted: June 25, 2026

URL: <https://doi.org/10.14295/bjs.v5i11.915>

Published: June 30, 2026

Abstract

SnO₂-based nanocomposites have emerged as promising anode materials for lithium-ion batteries due to their high theoretical capacity, low cost, and favorable electrochemical properties. However, pristine SnO₂ suffers from poor electrical conductivity, large volume expansion, unstable solid electrolyte interphase formation, and rapid capacity fading during cycling. To address these issues, various nanocomposite design strategies have been developed, including carbon hybridization, heterostructure engineering, morphology control, porous architecture construction, and interface optimization. These approaches improve charge transport, shorten Li⁺ diffusion pathways, buffer volume changes, and enhance cycling stability. This review summarizes the lithium-storage mechanisms of SnO₂, key performance challenges, and recent design strategies for developing high-performance SnO₂-based nanocomposite anodes for next-generation lithium-ion batteries.

Keywords: SnO₂ nanocomposites, Lithium-ion batteries, anode materials, volume expansion, design strategies.

Nanocompósitos à base de SnO₂ como materiais avançados de ânodo para baterias de íons de Lítio: mecanismos, desafios e estratégias de projeto

Resumo

Os nanocompósitos à base de SnO₂ têm emergido como materiais promissores para ânodos de baterias de íons de lítio devido à sua elevada capacidade teórica, baixo custo e propriedades eletroquímicas favoráveis. No entanto, o SnO₂ puro apresenta limitações importantes, como baixa condutividade elétrica, grande expansão volumétrica durante os ciclos de carga e descarga, formação instável da camada de interfase eletrolítica sólida (SEI, por sua sigla em inglês, Solid Electrolyte Interphase) e rápida perda de capacidade ao longo da ciclagem. Para superar esses desafios, diversas estratégias de desenvolvimento de nanocompósitos têm sido propostas, incluindo a hibridização com carbono, a engenharia de heteroestruturas, o controle da morfologia, a construção de arquiteturas porosas e a otimização das interfaces. Essas abordagens melhoram o transporte de cargas, reduzem os caminhos de difusão dos íons Li⁺, amortecem as variações de volume e aumentam a estabilidade eletroquímica durante a ciclagem. Esta revisão apresenta os mecanismos de armazenamento de lítio no SnO₂, os principais desafios associados ao seu desempenho e as estratégias de projeto mais recentes para o desenvolvimento de ânodos de nanocompósitos à base de SnO₂ de alto desempenho para baterias de íons de lítio de próxima geração.

Palavras-chave: nanocompósitos à base de SnO₂, baterias de íons de Lítio, materiais de ânodo, expansão volumétrica, estratégias de projeto.

1. Introduction

The rapid growth of portable electronics, electric vehicles, hybrid energy systems, and renewable-energy storage technologies has created an urgent demand for rechargeable batteries with higher energy density, longer cycle life, improved safety, and lower cost (Gul et al., 2025). Among various energy-storage systems, lithium-ion batteries (LIBs) remain one of the most successful and widely used technologies because of their high operating voltage, good energy efficiency, long service life, and relatively mature manufacturing infrastructure. However, the continuous expansion of modern energy applications requires electrode materials that can deliver higher reversible capacity, faster charge–discharge performance, and better structural stability than conventional materials. In this context, the development of advanced anode materials has become a major research direction for next-generation LIBs (Shah et al., 2024).

Commercial LIBs mainly use graphite as the anode material because of its stable cycling behavior, low working potential, good electrical conductivity, and excellent structural reversibility (Mohammad et al., 2010). However, graphite has a limited theoretical capacity of 372 mAh g^{-1} , which restricts further improvement in the energy density of LIBs. In addition, graphite suffers from poor rate performance under high-current operation and potential lithium plating during fast charging, which may raise safety concerns (Khan et al., 2023). These limitations have encouraged researchers to explore alternative anode materials with higher lithium-storage capacity and improved electrochemical performance. Various metal oxides, metal sulfides, silicon-based materials, tin-based materials, transition metal compounds, carbonaceous hybrids, and emerging two-dimensional materials have been investigated as possible replacements or supplements for graphite anodes (Ahmad et al., 2009).

Among these candidates, tin dioxide (SnO_2) has attracted significant attention as a promising anode material due to its high theoretical capacity, natural abundance, low cost, environmental compatibility, and rich redox chemistry. SnO_2 can store lithium through both conversion and alloying reactions, which gives it a much higher theoretical capacity than graphite (Ahmad et al., 2015). During the initial lithiation process, SnO_2 is first reduced to metallic Sn and Li_2O through a conversion reaction:

This dual lithium-storage mechanism enables SnO_2 -based anodes to deliver high specific capacity, making them attractive for high-energy LIB applications (Ahmed et al., 2021). In addition, SnO_2 possesses a relatively safe operating potential compared with graphite, which may reduce the risk of lithium dendrite formation during cycling. Its structural flexibility, chemical stability, and ability to form different nanostructures also make SnO_2 a suitable platform for rational electrode design (Khan et al., 2014).

Despite these advantages, the practical application of pristine SnO_2 anodes is still limited by several critical challenges (M. Khan et al., 2024). The most serious issue is the large volume expansion that occurs during the repeated lithiation and delithiation processes, especially during the formation and decomposition of Li_xSn alloys (Khan et al., 2014). This repeated volume fluctuation can cause particle pulverization, electrode cracking, loss of electrical contact, and structural collapse (Ahmad et al., 2013).

As a result, the active material gradually becomes isolated from the conductive network, leading to rapid capacity fading and poor cycling stability (Bakhtiar et al., 2023). Another major limitation is the intrinsically poor electrical conductivity of SnO_2 , which slows electron transport and reduces rate capability (Ahmed et al., 2015). In addition, unstable solid electrolyte interphase formation on the electrode surface can consume lithium ions and electrolyte, resulting in low initial Coulombic efficiency and continuous capacity loss (Zhang et al., 2021). These problems strongly restrict the long-term performance and practical use of SnO_2 -based anodes (Madani et al., 2021).

To overcome these limitations, extensive research has focused on the design of SnO_2 -based nanocomposites (Jan et al., 2025). Nanostructuring and composite engineering provide effective routes to improve the electrochemical behavior of SnO_2 by controlling particle size, morphology, interface structure, porosity, and electrical connectivity. Reducing SnO_2 to the nanoscale can shorten lithium-ion diffusion pathways, increase active surface area, and improve reaction kinetics (Yasmeen et al., 2019). However, nanosized SnO_2 alone may still suffer from aggregation and excessive side reactions with the electrolyte (Muhsin et al., 2025). Therefore, combining SnO_2 with conductive and mechanically stable matrices has become an important strategy for improving its overall performance (Maatki et al., 2025).

Carbon-based materials are among the most widely used components for SnO_2 nanocomposite anodes. Graphene, reduced graphene oxide, carbon nanotubes, carbon nanofibers, porous carbon, amorphous carbon, and

biomass-derived carbon can improve electrical conductivity, provide flexible buffering space, and suppress the aggregation of SnO₂ nanoparticles (Wang et al., 2023). These carbon matrices form continuous conductive networks that facilitate electron transfer and maintain electrode integrity during cycling (Hayat et al., 2022). In addition, carbon coatings can stabilize the electrode/electrolyte interface and improve Coulombic efficiency by regulating solid electrolyte interphase formation (Ahmad et al., 2017).

Heterostructure engineering is another effective approach for enhancing the lithium-storage performance of SnO₂-based anodes (Ullah et al., 2025). Coupling SnO₂ with other metal oxides, sulfides, phosphides, nitrides, MXenes, or conductive polymers can create interfacial electric fields, improve charge-transfer kinetics, and provide multiple active sites for lithium storage (Sun et al., 2024). The synergistic interaction between SnO₂ and secondary components can improve structural stability and electrochemical reversibility (Aziz et al., 2023). In particular, heterostructured materials can promote faster ion/electron transport and accommodate mechanical stress more effectively than single-component electrodes (Li et al., 2025).

Morphology control also plays a crucial role in the performance optimization of SnO₂-based nanocomposites (Ahmad et al., 2024). Various structures, including nanoparticles, nanorods, nanosheets, hollow spheres, core-shell structures, yolk-shell architectures, hierarchical microspheres, and three-dimensional porous frameworks, have been designed to address volume-change problems and improve electrode kinetics (Hasan et al., 2026). Hollow and porous structures can provide internal void space to buffer volume expansion, while hierarchical architectures can increase electrolyte penetration and expose more active sites. Core-shell and yolk-shell designs are especially useful because they can confine SnO₂ within protective conductive shells while allowing sufficient space for expansion during lithiation (Pervaiz et al., 2025).

Interface optimization and defect engineering have recently become important topics in SnO₂-based anode research (Zada; Azizi, 2026). Carefully designed interfaces can improve charge transfer, regulate lithium-ion adsorption, and stabilize the electrode structure (Tanweer et al., 2025). Oxygen vacancies, dopants, and surface defects can modify the electronic structure of SnO₂ and enhance its conductivity and reaction activity (Khazaal et al., 2019). However, these modifications must be carefully controlled because excessive defects or unstable interfaces may increase side reactions and reduce cycling efficiency. Therefore, understanding the relationship between structure, interface chemistry, and electrochemical behavior is essential for rational material design (Ahmad et al., 2014).

Although many SnO₂-based nanocomposites have shown excellent performance in laboratory-scale studies, several challenges remain before practical application (Mao et al., 2026). These include low initial Coulombic efficiency, complex synthesis routes, poor tap density in highly porous structures, limited areal capacity, scalability issues, and insufficient evaluation under commercially relevant conditions (Ishraque et al., 2026). Many reported materials exhibit high capacity at low mass loading but may not maintain the same performance in thick electrodes or full-cell configurations (Shah et al., 2026). Therefore, future research should focus not only on achieving high specific capacity but also on improving electrode-level performance, manufacturing feasibility, long-term durability, and compatibility with commercial battery systems (Shah et al., 2025).

This review focuses on SnO₂-based nanocomposites as advanced anode materials for lithium-ion batteries, with particular emphasis on their lithium-storage mechanisms, major performance challenges, and rational design strategies. First, the fundamental electrochemical reactions of SnO₂ are discussed, including conversion and alloying/dealloying mechanisms. Then, the key limitations of pristine SnO₂ anodes, such as poor conductivity, volume expansion, unstable solid electrolyte interphase, and capacity fading, are critically examined. Recent progress in nanocomposite design, including carbon hybridization, heterostructure engineering, morphology regulation, porous architecture construction, and interface optimization, is then reviewed. Finally, current limitations and future perspectives are presented to guide the development of high-performance SnO₂-based anodes for next-generation lithium-ion batteries.

2.2 Overview of SnO₂ as an anode material for Lithium-ion batteries

Tin dioxide (SnO₂) is one of the most widely studied metal oxide anode materials for lithium-ion batteries (Figure 1) because of its high lithium-storage capacity, low cost, natural abundance, environmental compatibility, and good chemical stability (Liu et al., 2026). Compared with commercial graphite, which has a limited theoretical capacity of 372 mAh g⁻¹, SnO₂ offers much higher lithium-storage potential and is therefore considered a promising candidate for next-generation high-energy-density lithium-ion batteries (Alsaiani et al., 2023).

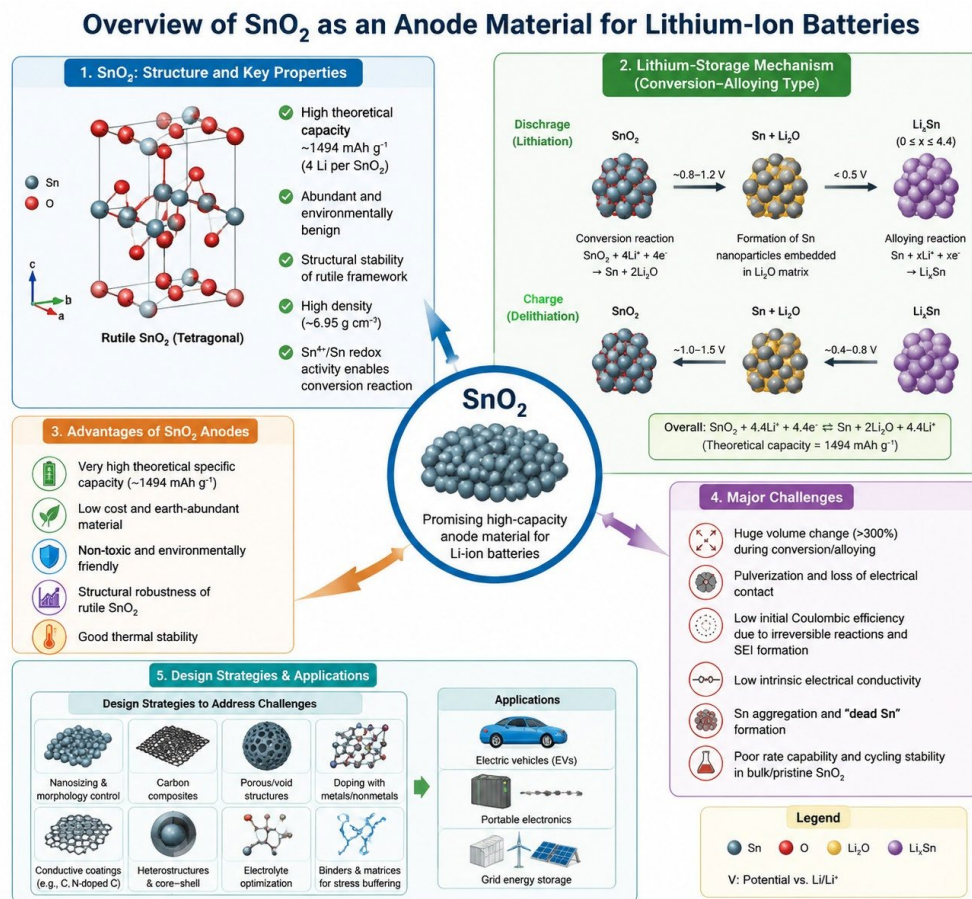


Figure 1. Overview of SnO₂ as an anode material for Lithium-ion batteries. Source: Authors, 2026.

The lithium-storage behavior of SnO₂ is mainly based on two electrochemical reactions: a conversion reaction and an alloying/dealloying reaction (Hasan et al., 2026). During the initial lithiation process, SnO₂ reacts with lithium ions to form metallic Sn and Li₂O (Ali et al., 2026).

This combined conversion-alloying mechanism allows SnO₂ to deliver a much higher theoretical capacity than graphite. Depending on whether the full conversion and alloying processes are considered, the theoretical capacity of SnO₂ is commonly reported as approximately 1494 mAh g⁻¹, while the reversible alloying contribution of Sn is often discussed around 782–783 mAh g⁻¹. This high capacity makes SnO₂ highly attractive for advanced anode development (Zia et al., 2025).

In addition to its high capacity, SnO₂ has several other advantages. It is chemically stable, relatively inexpensive, and can be synthesized through various simple methods such as hydrothermal, solvothermal, sol-gel, precipitation, electrospinning, and thermal decomposition routes. SnO₂ can also be prepared in many nanostructured forms, including nanoparticles, nanorods, nanosheets, nanowires, hollow spheres, porous frameworks, and core-shell architectures (Anwar et al., 2025). These structural possibilities make SnO₂ a flexible platform for rational electrode design (Jamil et al., 2025).

However, pristine SnO₂ still faces serious limitations that restrict its practical use in commercial lithium-ion batteries (Bibi et al., 2024). The most important problem is the large volume change that occurs during repeated lithiation and delithiation (Ahmad et al., 2026). This volume expansion can cause particle pulverization, electrode cracking, loss of electrical contact, and continuous destruction of the solid electrolyte interphase (Ahmad et al., 2021). As a result, the electrode suffers from rapid capacity fading and poor long-term cycling stability. Another major drawback is the poor intrinsic electrical conductivity of SnO₂, which slows electron transport and reduces rate performance, especially at high current densities (Ahmad et al., 2018).

The electrochemical performance of SnO₂ is strongly influenced by particle size, morphology, surface area, porosity, crystallinity, and electrode architecture (Akhtar et al., 2025). Nanosizing can shorten Li⁺ diffusion

pathways and increase active reaction sites, while porous and hollow structures can provide internal space to accommodate volume expansion (N. Ahmad, Fouad, & Engineering, 2017). However, excessive surface area may also increase side reactions with the electrolyte and reduce initial Coulombic efficiency (Ahmad et al., 2025). Therefore, careful structural design is required to balance high capacity, stable cycling, and efficient charge transport (Hasan et al., 2025).

To address these issues, SnO₂ is commonly combined with conductive and mechanically stable components to form nanocomposites (Rehman et al., 2016). Carbon materials such as graphene, reduced graphene oxide, carbon nanotubes, carbon nanofibers, porous carbon, and amorphous carbon are widely used to enhance electrical conductivity, suppress particle aggregation, and buffer volume changes (Ye et al., 2024). Similarly, coupling SnO₂ with other metal oxides, sulfides, phosphides, MXenes, or conductive polymers can create heterostructures with improved interfacial charge transfer and structural stability (Ye et al., 2024).

Overall, SnO₂ is a highly promising anode material because of its high theoretical capacity and versatile electrochemical behavior (Syed et al., 2024). Nevertheless, its practical application depends on solving key problems related to volume expansion, poor conductivity, unstable SEI formation, and capacity decay. Therefore, the development of SnO₂-based nanocomposites has become an important research direction for improving lithium-storage performance and advancing high-capacity anodes for future lithium-ion batteries.

To better position SnO₂ among commercially available and emerging anode materials, (Table 1) summarizes the main electrochemical characteristics of representative anode candidates for lithium-ion batteries. The comparison highlights the advantages of SnO₂ regarding theoretical capacity while also emphasizing its major limitation associated with large volume expansion during cycling.

Table 1. Comparison of representative anode materials for lithium-ion batteries.

Anode material	Theoretical capacity (mAh g ⁻¹)	Initial Coulombic efficiency (ICE, %)	Typical cycling stability	Typical current density (mA g ⁻¹)	Volume expansion (%)	Main advantages	Main limitations
Graphite	372	90–95	>1000 cycles	100–1000	~10	Commercially mature, excellent cycling stability	Low capacity
TiO ₂	168–335	90–98	>3000 cycles	100–5000	<4	Outstanding structural stability and safety	Low capacity
Nb ₂ O ₅	200–250	85–95	1000–5000 cycles	100–5000	<10	Fast Li ⁺ diffusion, excellent rate capability	Low gravimetric capacity
Fe ₂ O ₃	1007	70–85	200–800 cycles	100–1000	~100	High capacity, low cost	Poor conductivity, conversion reaction
Co ₃ O ₄	890	70–85	200–1000 cycles	100–1000	~120	High reversible capacity	High cost and toxicity of Co
Ge	1624	80–95	500–1500 cycles	100–5000	~260–300	Excellent conductivity and fast Li diffusion	Very high cost
Si	3579	75–90	200–1000 cycles	100–2000	~300	Highest theoretical capacity	Extreme volume expansion
SnO ₂	1494	60–80	200–1000 cycles	100–2000	250–300	High capacity, low cost, environmentally	Large volume expansion, unstable SEI,

Anode material	Theoretical capacity (mAh g ⁻¹)	Initial Coulombic efficiency (ICE, %)	Typical cycling stability	Typical current density (mA g ⁻¹)	Volume expansion (%)	Main advantages	Main limitations
						friendly	low conductivity

Source: Authors, 2026.

As shown in Table 1, SnO₂ occupies an intermediate position between conventional graphite and emerging alloy-type anodes such as silicon and germanium. Although its theoretical capacity (1494 mAh g⁻¹) is considerably higher than that of graphite and most transition-metal oxides, it remains significantly lower than that of silicon. Nevertheless, SnO₂ offers important practical advantages, including lower cost, environmental compatibility, easier synthesis, and greater structural versatility. Its principal drawback remains the severe volume expansion during lithiation/delithiation, which compromises cycling stability and motivates the development of rational nanocomposite engineering strategies discussed throughout this review.

3. Lithium-storage mechanisms of SnO₂-based anodes

The lithium-storage behavior of SnO₂-based anodes (Table 2 and Figure 2) is mainly governed by a combined conversion and alloying/dealloying mechanism (Gul et al., 2025). Unlike graphite, which stores lithium through intercalation, SnO₂ reacts with lithium ions through multiple electrochemical steps that provide much higher theoretical capacity (Kashif et al., 2026). During the initial discharge process, SnO₂ first undergoes a conversion reaction with lithium ions and electrons, producing metallic tin and lithium oxide (Shah et al., 2024).

Table 2. Lithium-storage mechanisms of SnO₂-based anodes for lithium-ion batteries.

Mechanism	Main electrochemical reaction	Typical voltage region vs. Li/Li ⁺	Description of Li-storage process	Contribution to capacity	Main limitations	References
Initial Li ⁺ insertion/surface adsorption	$\text{SnO}_2 + x\text{Li}^+ + xe^- \rightarrow \text{Li}_x\text{SnO}_2$	Usually above ~1.0 V during initial discharge	A small amount of Li ⁺ may insert into defects, surface sites, or amorphous regions before full conversion begins. This process is more noticeable in nanosized, defective, or amorphous SnO ₂ .	Minor capacity contribution; may improve reaction kinetics in nanostructured SnO ₂ .	Often difficult to distinguish from surface capacitive storage and electrolyte decomposition.	01
Conversion reaction	$\text{SnO}_2 + 4\text{Li}^+ + 4e^- \rightarrow \text{Sn} + 2\text{Li}_2\text{O}$	Around ~0.8–1.2 V during first lithiation	SnO ₂ is reduced to metallic Sn nanoparticles embedded in a Li ₂ O matrix. This reaction breaks the original Sn–O framework and forms electrochemically active Sn for the next alloying step.	Provides a large part of theoretical capacity; approximately 711 mAh g ⁻¹ based on 4 Li per SnO ₂ .	Conversion is partly irreversible in pristine SnO ₂ , causing low initial Coulombic efficiency and first-cycle capacity loss.	02
Alloying reaction of Sn with Li	$\text{Sn} + x\text{Li}^+ + xe^- \rightleftharpoons \text{Li}_x\text{Sn}, 0 \leq x \leq 4.4$	Usually below ~0.5 V during lithiation; dealloying commonly occurs around ~0.4–0.8 V	Metallic Sn formed from conversion reacts with Li ⁺ to form Li–Sn alloy phases, ultimately approaching Li _{4.4} Sn. This is the major reversible lithium-storage step	Approximately 782 mAh g ⁻¹ based on 4.4 Li per SnO ₂ ; major reversible capacity source.	Causes huge volume expansion/contraction, leading to pulverization, Sn aggregation, and loss of electrical contact.	03

			in many SnO ₂ -based anodes.			
Dealloying reaction	$\text{Li}_x\text{Sn} \rightleftharpoons \text{Sn} + x\text{Li}^+ + x\text{e}^-$	Mainly ~0.4–0.8 V during charge	Li is extracted from Li _x Sn phases, and metallic Sn is regenerated. The reversibility of this step strongly controls cycling stability.	Main reversible capacity during repeated cycles.	Repeated dealloying/alloying causes mechanical stress, particle cracking, and unstable SEI growth.	04
Partial reversible conversion	$\text{Sn} + 2\text{Li}_2\text{O} \rightleftharpoons \text{SnO}_2 + 4\text{Li}^+ + 4\text{e}^-$	Usually above ~1.0 V during charge	In well-designed SnO ₂ -based nanocomposites, part of the conversion reaction can become reversible. Small Sn domains, carbon confinement, transition-metal additives, and oxygen vacancies can promote reconversion.	Adds extra reversible capacity beyond simple Sn alloying/dealloying.	In bulk/pristine SnO ₂ , reconversion is kinetically sluggish and often incomplete.	05
Formation of intermediate lithium tin oxides	$\text{SnO}_2 + \text{Li}^+/\text{e}^- \rightarrow \text{Li}_2\text{SnO}_3, \text{Li}_8\text{SnO}_6, \text{and related phases}$	Mostly in intermediate voltage regions during cycling	Some studies show that lithiation/delithiation of SnO ₂ can involve intermediate lithium tin oxide phases, not only direct SnO ₂ -to-Sn conversion.	May explain additional capacity, voltage hysteresis, and complex redox behavior.	The reaction pathway is complex and depends on electrode structure, electrolyte, particle size, and cycling conditions.	06

Interfacial lithium storage	Li^+ storage at Sn/Li ₂ O, SnO ₂ /carbon, and defect-rich interfaces	Broad/sloping regions over a wide voltage window	Nanoscale Sn, Li ₂ O, carbon, oxygen vacancies, and grain boundaries create interfacial sites for extra Li^+ storage. This mechanism becomes more important in nanocomposites and porous structures.	Can provide capacity beyond the theoretical alloying value and improve high-rate behavior.	Excessive surface area may increase SEI formation and irreversible capacity loss.	07
Pseudocapacitive lithium storage	Surface/near-surface fast redox reactions rather than solid-state diffusion only	Broad voltage response; rate-dependent	In ultra fine, porous, carbon-supported, or defect-engineered SnO ₂ , fast surface-controlled reactions can contribute significantly to capacity.	Enhances rate capability and reduces diffusion limitations.	May reduce initial Coulombic efficiency due to the large surface area and electrolyte decomposition.	08
Carbon/composite-assisted mechanism	$\text{SnO}_2/\text{C} + \text{Li}^+ + \text{e}^- \rightarrow$ conversion/alloying reactions with improved electron/ion transport	Across the full operating voltage range	Carbon matrices, graphene, CNTs, porous carbon, MXene, or conductive polymers improve electronic conductivity, buffer volume change, and confine Sn/SnO ₂ particles.	Improves reversible capacity, rate capability, and cycle life.	Excess inactive carbon may reduce tap density and volumetric capacity.	09

Transition-metal-assisted reversible conversion	$M/SnO_2/C + Li^+ + e^- \rightleftharpoons Sn/Li_2O/M$ or M–Sn species	Mainly conversion region above ~1.0 V and alloying region below ~0.5 V	Transition metals such as Co, Fe, Cu, Ni, or Mn can enhance electrical conductivity, suppress Sn coarsening, promote Li_2O activation, and improve conversion reversibility.	Improves initial Coulombic efficiency, reversible capacity, and cycling stability.	Added metal phases may increase synthesis complexity and reduce gravimetric energy density if excessive.	10
---	--	--	--	--	--	----

Source: Authors, 2026.

Lithium-storage mechanisms of SnO₂-based anodes

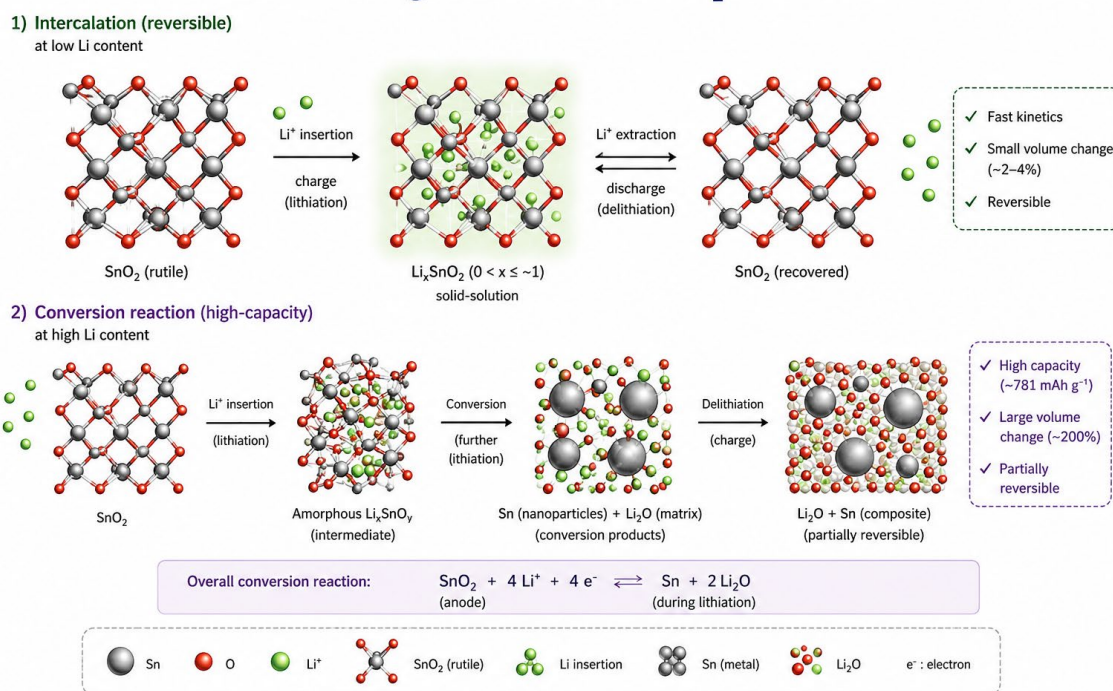


Figure 2. Schematic illustration of the lithium-storage mechanisms in SnO₂-based anodes, highlighting the conversion and alloying/dealloying reactions that occur during lithiation and delithiation. Initially, SnO₂ is reduced to metallic Sn and Li₂O through a conversion reaction, followed by the reversible formation of Li_xSn alloys, which are responsible for the high lithium-storage capacity. The schematic also illustrates the transport of Li⁺ ions and electrons, the structural evolution of the active material, and the major challenges associated with SnO₂ anodes, including volume expansion, solid electrolyte interphase (SEI) formation, and structural degradation during repeated charge–discharge cycling. Source: Authors, 2026.

This conversion reaction plays an important role in activating the SnO₂ electrode and forming nanosized Sn domains embedded in a Li₂O matrix (Ahmad, 2013). The formation of Li₂O can help disperse metallic Sn particles and partially buffer volume changes during cycling (Hussain et al., 2025). However, this process is often associated with irreversible capacity loss, especially in the first cycle, because part of the Li₂O formation and electrolyte decomposition may not be fully reversible. In addition, the solid electrolyte interphase formed on the electrode surface consumes lithium ions and contributes to low initial Coulombic efficiency (Amina et al., 2025).

This alloying/dealloying reaction is mainly responsible for the high reversible capacity of SnO₂-based anodes. During lithiation, lithium atoms enter the Sn phase and form different Li_xSn alloy phases (Zahoor et al., 2026). During delithiation, lithium is extracted from Li_xSn, and metallic Sn is regenerated. Although this reaction provides high capacity, it also causes severe volume expansion and contraction (Figure 3) (Khan et al., 2025). The repeated volume fluctuation can lead to particle pulverization, electrode cracking, loss of electrical contact, unstable SEI formation, and rapid capacity fading (Kashif et al., 2024). Therefore, controlling the mechanical stress generated during alloying/dealloying is essential for improving the long-term stability of SnO₂-based electrodes (Khan et al., 2026).

The overall electrochemical performance of SnO₂-based anodes depends not only on these conversion and alloying reactions but also on charge-transfer kinetics and Li⁺ diffusion behavior (Syed et al., 2024). Pristine SnO₂ has relatively poor intrinsic electrical conductivity, which limits fast electron transport during charge and discharge processes (Fahim et al., 2025). Slow charge transfer increases polarization and reduces rate capability, particularly at high current densities. In addition, long Li⁺ diffusion pathways in bulk SnO₂ particles can restrict

reaction kinetics and lead to incomplete utilization of active material. These kinetic limitations become more serious during repeated cycling when structural degradation and unstable interfaces further interrupt ion and electron transport (Arshad et al., 2025).

Nanostructuring and composite design are effective approaches for improving the lithium-storage kinetics of SnO_2 . Reducing SnO_2 particle size can shorten Li^+ diffusion distances and increase electrochemically active surface area (Al-Khazaal et al., 2022). Porous, hollow, and hierarchical architectures (Figure 3) provide more electrolyte-accessible channels and internal void spaces, which facilitate ion transport and accommodate volume expansion. Similarly, coupling SnO_2 with conductive matrices such as graphene, carbon nanotubes, carbon nanofibers, porous carbon, MXenes, or conductive polymers can build continuous electron-transfer pathways and improve overall electrode conductivity. These conductive networks help maintain electrical contact even after repeated lithiation/delithiation cycles (Jabeen et al., 2023).

In SnO_2 -based nanocomposites (Figure 3), interfacial interactions between SnO_2 and the supporting matrix also strongly influence lithium-storage behavior. Well-designed interfaces can accelerate charge transfer, regulate Li^+ adsorption, suppress particle aggregation, and stabilize the electrode/electrolyte contact. The presence of defects, oxygen vacancies, or heteroatom doping may further modify the electronic structure of SnO_2 and enhance reaction activity. However, excessive surface defects or very high surface area can also promote side reactions and unstable SEI growth. Therefore, an optimized balance between active surface area, conductivity, structural stability, and interface chemistry is required (Ahmad et al., 2025).

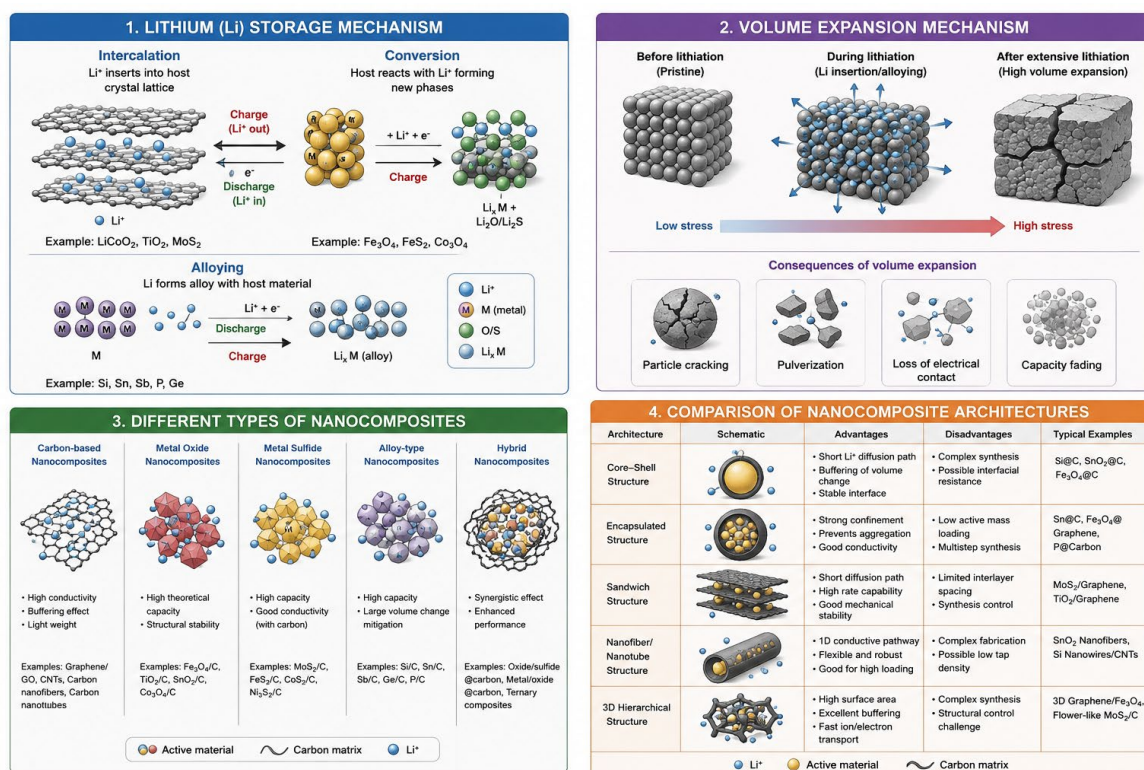


Figure 3. Schematic illustration of lithium (Li) storage mechanisms, volume expansion, nanocomposite classifications, and nanocomposite architecture comparison for advanced lithium-ion battery anodes. Source: Authors, 2026.

Overall, the lithium-storage mechanism of SnO_2 -based anodes involves a complex interaction between conversion reactions, alloying/dealloying processes, charge-transfer behavior, and Li^+ diffusion kinetics (Zhu et al., 2024). The high capacity of SnO_2 originates from its ability to participate in both conversion and alloying reactions, while its major performance limitations arise from large volume change, poor conductivity, irreversible lithium consumption, and unstable interfaces. Rational nanocomposite design can effectively address these issues by improving electrical conductivity, shortening Li^+ diffusion pathways, buffering mechanical strain, and stabilizing the SEI layer. Therefore, understanding these mechanisms is essential for developing

high-performance SnO₂-based anodes for next-generation lithium-ion batteries.

4. Major challenges of pristine SnO₂ anodes

Although SnO₂ is considered a promising high-capacity anode material for lithium-ion batteries (Table 3), its practical application is strongly limited by several intrinsic drawbacks (Chetry et al., 2025). These limitations mainly arise from its poor electrical conductivity, severe volume variation during cycling, unstable solid electrolyte interphase formation, and progressive structural degradation (Chetry et al., 2025). As a result, pristine SnO₂ usually shows poor rate capability, low initial Coulombic efficiency, rapid capacity fading, and unsatisfactory long-term cycling stability (Jamila et al., 2025). Understanding these challenges is essential for designing advanced SnO₂-based nanocomposites with improved electrochemical performance (Hasan et al., 2026).

Table 3. Major challenges associated with pristine SnO₂ anodes for lithium-ion batteries.

Serial no	Major challenge	Mechanistic origin in pristine SnO ₂	Effect on electrochemical performance	Typical observation during cycling	References
01	Severe volume expansion/contraction	SnO ₂ undergoes a conversion reaction to metallic Sn and Li ₂ O, followed by alloying/de-alloying of Sn with Li to form Li _x Sn. This multistep reaction causes a very large volume variation, often reported as >300%.	Generates high internal stress, cracks the electrode, and accelerates capacity fading.	Electrode swelling, cracking, pulverization, and unstable cycling profiles.	Ryan (2023)
02	Pulverization of active material	Repeated lithiation/delithiation causes mechanical fracture of SnO ₂ particles or nanostructures.	Loss of electrical contact between active material, conductive additive, binder, and current collector.	Rapid decline in reversible capacity and increase in electrode resistance.	Yan et al. (2026)
03	Low initial Coulombic efficiency	The first-cycle conversion of SnO ₂ to Sn and Li ₂ O is partly irreversible. Additional irreversible capacity is consumed by electrolyte decomposition and SEI formation.	Large first-cycle capacity loss, low practical energy efficiency, and reduced lithium inventory in full cells.	High first-discharge capacity but much lower first-charge capacity.	Lan et al. (2022)

04	Poor reversibility of the conversion reaction	The reconversion of Sn and Li_2O back to SnO_2 is kinetically difficult, especially in bulk or poorly engineered pristine SnO_2 .	Progressive loss of active lithium-storage sites and reduced long-term capacity retention.	Declining contribution from the conversion-reaction region during repeated cycles.	Ferraresi et al. (2018)
05	Poor intrinsic electrical conductivity	Pristine SnO_2 has limited electronic conductivity, and the Li_2O generated during conversion is electronically insulating.	Slow charge transfer, high polarization, poor rate capability, and incomplete utilization of active material.	Large charge-transfer resistance in EIS and poor capacity at high current density.	Hu et al. (2016)
06	Unstable and continuously growing SEI	Volume change and particle cracking expose fresh Sn/ SnO_2 surfaces to the electrolyte, causing repeated SEI formation.	Continuous electrolyte and lithium consumption, impedance growth, and low Coulombic efficiency during cycling.	Thick/unstable SEI layer, increasing polarization, and gradual capacity decay.	Nath (2024)
07	Sn aggregation/coarsening and dead Sn formation	Metallic Sn produced during conversion can migrate, aggregate, or coarsen during cycling. Some Sn becomes electrochemically isolated as “dead Sn.”	Reduces active surface area and weakens the reversibility of alloying/de-alloying reactions.	Growth of Sn domains, inactive Sn accumulation, and progressive capacity loss.	Wang et al. (2025)
08	Complex multiphase reaction pathway	SnO_2 lithiation can involve overlapping reactions and intermediate phases such as Li_2SnO_3 and Li_8SnO_6 , in addition to Sn/ Li_2O and Li–Sn alloy phases.	Complicates reaction reversibility, increases voltage hysteresis, and limits kinetic efficiency.	Broad redox peaks, sloping voltage profiles, and ambiguous phase evolution.	Sun et al. (2025)

09	Electrode-level instability at practical loading	Pristine SnO ₂ lacks a buffering/conductive matrix; therefore, high active-material loading intensifies stress accumulation and transport limitations.	Poor areal capacity retention and weak commercial scalability compared with engineered composites.	Delamination, electrode thickening, high impedance, and poor cycling at high current density.	Saleh et al. (2016)
----	--	---	--	---	---------------------

Source: Authors, 2026.

One of the major limitations of pristine SnO₂ is its relatively poor intrinsic electrical conductivity. During lithiation and delithiation, efficient electron transport is required to support fast electrochemical reactions (Saddam et al., 2023). However, the low conductivity of SnO₂ slows down charge transfer between the active material and the current collector. This leads to high electrode polarization, sluggish reaction kinetics, and incomplete utilization of the active material, especially at high current densities (Jamalet al., 2024).

Poor electrical conductivity also limits the rate capability of SnO₂ anodes. Under fast charge–discharge conditions, electrons cannot move rapidly through the electrode network, resulting in delayed lithiation/delithiation reactions and reduced capacity retention. In addition, repeated cycling may further weaken the electrical contact between SnO₂ particles due to volume-induced mechanical stress. Once active particles become disconnected from the conductive pathway, they can no longer participate effectively in lithium storage, causing continuous capacity loss (Kashif et al., 2024).

To overcome this issue, SnO₂ is often combined with conductive components such as graphene, reduced graphene oxide, carbon nanotubes, carbon nanofibers, porous carbon, MXenes, or conductive polymers (Ahmad et al., 2012). These materials can form continuous electron-transport networks, reduce internal resistance, and improve the electrochemical reaction kinetics of SnO₂-based electrodes. Another critical challenge of SnO₂ anodes is the large volume expansion that occurs during lithium insertion (Ahmad et al., 2012). The lithium-storage process of SnO₂ involves both conversion and alloying reactions. In particular, the formation of Li_xSn alloys during lithiation causes significant volume expansion, while lithium extraction during delithiation leads to volume contraction. This repeated expansion and shrinkage generate strong mechanical stress within the electrode (Gasimova et al., 2025).

Large volume variation can damage the electrode structure in several ways. It can fracture SnO₂ particles, break the contact between active material and conductive additives, and weaken the adhesion between the electrode layer and current collector (Haider et al., 2026). Over repeated cycles, these mechanical changes lead to electrode pulverization and structural collapse. As a result, the reversible capacity decreases rapidly, and the cycling stability becomes poor (Jabeen et al., 2023).

Nanostructured and porous designs are commonly used to reduce the negative effects of volume expansion (Khan et al., 2025). Hollow structures, yolk–shell architectures, porous frameworks, and flexible carbon-supported composites can provide internal void space to accommodate volume changes. These designs help maintain electrode integrity and improve cycling performance. The formation of a solid electrolyte interphase (SEI) layer is another important factor affecting the performance of pristine SnO₂ anodes (Ahmad et al., 2023). During the initial lithiation process, electrolyte decomposition occurs on the electrode surface, forming an SEI film. A stable SEI layer can protect the electrode and allow Li⁺ transport, but an unstable or repeatedly damaged SEI can seriously reduce battery performance (Bashiret al., 2023).

Because SnO₂ undergoes large volume changes during cycling, the SEI layer formed on its surface is often broken and regenerated repeatedly (DeI Toro et al., 2022). Each time the SEI ruptures, a fresh SnO₂ surface is exposed to the electrolyte, leading to continuous electrolyte decomposition and lithium consumption. This process lowers the initial Coulombic efficiency and causes irreversible capacity loss. Continuous SEI reconstruction also increases interfacial resistance, slows Li⁺ transport, and accelerates capacity fading (Deng et al., 2025).

The instability of the SEI is more serious in nanosized SnO₂ because the high surface area increases contact with the electrolyte. Although nanosizing improves reaction kinetics, excessive surface exposure can promote side

reactions. Therefore, surface coating, carbon encapsulation, electrolyte optimization, and interface engineering are important strategies for stabilizing the SEI layer in SnO₂-based anodes. Structural pulverization is a direct consequence of repeated volume expansion and contraction during cycling (Shah et al., 2024). As SnO₂ particles expand during lithiation and shrink during delithiation, mechanical stress accumulates inside the electrode. Over time, this stress causes cracking, fragmentation, and loss of structural continuity. The pulverized particles may become electrically isolated, reducing the amount of active material available for lithium storage (Sun et al., 2024).

Capacity fading in pristine SnO₂ anodes results from several connected processes, including particle pulverization, loss of electrical contact, unstable SEI growth, irreversible lithium consumption, and sluggish charge-transfer kinetics. These problems reduce reversible capacity and shorten battery life. In many cases, pristine SnO₂ may show high capacity in the initial cycles but quickly loses performance during prolonged cycling (Ikram et al., 2025).

To improve capacity retention, researchers have focused on rational nanocomposite design. Conductive carbon frameworks can maintain electron pathways, flexible matrices can buffer mechanical stress, and porous or hollow architectures can accommodate volume expansion. Heterostructure engineering can further enhance interfacial stability and reaction kinetics. Therefore, addressing the structural instability of pristine SnO₂ is central to the development of durable and high-performance SnO₂-based anodes.

Overall, the major challenges of pristine SnO₂ anodes are closely interrelated. Poor conductivity limits electron transport, volume expansion causes mechanical degradation, unstable SEI formation consumes lithium and electrolyte, and structural pulverization leads to rapid capacity fading. These limitations explain why pristine SnO₂ alone is not sufficient for practical lithium-ion battery applications. The development of SnO₂-based nanocomposites is therefore essential to improve conductivity, buffer volume changes, stabilize the electrode/electrolyte interface, and achieve long-term cycling stability (Sun et al., 2025).

5. Design strategies for SnO₂-based nanocomposite anodes

The intrinsic limitations of pristine SnO₂ anodes, including poor electrical conductivity, severe volume expansion, unstable solid electrolyte interphase (SEI) formation, and rapid capacity fading, can be effectively mitigated through rational nanocomposite engineering. Rather than employing SnO₂ as a single-component electrode (Figure 4), researchers have increasingly integrated it with conductive, flexible, porous, and electrochemically active materials to enhance structural stability, electrical conductivity, lithium-storage kinetics, and long-term cycling performance. These design strategies primarily aim to accelerate charge transport, shorten Li⁺ diffusion pathways, buffer mechanical stress induced by repeated lithiation/delithiation, stabilize the electrode/electrolyte interface, and preserve electrode integrity during prolonged cycling (Sun et al., 2022; Zeng; Sun, 2025).

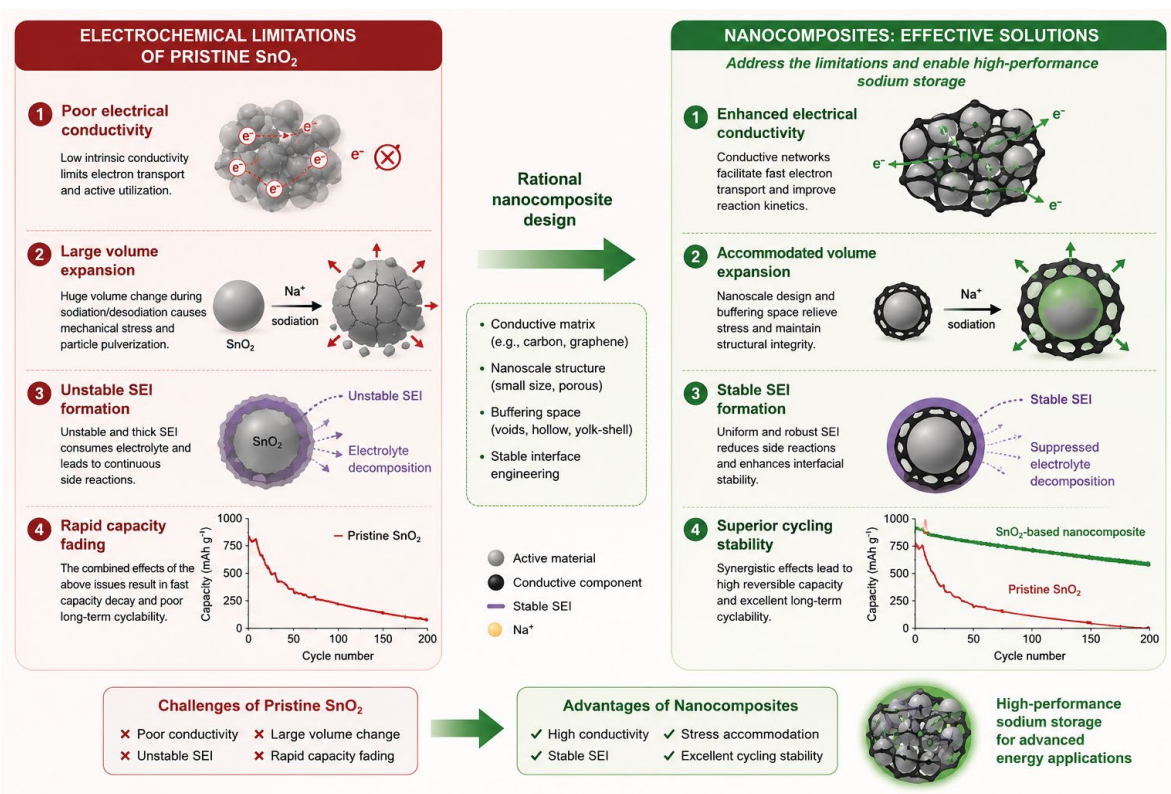


Figure 4. Schematic illustration of the electrochemical limitations of pristine SnO_2 anodes and their mitigation through rational nanocomposite design for enhanced lithium/sodium storage performance. Source: Authors, 2026.

Carbon hybridization (Table 4) represents one of the most successful and extensively investigated strategies for improving SnO_2 -based anodes. Carbonaceous materials, including graphene, reduced graphene oxide (rGO), carbon nanotubes (CNTs), carbon nanofibers (CNFs), porous carbon, amorphous carbon, and biomass-derived carbon, create highly conductive three-dimensional networks surrounding SnO_2 nanoparticles. These conductive matrices significantly improve electron transport, reduce charge-transfer resistance and electrode polarization, and enhance rate capability. Simultaneously, their flexible frameworks act as mechanical buffers that accommodate the substantial volume expansion of SnO_2 during cycling, thereby suppressing particle aggregation, preventing electrode pulverization, and maintaining structural integrity. Carbon coatings or encapsulation further minimize direct contact between SnO_2 nanoparticles and the electrolyte, promoting the formation of a thinner and more stable SEI layer, reducing irreversible capacity loss, improving Coulombic efficiency, and enhancing cycling stability (Shah et al., 2024; Sun et al., 2026).

Table 4. SnO_2 Nanocomposites via carbon hybridization.

Material	Specific capacity (mAh g ⁻¹)	Current density (mA g ⁻¹)	Capacity Retention After Cycling	Initial Coulombic Efficiency (ICE)	Reference
SnO_2/rGO	~980	100	85% after 200 cycles	~72%	Wang et al. (2023)
SnO_2/CNTs	~1100	200	83% after 200 cycles	~65%	Ullah et al. (2025)
$\text{SnO}_2@\text{Porous carbon}$	~1250	500	91% after 600 cycles	~79%	Li et al. (2025)
$\text{SnO}_2/\text{carbon}$	~850	1000	80% after 150 cycles	~71%	Aziz et al.

Source: Authors, 2026.

Heterostructure engineering (Table 5) has emerged as another highly effective strategy for enhancing the electrochemical performance of SnO₂-based nanocomposites. Coupling SnO₂ with functional materials such as metal oxides, sulfides, phosphides, nitrides, MXenes, conductive polymers, or other semiconductors creates synergistic heterointerfaces that facilitate rapid electron transport, accelerate Li⁺ diffusion, and improve reaction reversibility.

The built-in electric fields, interfacial defects, and charge redistribution generated at these interfaces reduce reaction polarization while providing additional active sites for lithium storage. Furthermore, the secondary phases serve as mechanically robust supports that effectively buffer volume expansion, prevent structural collapse, and inhibit particle pulverization during repeated alloying/dealloying reactions. Consequently, heterostructured SnO₂ nanocomposites generally exhibit higher reversible capacity, superior rate capability, and significantly improved cycling stability compared with pristine SnO₂ (Li et al., 2025; Sun et al., 2026).

Morphology control also plays a central role in optimizing the electrochemical behavior of SnO₂ anodes. SnO₂ has been engineered into a wide range of nanostructures, including zero-dimensional nanoparticles, one-dimensional nanorods, nanowires, and nanotubes, two-dimensional nanosheets, and three-dimensional hierarchical, hollow, core-shell, and yolk-shell architectures. Each morphology provides distinct advantages for lithium storage.

Nanoparticles offer high surface area and short Li⁺ diffusion distances, while one-dimensional nanostructures provide continuous electron transport pathways. Two-dimensional nanosheets expose abundant electrochemically active sites and improve electrolyte accessibility. Hollow, core-shell, yolk-shell, and hierarchical structures are particularly advantageous because their internal void spaces effectively accommodate the large volume variation of SnO₂ during lithiation while maintaining structural integrity. However, excessively small nanoparticles may suffer from increased surface side reactions and unstable SEI formation; therefore, morphology optimization is essential for balancing high capacity, fast reaction kinetics, structural robustness, and interfacial stability (Jamil et al., 2025; Li et al., 2026).

Table 5. SnO₂ nanocomposites via heterostructure engineering.

Material	Specific capacity (mAh g ⁻¹)	Current density (mA g ⁻¹)	Capacity Retention After Cycling	Initial Coulombic Efficiency (ICE)	Reference
SnO ₂ /TiO ₂	~820	200	94% after 300 cycles	~78%	Sun et al. (2024)
SnO ₂ /MoS ₂	~1150	100	83% after 200 cycles	~65%	Ullah et al. (2025)
SnO ₂ /Ti ₃ C ₂ T _x (MXene)	~1310	500	91% after 600 cycles	~79%	Li et al. (2025)
SnO ₂ /ZnO	~900	200	80% after 150 cycles	~71%	Aziz et al. (2023)

Source: Authors, 2026.

Porous architecture design (Table 6) further enhances the electrochemical performance of SnO₂-based nanocomposites by generating interconnected ion- and electron-transport pathways together with internal buffer spaces. Mesoporous, microporous, macroporous, hollow, and hierarchical porous structures facilitate electrolyte penetration, expose abundant electrochemically active sites, and significantly shorten Li⁺ diffusion distances, thereby improving reaction kinetics and rate performance. Simultaneously, interconnected pore networks efficiently accommodate the large volume expansion associated with SnO₂ lithiation, reducing mechanical stress accumulation, particle fracture, electrode cracking, and pulverization while maintaining stable electrical contact between active materials and conductive frameworks.

Hierarchical porous structures, combining micro-, meso-, and macropores, are particularly attractive because they simultaneously provide high surface area, efficient mass transport, and enhanced mechanical stability. Nevertheless, excessive porosity may decrease tap density and increase undesirable side reactions with the electrolyte; therefore, pore size distribution, pore volume, and structural compactness must be carefully optimized for practical battery applications (Sun et al., 2024; Zhanget al., 2026a).

Interface and defect engineering have recently become powerful approaches for tuning the electrochemical properties of SnO₂-based anodes. The interface between SnO₂ and conductive matrices strongly influences charge-transfer resistance, Li⁺ adsorption behavior, SEI formation, and structural stability. Carefully engineered interfaces established through surface coatings, chemical bonding, heteroatom doping, or interfacial anchoring strengthen electronic coupling, improve charge transfer, prevent particle detachment, and promote uniform electrochemical reactions.

Simultaneously, defect engineering through oxygen vacancies, dopant atoms, grain boundaries, and interfacial defects modifies the electronic structure of SnO₂, increases intrinsic electrical conductivity, generates additional lithium-storage active sites, and accelerates Li⁺ adsorption and diffusion. However, excessive defect concentrations may induce irreversible side reactions and unstable SEI growth, emphasizing the importance of precisely controlling defect density to maximize electrochemical efficiency and long-term cycling stability (Muhammad et al., 2026; Zhanget al., 2026b).

Overall, the development of high-performance SnO₂-based nanocomposite anodes requires the synergistic integration of multiple structural and compositional design strategies rather than reliance on a single modification approach (Wang et al., 2026). Carbon hybridization enhances electrical conductivity and mechanical flexibility; heterostructure engineering promotes interfacial charge transfer and synergistic electrochemical activity; morphology control optimizes ion diffusion kinetics and structural durability; porous architectures provide efficient ion-transport channels and volume-buffering space; and interface/defect engineering improves electronic conductivity, reaction kinetics, and surface reactivity (Li et al., 2025). Through the rational combination of these complementary strategies, SnO₂-based nanocomposites effectively overcome the intrinsic limitations of pristine SnO₂, resulting in higher reversible capacity, superior Coulombic efficiency, enhanced rate capability, prolonged cycling stability, and greater potential for practical implementation in next-generation lithium-ion batteries (Jia et al., 2026).

Table 6. Nanocomposites with controlled morphology and porous architecture.

Material	Specific capacity (mAh g ⁻¹)	Current density (mA g ⁻¹)	Capacity Retention After Cycling	Initial Coulombic Efficiency (ICE)	Reference	Structure/morphology
SnO ₂ Yolk-Shell	~1120	500	88% after 400 cycles	~74%	Pervaiz et al. (2025)	Encapsulated hollow spheres
SnO ₂ Framework 3D	~1050	1000	86% after 800 cycles	~71%	Hasan et al. (2026)	Ordered microporous
SnO ₂ nanotubes	~950	200	82% after 300 cycles	~69%	Mamil et al. (2025)	1D hollow
SnO ₂ /ZnO Hierarchical	~1280	100	90% after 200 cycles	~76%	Sun et al. (2024)	Micro/Mesoporous

Source: Authors, 2026.

6. Electrochemical performance of SnO₂-based nanocomposite anodes

The electrochemical performance of SnO₂-based nanocomposite anodes is commonly evaluated through specific capacity, cycling stability, rate capability, and Coulombic efficiency, as these parameters collectively determine their practical suitability for lithium-ion batteries. Pristine SnO₂ possesses a high theoretical capacity because lithium storage occurs through both conversion and alloying/dealloying reactions. However, its practical performance is usually limited by poor electronic conductivity, large volume variation, unstable solid electrolyte

interphase formation, and gradual structural degradation. The development of SnO₂-based nanocomposites has therefore become an effective approach to improve electrochemical behavior by enhancing charge transport, stabilizing the electrode structure, and maintaining reversible lithium-storage reactions during repeated cycling (Zhao et al., 2025).

Specific capacity is one of the most important indicators of lithium-storage ability. SnO₂-based nanocomposites generally show higher reversible capacity than pristine SnO₂ because the incorporation of conductive carbon materials, secondary metal oxides, sulfides, or other functional components increases electrical conductivity and improves the utilization of active material. Nanostructured designs such as nanoparticles, hollow spheres, nanosheets, nanorods, and porous frameworks provide a larger electrode–electrolyte contact area and expose more active sites for Li⁺ insertion and extraction. In addition, defect-rich interfaces and heterostructures can introduce extra lithium-storage sites and promote faster charge-transfer reactions. As a result, well-designed SnO₂ nanocomposites can deliver high reversible capacities, especially when the active SnO₂ phase is uniformly dispersed within a conductive and mechanically stable matrix (Zhao et al., 2025).

Cycling stability is a major challenge for SnO₂-based anodes because repeated lithiation and delithiation cause severe volume expansion and contraction. This volume fluctuation can lead to particle pulverization, loss of electrical contact, continuous SEI reconstruction, and rapid capacity fading. Nanocomposite engineering greatly improves cycling stability by introducing flexible buffering components and stable structural frameworks. Carbon coatings, graphene networks, carbon nanotubes, and porous carbon matrices can accommodate mechanical stress and preserve electron pathways during long-term cycling. Similarly, hollow and porous architectures provide internal void space to reduce structural strain, while heterostructured interfaces help maintain the integrity of the electrode. These design features suppress electrode cracking and active material detachment, resulting in improved capacity retention over extended charge–discharge cycles (Sun et al., 2024).

Rate capability reflects the ability of an electrode to deliver capacity at high current densities. For SnO₂-based anodes, rate performance is strongly influenced by electronic conductivity, Li⁺ diffusion kinetics, and the accessibility of active sites. Pristine SnO₂ often shows poor rate capability because of sluggish charge transfer and limited ion diffusion. In contrast, SnO₂-based nanocomposites can maintain considerable capacity even at high current rates due to shortened Li⁺ diffusion pathways, improved electrolyte penetration, and enhanced electron transport. Conductive networks formed by graphene, carbon nanotubes, carbon nanofibers, or amorphous carbon reduce internal resistance and facilitate rapid electron movement. At the same time, nanoscale morphology and porous structures accelerate Li⁺ migration by providing open channels and reducing diffusion distances. Therefore, optimized SnO₂ nanocomposites show better high-rate performance and faster electrochemical response than bulk or pristine SnO₂ (Sun et al., 2024).

Coulombic efficiency is another important parameter that indicates the reversibility of lithium insertion and extraction during cycling. SnO₂-based anodes often show low initial Coulombic efficiency because of irreversible conversion reactions, formation of Li₂O, electrolyte decomposition, and SEI formation during the first discharge process. However, after the initial cycles, a stable SnO₂ nanocomposite structure can promote higher Coulombic efficiency by reducing continuous side reactions and stabilizing the electrode–electrolyte interface. Carbon coating, surface modification, and interface engineering are particularly useful for forming a more uniform and stable SEI layer. A stable SEI prevents excessive electrolyte consumption, improves reaction reversibility, and contributes to long-term capacity retention. In this way, improved Coulombic efficiency is closely related to better structural stability and controlled interfacial chemistry.

Overall, the electrochemical performance of SnO₂-based nanocomposite anodes depends on the successful balance between high capacity, structural durability, fast reaction kinetics, and interfacial stability. High specific capacity is achieved through efficient utilization of SnO₂ and additional active interfaces, while cycling stability is improved by buffering volume changes and preventing structural collapse. Enhanced rate capability results from improved electron conductivity and shortened Li⁺ diffusion pathways, whereas high Coulombic efficiency is obtained by stabilizing the SEI and minimizing irreversible reactions. Therefore, rationally designed SnO₂-based nanocomposites offer a promising route toward high-performance lithium-ion battery anodes with improved reversible capacity, long cycle life, strong rate performance, and stable electrochemical efficiency.

7. Structure performance relationship

The electrochemical performance of SnO₂-based nanocomposite anodes is strongly governed by their structural features, including particle size, morphology, porosity, crystallinity, conductive network formation, interface quality, and defect concentration. Since SnO₂ undergoes both conversion and alloying/dealloying reactions

during lithium storage, its structure must be carefully designed to accommodate large volume changes, maintain continuous electron transport, and allow rapid Li^+ diffusion. Therefore, understanding the structure–performance relationship is essential for developing high-capacity, long-life, and high-rate SnO_2 -based anode materials (Khan et al., 2025).

Particle size has a direct influence on lithium-storage behavior. Nanosized SnO_2 particles provide shorter Li^+ diffusion pathways and larger surface area compared with bulk SnO_2 , which improves reaction kinetics and increases the number of accessible active sites. However, extremely small particles may cause excessive surface reactions with the electrolyte, leading to unstable solid electrolyte interphase formation and low initial Coulombic efficiency. Therefore, an optimized nanoscale size is required to balance high capacity with interfacial stability. Uniform dispersion of SnO_2 nanoparticles within a conductive matrix is especially important because it prevents particle aggregation and maintains effective electrical contact during repeated charge–discharge cycles (Khan et al., 2026).

Morphology also plays a key role in determining electrochemical performance. One-dimensional structures such as nanowires, nanotubes, and nanorods provide direct electron-transport pathways and improve mechanical stability. Two-dimensional nanosheets expose abundant active sites and facilitate electrolyte contact, while three-dimensional hierarchical architectures combine high surface area, structural robustness, and efficient ion/electron transport. Hollow and yolk–shell structures are particularly effective for SnO_2 -based anodes because their internal void spaces can accommodate volume expansion during lithiation, reducing mechanical stress and preventing structural pulverization. As a result, morphology-controlled SnO_2 nanocomposites generally show improved cycling stability and rate capability (Hussain et al., 2026).

Porosity is another important structural factor that affects battery performance. Porous SnO_2 -based composites provide interconnected channels for electrolyte penetration and Li^+ migration, which enhances charge-transfer efficiency and improves rate performance. The presence of mesopores and macropores can buffer volume expansion and reduce electrode cracking, while micropores may contribute additional active sites for lithium storage. However, excessive porosity may reduce tap density and volumetric energy density, which can limit practical application. Therefore, a well-balanced porous structure is needed to achieve both high gravimetric capacity and acceptable electrode density (Welegergs et al., 2025).

The incorporation of conductive networks is critical because SnO_2 has poor intrinsic electrical conductivity. Carbon materials such as graphene, reduced graphene oxide, carbon nanotubes, carbon nanofibers, and amorphous carbon can form continuous conductive pathways that accelerate electron transport and reduce internal resistance. These carbon frameworks also improve structural flexibility and help maintain electrode integrity during repeated volume expansion and contraction. A well-integrated SnO_2 /carbon interface ensures efficient charge transfer and prevents active material isolation, leading to higher reversible capacity, better rate capability, and longer cycle life (Nelwamondo et al., 2024).

Interface engineering strongly affects the reversibility and stability of SnO_2 -based nanocomposite anodes. Heterointerfaces between SnO_2 and other metal oxides, sulfides, phosphides, or carbonaceous materials can create synergistic effects that enhance charge redistribution, promote Li^+ adsorption, and improve reaction kinetics. These interfaces may also generate built-in electric fields, which facilitate electron and ion transport. Moreover, stable interfaces help suppress continuous SEI reconstruction and reduce unwanted side reactions with the electrolyte. As a result, well-designed heterostructures often exhibit higher capacity retention and improved Coulombic efficiency compared with single-component SnO_2 (Ikhioya et al., 2024).

Defects and crystallinity also influence the electrochemical behavior of SnO_2 . Oxygen vacancies, dopant atoms, grain boundaries, and lattice distortions can improve electronic conductivity and provide additional lithium-storage sites. Defect-rich structures can accelerate charge transfer and enhance Li^+ diffusion, contributing to improved rate performance. However, excessive defects may increase irreversible reactions and destabilize the electrode–electrolyte interface. Similarly, crystallinity must be carefully controlled. Highly crystalline SnO_2 may offer better structural order and stability, while amorphous or partially crystalline structures can provide more active sites and better strain tolerance. Therefore, an appropriate balance between crystallinity and defect concentration is necessary for optimal performance (Noukelag et al., 2023).

Overall, the structure–performance relationship of SnO_2 -based nanocomposite anodes shows that no single structural parameter alone determines electrochemical performance. High capacity is mainly associated with abundant active sites, nanoscale dimensions, and efficient utilization of SnO_2 . Cycling stability depends on structural buffering, strong interfaces, and stable conductive networks. Rate capability is improved by short Li^+ diffusion paths, open porous channels, and fast electron transport. Coulombic efficiency is closely related to

controlled surface chemistry and stable SEI formation. Therefore, rational structural design that integrates nanoscale morphology, porous architecture, conductive frameworks, heterointerfaces, and controlled defects is essential for developing advanced SnO₂-based nanocomposite anodes for next-generation lithium-ion batteries.

8. Future perspectives

SnO₂-based nanocomposite anodes have shown strong potential for next-generation lithium-ion batteries because of their high theoretical capacity, multiple lithium-storage reactions, tunable nanostructures, and compatibility with various conductive and buffering components. However, despite significant progress, several challenges must still be addressed before these materials can be practically used in commercial batteries. Future research should focus on developing SnO₂-based anodes with high reversible capacity, long-term cycling stability, high initial Coulombic efficiency, excellent rate capability, and scalable synthesis routes.

One important future direction is the precise control of nanocomposite architecture. Although nanosizing improves lithium-ion diffusion and increases active surface area, excessive surface exposure can cause serious electrolyte decomposition and unstable SEI formation. Therefore, future designs should aim for optimized particle size, controlled porosity, and stable hierarchical structures that balance high electrochemical activity with interfacial stability. Hollow, yolk-shell, porous, and core-shell structures remain promising because they can buffer volume expansion while maintaining efficient charge transport. However, these architectures must be simplified for large-scale production and should maintain structural integrity under high mass loading conditions.

Another key research area is interface and defect engineering. Rationally designed interfaces between SnO₂ and carbon materials, metal oxides, sulfides, phosphides, or other functional components can improve electronic conductivity, promote Li⁺ diffusion, and enhance reaction reversibility. Controlled defects such as oxygen vacancies and doped sites may also provide additional active sites and improve charge-transfer kinetics. However, excessive defects can trigger irreversible side reactions and reduce Coulombic efficiency. Therefore, future studies should focus on controlled defect generation, stable interfacial bonding, and a deeper understanding of how interfacial chemistry affects SEI formation and lithium-storage behavior.

Improving initial Coulombic efficiency is also essential for practical application. SnO₂-based anodes often suffer from irreversible lithium consumption during the first discharge process due to SEI formation, electrolyte decomposition, and incomplete reversibility of the conversion reaction. Future work should explore surface coatings, artificial SEI layers, electrolyte additives, prelithiation strategies, and stable electrode-electrolyte interface designs to reduce initial lithium loss. These approaches can improve energy density and make SnO₂-based anodes more compatible with full-cell battery systems.

From a practical point of view, more attention should be given to full-cell evaluation rather than only half-cell testing. Many SnO₂-based nanocomposites show excellent performance in laboratory half-cells using lithium metal as the counter electrode, but their real performance in full cells with commercial cathodes may be different. Future research should therefore investigate full-cell configurations, realistic electrode mass loading, limited electrolyte conditions, long-term cycling, and practical areal capacity. In addition, volumetric energy density should be considered because highly porous or low-density structures may show high gravimetric capacity but poor practical packing density.

Scalable, low-cost, and environmentally friendly synthesis methods are another major requirement for future development. Many reported SnO₂-based nanocomposites are prepared using complex multi-step routes, expensive precursors, high-temperature treatments, or laboratory-scale methods. To move toward commercialization, synthesis strategies should be simple, reproducible, energy-efficient, and suitable for large-scale production. Green synthesis, aqueous processing, low-temperature methods, and binder-compatible electrode fabrication should be further explored. The stability of these materials during electrode preparation, slurry mixing, calendaring, and cell assembly should also be carefully evaluated.

Advanced characterization and theoretical modeling will play an important role in future studies. In situ and operando techniques such as in situ XRD, Raman spectroscopy, TEM, XPS, and electrochemical impedance analysis can provide deeper insight into structural evolution, phase transformation, SEI formation, and reaction kinetics during cycling. Density functional theory calculations and machine-learning-assisted material screening can further help identify favorable compositions, interfaces, dopants, and structural designs. Combining experimental and theoretical approaches will provide a clearer understanding of the relationship between structure, interface, and electrochemical performance.

Overall, the future development of SnO₂-based nanocomposite anodes should move beyond achieving high capacity alone. Practical performance requires a balanced combination of high capacity, stable cycling, fast kinetics, high Coulombic efficiency, scalable synthesis, and full-cell compatibility. By integrating rational nanostructure design, conductive network construction, interface optimization, defect regulation, and practical electrode engineering, SnO₂-based nanocomposites may become promising high-performance anode materials for advanced lithium-ion batteries.

8.1 Commercialization prospects and industrial readiness of SnO₂-based anodes

Although SnO₂-based nanocomposite anodes have demonstrated remarkable electrochemical performance at the laboratory scale, their transition toward commercial lithium-ion batteries remains limited. Most reported materials are currently positioned between Technology Readiness Levels (TRLs) 2–4, where research is focused on proof-of-concept, laboratory validation, and optimization of material properties. Only a small number of studies have progressed toward pilot-scale electrode fabrication or full-cell validation under industrially relevant conditions. Consequently, increasing the TRL of SnO₂-based anodes requires not only improvements in electrochemical performance but also advances in scalable manufacturing, cost reduction, process reproducibility, and compatibility with existing battery production lines (Eshetu et al., 2021; Schwan et al., 2020).

From an industrial perspective, commercial lithium-ion battery manufacturers such as Tesla, BYD, CATL, and Panasonic currently rely predominantly on graphite-based anodes or graphite reinforced with small amounts of silicon or silicon oxide rather than SnO₂. Silicon-containing composite anodes have already entered commercial batteries because they provide moderate increases in energy density while remaining compatible with conventional slurry preparation, coating, drying, calendaring, and cell assembly processes. Tesla and Panasonic, for example, have adopted silicon-containing graphite anodes in several commercial battery platforms, demonstrating that gradual incorporation of high-capacity materials is presently more attractive than complete replacement of graphite (Feyzi et al., 2025).

Compared with silicon, SnO₂ offers several attractive characteristics for industrial applications. Tin dioxide is abundant, environmentally benign, relatively inexpensive, and can be synthesized using well-established hydrothermal, sol-gel, precipitation, spray pyrolysis, and thermal oxidation routes (Schwan et al., 2020). Furthermore, SnO₂ exhibits greater chemical stability than many alloy-type anodes and can be integrated with numerous conductive matrices, including graphene, carbon nanotubes, porous carbon, MXenes, and conductive polymers. Nevertheless, its severe volume expansion, low intrinsic electrical conductivity, unstable solid electrolyte interphase formation, and relatively low initial Coulombic efficiency still hinder large-scale commercialization. These drawbacks increase manufacturing complexity because they require advanced nanostructuring, surface engineering, and optimized electrode formulations (Schwan et al., 2020).

Another important challenge concerns industrial scalability. Many high-performance SnO₂ nanocomposites reported in the literature are synthesized through multistep laboratory procedures involving hydrothermal treatment, freeze drying, electrospinning, chemical vapor deposition, or template-assisted synthesis. Although these approaches produce outstanding electrochemical properties, they frequently require expensive precursors, long processing times, high energy consumption, or low production yields, making large-scale manufacturing difficult (Schwan et al., 2020). Future research should therefore prioritize continuous, low-cost, environmentally friendly, and scalable synthesis routes that are compatible with existing lithium-ion battery manufacturing infrastructure (Eshetu et al., 2021).

Industrial implementation also depends on electrode-level metrics rather than only material-level performance. Commercial battery manufacturers typically require electrodes with high areal capacity (>3–4 mAh cm⁻²), high tap density, stable cycling under limited electrolyte conditions, excellent mechanical integrity during calendaring, and compatibility with roll-to-roll manufacturing processes. Consequently, future studies should increasingly evaluate SnO₂-based anodes under practical electrode loadings, full-cell configurations, industrial binders, commercial electrolytes, and realistic cycling protocols (Eshetu et al., 2021). Such investigations will provide a more accurate assessment of the true commercial potential of SnO₂ nanocomposites.

Overall, SnO₂-based nanocomposites possess considerable long-term commercial potential because they combine high theoretical capacity with relatively low raw-material cost and versatile structural engineering. However, unlike silicon-containing graphite anodes that have already reached industrial deployment, SnO₂-based systems still require significant advances in electrode engineering, manufacturing scalability, cost-effective synthesis, and industrial validation before reaching commercial maturity (Eshetu et al., 2021; Feyzi et al., 2025). Bridging the gap between laboratory demonstrations and industrial battery production will therefore represent

one of the major research priorities for next-generation lithium-ion battery technology.

9. Current research gaps

Despite the remarkable progress achieved in the development of SnO₂-based nanocomposite anodes, several fundamental and technological challenges remain unresolved. Addressing these research gaps is essential to bridge the transition from laboratory-scale demonstrations to commercially viable lithium-ion batteries.

One of the most significant research gaps concerns the lack of standardized electrochemical evaluation protocols. Most published studies employ different electrode compositions, electrolyte formulations, current densities, voltage windows, and cycling conditions, making direct comparisons among reported SnO₂ nanocomposites difficult. The adoption of standardized testing protocols, including practical mass loading, limited electrolyte conditions, and full-cell configurations, would greatly improve the reliability and reproducibility of future investigations (Eshetu et al., 2021; Zhao et al., 2025).

Another important limitation is the continued reliance on half-cell testing using lithium metal counter electrodes. Although half-cell configurations provide valuable mechanistic information, they often overestimate electrochemical performance compared with practical battery systems. Future studies should increasingly prioritize full-cell evaluation using commercially relevant cathodes, realistic electrode balancing, industrial binders, and high areal capacities to better assess the true application potential of SnO₂-based anodes (Eshetu et al., 2021; Feyzi et al., 2025).

The relationship between nanostructure and electrochemical performance also remains insufficiently understood. Numerous studies report improved battery performance through carbon hybridization, heterostructure engineering, morphology control, or defect engineering; however, the individual contribution of each design parameter is often difficult to distinguish because several modification strategies are simultaneously employed. More systematic investigations combining experimental characterization with theoretical modeling are needed to establish quantitative structure–property relationships (Schwan et al., 2020; Sunjaya et al., 2026).

Interfacial chemistry represents another major knowledge gap. Although the formation and evolution of the solid electrolyte interphase (SEI) largely determine cycling stability and Coulombic efficiency, its dynamic behavior on SnO₂-based nanocomposites remains poorly understood. Advanced operando characterization techniques, including operando X-ray diffraction, transmission electron microscopy, Raman spectroscopy, X-ray photoelectron spectroscopy, neutron scattering, and synchrotron-based methods, should be increasingly employed to monitor structural evolution and interfacial reactions during battery operation (Eshetu et al., 2021; Sun et al., 2026).

Another underexplored area involves data-driven materials discovery. Artificial intelligence, machine learning, and density functional theory (DFT) calculations have demonstrated considerable potential for predicting stable interfaces, identifying optimal dopants, screening nanocomposite architectures, and accelerating materials discovery. Nevertheless, these computational approaches remain relatively underutilized in SnO₂ research compared with experimental trial-and-error strategies. Greater integration between computational design and experimental validation may significantly shorten the development cycle of next-generation anode materials (Feyzi et al., 2025; Sunjaya et al., 2026).

Scalable manufacturing also remains a critical bottleneck. Many high-performance SnO₂ nanocomposites rely on complex synthesis routes involving hydrothermal reactions, electrospinning, freeze drying, chemical vapor deposition, or template-assisted fabrication, which are difficult to scale economically. Future research should prioritize simple, continuous, low-cost, environmentally friendly, and energy-efficient manufacturing processes that are compatible with existing roll-to-roll electrode production technologies (Schwan et al., 2020).

Finally, insufficient attention has been devoted to practical industrial requirements. While most studies emphasize gravimetric capacity, considerably fewer investigate volumetric energy density, tap density, electrode density, mechanical integrity after calendaring, long-term storage stability, manufacturing reproducibility, recycling, and life-cycle assessment. These factors are increasingly recognized as decisive parameters for industrial adoption and should become central objectives of future research rather than secondary considerations (Eshetu et al., 2021).

Overall, future progress in SnO₂-based nanocomposite anodes will depend not only on achieving higher laboratory capacities but also on establishing standardized testing methodologies, improving mechanistic understanding, integrating computational materials design, developing scalable synthesis technologies, and validating performance under realistic commercial battery conditions. Addressing these research gaps will be

essential for advancing SnO₂-based materials from fundamental research toward practical implementation in next-generation lithium-ion batteries.

10. Conclusions

SnO₂-based nanocomposites have emerged as one of the most promising alternatives to conventional graphite anodes because they combine a high theoretical capacity (1494 mAh g⁻¹), abundant raw materials, relatively low cost, and remarkable structural versatility. Unlike graphite, SnO₂ stores lithium through both conversion and alloying/dealloying reactions, enabling significantly higher lithium-storage capacity. However, its practical implementation continues to be limited by poor intrinsic electrical conductivity, severe volume expansion during cycling, unstable solid electrolyte interphase (SEI) formation, and low initial Coulombic efficiency.

This review demonstrates that no single modification strategy is sufficient to overcome all intrinsic limitations of SnO₂. Instead, the best electrochemical performance is consistently achieved through the synergistic integration of multiple design approaches. Among the available strategies, carbon hybridization combined with heterostructure engineering appears to be the most promising because conductive carbon frameworks simultaneously improve electronic conductivity, buffer mechanical stress, and stabilize the electrode structure, while heterointerfaces accelerate charge transfer, facilitate lithium-ion diffusion, and enhance reaction reversibility. When these approaches are further combined with rational morphology control, porous architectures, and interface/defect engineering, substantial improvements in reversible capacity, cycling stability, rate capability, and Coulombic efficiency can be achieved.

Despite these advances, significant challenges remain before SnO₂-based anodes can be commercially deployed. Most reported materials still exhibit relatively low initial Coulombic efficiency, insufficient long-term stability under practical electrode loadings, and synthesis routes that are difficult to scale economically. Furthermore, many studies continue to evaluate electrochemical performance only in half-cell configurations using lithium metal counter electrodes, whereas industrial implementation requires validation under realistic full-cell conditions, high areal capacities, limited electrolyte volumes, and commercially relevant manufacturing processes. These issues currently represent the principal barriers preventing SnO₂-based nanocomposites from reaching high technology readiness levels and large-scale industrial adoption.

From a broader perspective, SnO₂ is unlikely to completely replace graphite or silicon in the near future. Instead, it is more likely to become part of multifunctional composite anodes in which each component contributes complementary electrochemical and mechanical properties. Such hybrid electrode architectures may provide a practical balance between high energy density, structural stability, safety, cost, and manufacturability. Consequently, future commercial batteries may increasingly incorporate SnO₂ as a functional component rather than as a single active material.

Future research should therefore move beyond maximizing specific capacity alone and focus on practical battery engineering. Priority should be given to scalable and environmentally friendly synthesis methods, high-mass-loading electrodes, improved initial Coulombic efficiency, artificial SEI design, advanced operando characterization, computationally guided material optimization, and systematic full-cell evaluation under industrially relevant conditions. Integrating these approaches will accelerate the transition of SnO₂-based nanocomposites from laboratory-scale materials toward commercially viable next-generation lithium-ion batteries.

Overall, SnO₂-based nanocomposites represent a highly promising class of advanced anode materials whose future success will depend less on achieving record-breaking laboratory capacities and more on balancing electrochemical performance with industrial scalability, manufacturing compatibility, cost-effectiveness, and long-term operational reliability. Bridging this gap between fundamental materials research and practical battery engineering will ultimately determine whether SnO₂ can become a key component of future high-energy lithium-ion batteries.

11. Authors' Contributions

Ibrahim: contributed to study conceptualization, methodology design, data collection, and initial manuscript drafting. *Azmat Ali Khan*: contributed to data analysis, interpretation of results, and critical revision of the manuscript. *Shah Zeb*: assisted in literature review, data interpretation, and manuscript editing. *Esha Noor*: supported data organization, validation, and formatting of the manuscript. *Jalal Amir*: provided technical review, supervision, and refinement of the research structure. *Ajmal Shah*: supervised the overall research work,

provided critical feedback, and approved the final manuscript.

12. Conflicts of Interest

No conflicts of interest.

13. Ethics Approval

Not applicable.

14. References

- Ahmad, F., Ahmad, N., Al-Khazaal, A. A. Z. J. E., Technology, & Research, A. S. (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, F., Al-Khazaal, A. Z., Ahmad, N., Alenezi, I. J. E., Technology, & Research, A. S. (2018). Remediation of sulfidic wastewater by aeration in the presence of ultrasonic vibration. *Engineering, Technology & Applied Science Research*, 8(3), 2919-2922.
- 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, F., Maitra, S., & Ahmad, N. (2017). Treatment of sulfidic wastewater using iron salts. *Arabian Journal for Science and Engineering*, 42(4), 1455-1462. <https://doi.org/10.1007/s13369-016-2315-z>
- 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. *Environmental Science and Pollution Research*, 32(40), 23054-23067. <https://doi.org/10.1007/s11356-025-37028-5>
- Ahmad, N. (2013). Relationship between rheology and molecular structure of innovative crystalline elastomers. Thesis for the Degree of Doctor of Philosophy. Department of Chemistry. University of Naples, Federico II, Italy.
- Ahmad, N., Ahmad, F., & Alenezi, I. (2021). Influence of starch content on the thermal and viscoelastic properties of syndiotactic polypropylene/starch composites. *Engineering, Technology & Applied Science Research*, 11(3), 7228-7232. <https://doi.org/10.48084/etasr.4161>
- Ahmad, N., Ahmad, F., Khan, I., & Khan, A. D. (2015). Studies on the oxidative removal of sodium thiosulfate from aqueous solution. *Arabian Journal for Science and Engineering*, 40(2), 289-293. <https://doi.org/10.1007/s13369-014-1473-0>
- 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., 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>
- Ahmad, N., & Fouad, E. (2017). Influence of clay contents on rheology of syndiotactic polypropylene/clay composites. *Arabian Journal for Science and Engineering*, 42(4), 1537-1543. <https://doi.org/10.1007/s13369-016-2389-7>
- Ahmad, N., Maitra, S., Dutta, B. K., & Ahmad, F. (2009). Remediation of sulfidic wastewater by catalytic oxidation with 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, N., Pasquino, R., & Grizzuti, N. (2012). Relazioni tra reologia e stereo-regolarità della catena polimerica. Il caso del polipropilene sindiotattico. In Atti del XII Convegno Nazionale della Società Italiana di Reologia, 175-180, Associazione Italiana di Reologia-SIR.
- 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, S., Akhtar, N., Fazil, P., Ahmad, M. S., Khan, J. A., Mirza, S., & Ateeq, M. (2026). Visible - light - active magnetic CuFe₂O₄ and Fe₃O₄ nanoparticles: efficient photocatalysts for allura red dye degradation with enhanced antibacterial activity. *ChemistrySelect*, 11(16), e05042. <https://doi.org/10.1002/slct.202505042>
- Ahmed, I., Ali, M., Ahmad, N., & Ahmad, I. (2015). Production of biodiesel from algae. *Journal of Pure and Applied Microbiology*, 9(1), 79-85.
- Ahmed, S., Arshad, T., Zada, A., Afzal, A., Khan, M., Hussain, A., & Xu, S. (2021). Preparation and characterization of a novel sulfonated titanium oxide incorporated chitosan nanocomposite membranes for fuel cell application. *Membranes*, 11(6), 450. <https://doi.org/10.3390/membranes11060450>
- Akhtar, N., Ullah, H., Zada, A., Azizi, S., Ateeq, M., & Khan, J. A. (2025). CO₂ Reduction Reimagined: From Light-Driven to Electrocatalytic Pathways with Computational Insight Towards Enhanced Product Selectivity. *Carbon Capture Science & Technology*, 17, 100536. <https://doi.org/10.1016/j.ccst.2025.100536>
- Al-Khazaal, A. Z., Ahmad, F., & Ahmad, N. (2019). Study on the removal of thiosulfate from wastewater by catalytic oxidation. *Engineering, Technology & Applied Science Research*, 9(2), 4053-4056.
- Al-Khazaal, A. Z., & 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>
- Ali, S., Ali, S., Ismail, A., Iqbal, A., Wang, Y., Bakhtiar, S. H., & Raziq, F. (2026). Defective CeO₂/copper phthalocyanine s - scheme heterojunctions with molecular copper centers for selective CO₂ - To - CO photoconversion. *Electron*, e70050. <https://doi.org/10.1002/elt2.70050>
- Alsaiani, M., Roghani, K., Liaqat, S., Alkorbi, A. S., Sharif, F., Irfan, M., Rizk, M. A., Uroos, M., & Ahmad, 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, Husain, K., Alrefaee, S. H., Elhadi, M., Abduvalieva, D., Abiyev, A., . . . Materials. (2025). First-principles investigation of structural, electronic, mechanical and optical properties of TI based semiconducting perovskites TlVX₃ (X= Br, I) for reflective coating applications. *Journal of Inorganic and Organometallic Polymers and Materials*, 35(8), 6479-6490. <https://doi.org/10.1007/s10904-025-03670-2>
- Anwar, N., Shah, M., Anwar, S. H., Shah, M. I. A., Zada, A., Jan, H. A., Abd-Allah, E. F. (2025). Bio-catalytic activity of novel poly (ethylene glycol) methacrylate hybridized silver nanomaterials. *South African Journal of Botany*, 176, 197-206. <https://doi.org/10.1016/j.sajb.2024.11.017>
- Arshad, S. A., Ali, U. N., Taqvi, S. A. A., Kazmi, B., Khalid, A., & Ahmer, M. (2025). Towards sustainable methanol production: energy, exergy, economics, and environmental evaluation of Thar coal gasification. *Environment, Development and Sustainability*, 1-27. <https://doi.org/10.1007/s10668-025-06451-6>
- Aziz, S., Javed, R., Nowak, A., Liaqat, S., Khan, Z. U. H., Ahmad, N., & Muhammad, N. (2023). Effects of TiO₂, Ag-TiO₂, and Cu-TiO₂ nanoparticles on mechanical and anticariogenic properties of conventional pit and fissure sealants. *OpenNano*, 14, 100185. <https://doi.org/10.1016/j.onano.2023.100185>
- Bakhtiar, S. U. H., Zada, A., Raziq, F., Ali, S., Shah, M. I. A., Ateeq, M., Naeem, M. (2023). Zinc phthalocyanine sensitized g-C₃N₄ photocatalyst for exceptional photocatalytic hydrogen evolution and pollutant degradation. *International Journal of Hydrogen Energy*, 48(43), 16320-16329. <https://doi.org/10.1016/j.ijhydene.2023.01.152>
- Bashir, F., Muhammad, N., Alshamrani, M., Uroos, M., Salawi, A., Safhi, A. 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(4), 2277-2286.
- 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*, 502, 158185. <https://doi.org/10.1016/j.cej.2024.158185>
- Chetry, M., Feng, R., Babar, S., Sun, H., Zafar, I., Mohany, M., . . . Shafiq, M. J. P. C. S. (2025). Early detection and analysis of accurate breast cancer for improved diagnosis using deep supervised learning for enhanced

- patient outcomes. *Peer Journal Computer Science*, 11, e2784. <https://doi.org/10.7717/peerj-cs.2784>
- Courtney, I. A., & Dahn, J. R. (1997). Electrochemical and in situ X-ray diffraction studies of the reaction of lithium with tin oxide composites. *Journal of The Electrochemical Society*, 144(6), 2045-2052.
- Courtney, I. A., & Dahn, J. R. (1997). Key factors controlling the reversibility of the reaction of lithium with SnO₂ and Sn₂BPO₆ glass. *Journal of The Electrochemical Society*, 144(9), 2943-2948.
- Del Toro, F., Sun, H., Robinson, C., Jiménez, Á., Coviellas, E., Higuera, T., & Canto, T. (2022). In planta vs viral expression of HCPro affects its binding of nonplant 21 – 22 nucleotide small RNAs, but not its preference for 5' - terminal adenines, or its effects on small RNA methylation. *New Phytologist*, 233(5), 2266-2281. <https://doi.org/10.1111/nph.17935>
- Deng, Z., Xiang, Z., Zhu, S., Zhang, Y., Du, Y., Wang, S., & Liu, Y. (2025). Switching cathodic/anodic electrochemiluminescence of Ru (bpy) 32+ precisely via homogeneous nickel nanoparticles crystal facets sites modulated ORR/OER. *Exploration*, 5(5), 20250036. <https://doi.org/10.1002/EXP.20250036>
- Deng, P., Yang, J., Li, S., Fan, T-E., Wu, H-H., Huang, H., Zhang, Q., Peng, D-L., & Qu, B. (2019). High initial reversible capacity and long life of ternary SnO₂-Co-carbon nanocomposite anodes for lithium-ion batteries. *Nano-Micro Letters*, 11. <https://doi.org/10.1007/s40820-019-0246-4>
- Eshetu, G. G., Zhang, H., Judez, X., Adenusi, H., Armand, M., Passerini, S., & Figgemeier, E. (2021). Production of high-energy Li-ion batteries comprising silicon-containing anodes and insertion-type cathodes. *Nature Communications*, 12, 5459. <https://doi.org/10.1038/s41467-021-25334-8>
- Fahim, K. E., Silva, L. C. D., 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. *Energy Engineering*, 122(10). <http://dx.doi.org/10.32604/ee.2025.066484>
- Fattakhova-Rohlfing, D., Zoller, F., Böhm, D., & Bein, T. (2019). Tin oxide-based nanomaterials and their application as anodes in lithium-ion batteries and beyond. *ChemSusChem*, 12(18), 4140-4159.
- Ferraresi, G., Villevieille, C., Czekaj, I., Horisberger, M., Novák, P., & El Kazzi, M. E. (2018). SnO₂ model electrode cycled in Li-ion battery reveals the formation of Li₂SnO₃ and Li₈SnO₆ phases through conversion reactions. *ACS Applied Materials & Interfaces*, 10(10), 8712-8720. <https://doi.org/10.1021/acsami.7b19481>
- Feyzi, E., Anil, M. R. K., Li, X., Deng, S., Nanda, J., & Zaghib, K. (2025). A comprehensive review of silicon anodes for high-energy lithium-ion batteries: Challenges, latest developments, and perspectives. *Next Energy*, 5, 100176. <https://doi.org/10.1016/j.nxener.2024.100176>
- Gasimova, A., Manavalan, R. K., Hussain, S., Ahmad, N., & Elboughdiri, N. (2025). Co-Precipitation Synthesis of Tunable Cd. *Journal of Nanoelectronics and Optoelectronics*, 20, 1-7. <https://doi.org/10.1166/jno.2025.3827>
- Gul, M., Kashif, M., Muhammad, S., Azizi, S., Sun, H. J. C. G., & Design. (2025). Various methods of synthesis and applications of gold-based nanomaterials: a detailed review. *Cristal 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. (2026). Heterojunction-driven photocatalytic oxidation for synergistic pathogen and dye degradation in decentralized wastewater systems. *Environmental Science: Water Research & Technology*, 12(6), 1693-1712. <https://doi.org/10.1039/d6ew00043f>
- Hasan, M. N., Ishraque, M. F., Ahmed, M. S., Imam, F. T., Shezan, S. A., & Ahmad, N. (2026). An innovative method for enhanced energy management in hybrid power systems: Dual predator optimization (DPO). *Arabian Journal of Science and Engineering*, 51(6), 7269-7292. <https://doi.org/10.1007/s13369-025-10254-2>
- Hasan, M. N., Ishraque, M. F., Shezan, S. A., Kamwa, I., Ahmad, K., Alrwaili, A., & 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., Rahman, M. A., Ishraque, M. F., Ahmad, K., Shezan, S. A., & Ahmed, M. S. (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(3), 1-20. <https://doi.org/10.13044/j.sdewes.d13.0586>
- Hayat, A., Sohail, M., Hamdy, M. S., Mane, S. K. B., Amin, M. A., Zada, A., & Medina, D. I. (2022). Biomass

- lignin integrated polymeric carbon nitride for boosted photocatalytic hydrogen and oxygen evolution reactions. *Molecular Catalysis*, 518, 112064. <https://doi.org/10.1016/j.mcat.2021.112064>
- Hu, R., Chen, D., Waller, G., Ouyang, Y., Chen, Y., & Zhao, B. (2016). Dramatically enhanced reversibility of Li_2O in SnO_2 -based electrodes: the effect of nanostructure on high initial reversible capacity. *Energy & Environmental Science*, 9(2), 595-603. <https://doi.org/10.1039/c5ee03367e>
- Huang, J. Y. (2010). In situ observation of the electrochemical lithiation of a single SnO_2 nanowire electrode. *Science*, 330(6010), 1515-1520.
- Hussain, S., Kashif, M., Ali, M., Gul, M., Azizi, S., & Maaza, M. (2026). Ligand - engineered mesoporous silica: Cutting - edge architectures for targeted toxic heavy metal sequestration—A review. *Advances in Materials Sciences and Engineering*, 2026(1), 3228002. <https://doi.org/10.1155/amse/3228002>
- 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. *Optik*, 277, 170714. <https://doi.org/10.1016/j.ijleo.2023.170714>
- Hussain, T., Farhan, M., Kamran, Popa, I.-L., Ahmad, N., Alshammari, H. O., & Mahariq, I. (2025). Exact solutions of Einstein's field equations via homothetic symmetries of non-static plane symmetric spacetime. *Open Physics*, 23(1), 20250238. <https://doi.org/10.1515/phys-2025-0238>
- Idota, Y., Kubota, T., Matsufuji, A., Maekawa, Y., & Miyasaka, T. (1997). Tin-based amorphous oxide: A high-capacity lithium-ion-storage material. *Science*, 276(5317), 1395-1397.
- Ikhioya, I. M. L., Akpu, N. I., Onoh, E. U., Aisida, S. O., Ahmad, I., Maaza, M., & Ezema, M. (2024). Enhanced physical properties of nickel telluride metal chalcogenide material with molybdenum dopant. *Materials Research Innovations*, 28(1), 40-48.
- Ikram, S., Liaqat, S., Feroz, S., Sharif, F., Fawy, K. F., Ahmad, N., & Muhammad, N. (2025). Effect of zinc oxide-doped hydroxyapatite nanoparticles on the friction reduction and antibacterial properties of orthodontic ceramic brackets and stainless-steel wires. *Journal of Materials Science: Materials in Medicine*, 36(1), 1-13. <https://doi.org/10.1007/s10856-025-06958-4>
- Ishraque, M. F., Shezan, S. A., Kamwa, I., Li, Y., Shafiullah, G., & Ahmad, N. (2026). Novel intelligent model following controller and PQ droop controller operated nuclear-PV-bio gas hybrid microgrid and EV charging station. *Computer and Electrical Engineering*, 129, 110756. <https://doi.org/10.1016/j.compeleceng.2025.110756>
- Jabeen, H., Muhammad, N., Siddiqui, U., Sabir, M., Ahmad, N., & Liaqat, S. (2023). Effect of TiO_2 decorated cellulosic materials addition on mechanical and biological properties of dental adhesive composites. *Cellulose Chemistry Technology*, 57(5-6), 541-549.
- Jamal, M., Nabi, G. A. K., Sun, H., Ullah, K., Khattak, O. A., Kashif, M., & Ullah, M. (2024). Preparation of manganese-doped bismuth oxide for the photocatalytic degradation of methylene blue. *Archives of Advanced Engineering Science*, 1-7. <https://doi.org/10.47852/bonviewAAES42023402>
- Jamil, M., Shah, A., Aman, G., Shabir, F., Begum, R., Sun, H., & Aman, N. (2025). Bismuth vanadate nanoparticles: Structure, synthesis, and emerging engineering applications. *BIOMEDICAL Journal of Scientific & Technical Research*, 62(3). <https://dx.doi.org/10.26717/BJSTR.2025.62.009758>
- 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*, 20(8), 6513-6522. <https://doi.org/10.1007/s11468-025-02916-6>
- Jamila, N., Ullah, R., Khitab, F., Ahmad, N., Ahmad, F., Siddique Afridi, M., & Khan, N. (2025). 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*, 1-15. <https://doi.org/10.1080/00387010.2025.2602841>
- Jan, W., Khan, A., Iftikhar, F., Abbasi, M., Ali, G., Iwuoha, E., Shazhad, 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>
- Jia, B., Zhao, L., Tang, M., Xie, N., Huang, Y., Liang, X., Kwan, H. Y., Sun, H., & Xu, K. (2026). Neuron-tumor crosstalk in cancer: molecular mechanisms and translational advances. *Molecular Cancer*. <https://doi.org/10.1186/s12943-026-02715-5>

- Kashif, M., Jawad, M., Khan, A. A., Sun, H., Ullah, K., & Fakayode, O. (2024). Fe/Ti-codoped strontium oxide nanoparticles for enhanced photocatalytic degradation of methyl orange. *Journal of Applied Research in Water and Wastewater*, 11(1), 8-14.
- Kashif, M., Khan, A. A., Sun, H., Yousaf, J., Shah, M. I. A., Hussain, S., Ahmad, T. (2024). Synthesis and characterization of Fe-doped CuO nanoparticles: Catalytic efficiency in crystal violet dye degradation and exploration of electrical properties. *Brazilian Journal of Science*, 3(8), 1-18. <https://doi.org/10.14295/bjs.v3i8.601>
- Kashif, M., Sharif, T., Khan, S., Shahzad, N., Amir, J., Gul, M., Matinise, N. (2026). Synthesis strategies and multifaceted applications of molybdenum - based nanomaterials: A comprehensive review. *Scientifica*, 026(1), 1764400. <https://doi.org/10.1155/sci5/1764400>
- Khan, A. D., Khan, S. D., Khan, R., Ahmad, N., Ali, A., Khalil, A., & Khan, F. A. (2014). Generation of multiple Fano resonances in plasmonic split nanoring dimer. *Plasmonics*, 9(5), 1091-1102. <https://doi.org/10.1007/s11468-014-9719-y>
- Khan, A. D., Khan, S. D., Khan, 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(2), 461-475. <https://doi.org/10.1007/s11468-013-9644-5>
- Khan, H., Ullah, S., Khan, A. S., Nasrullah, A., Rehaman, A., Khan, P., Ahmed, 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*, 128496. <https://doi.org/10.1016/j.molliq.2025.128496>
- Khan, I., Khan, S., Wu, S. Y., Chen, H. T., Zada, A., Linlin, L., & Haider, M. (2023). Synergistic functionality of dopants and defects in Co - phthalocyanine/B - CN Z - scheme photocatalysts for promoting photocatalytic CO₂ reduction reactions. *Nano . Micro Small*, 19(25), 2208179. <https://doi.org/10.1002/smll.202208179>
- Khan, M., Hussain, A., Saleh, M. T., Ibrahim, M., Attique, F., Sun, X., & Khan, I. (2024). Cutting-edge advancements in MXene-derived materials: Revolutionary electrocatalysts for hydrogen evolution and high-performance energy storage. *Coordination Chemistry Reviews*, 506, 215722.
- Khan, M., Sun, X., Kashif, M., Zada, A., Azizi, S., Ragab, A. H., & Shehzad, K. (2025). Exploration of bismuth-based nanomaterials: From fundamental concepts to innovative synthesis techniques and emerging applications. *Coordination Chemistry Reviews*, 538, 216687. <https://doi.org/10.1016/j.ccr.2025.216687>
- Khan, S., Hussain, Z., Bibi, S., Kashif, M., Zubair, M., Azizi, S., & Maaza, M. (2026). Bias-free catalytic photoelectrochemical degradation of Congo Red using a boron-iron oxide coated electrode: A green and sustainable. *Catalysis Surveys from Asia*, 30(1), 64-76. <https://doi.org/10.1007/s10563-025-09465-2>
- Khan, S., Kalsoom, U., Kashif, M., Hussain, S. A., Gul, M., & Azizi, S. (2025). Smart and sustainable microplastic removal: Hybrid systems, bio-inspired technologies, real-time sensing, and policy integration. *Water, Air, & Soil Pollution*, 236(14), 900. <https://doi.org/10.1007/s11270-025-08468-z>
- Kim, H., Park, G. O., Muhammad, S., Yoo, J., Balasubramanian, M., Cho, Y-H., Kim, M-G., Lee, B., Kang, K., Kim, H., Kim, J. M., & Yoon, W-S. (2014). New insight into the reaction mechanism for exceptional capacity of ordered mesoporous SnO₂ electrodes via synchrotron-based X-ray analysis. *Chemistry of Materials*, 26(22), 6361-637. <https://doi.org/10.1021/cm5025603>
- Lan, X., Xiong, X., Liu, J., Yuan, B., Hu, R., & Zhu, M. (2022). Insight into reversible conversion reactions in SnO₂ - based anodes for lithium storage: a review. *Nano . Micro Small*, 18(26), 2201110. <https://doi.org/10.1002/smll.202201110>
- Li, J., Zhang, Y., Han, Y., Chen, J., Zada, A., & Han, Y. (2025). In-situ construction of Ni on fix-reduced graphene fibers by electroless plating strategy for extraordinary electromagnetic wave adsorption. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 139083. <https://doi.org/10.1016/j.colsurfa.2025.139083>
- Li, L., Mansor, Z., Ismail, F. F., Zhao, X., Guo, X., Sun, H., & Xu, Y. (2025). Compliance-aware and explainable GA-optimized neural network for cost estimation in safety-critical medical software. Research Square. <https://doi.org/10.21203/rs.3.rs-7593580/v1>
- Li, L., Mansor, Z., Zhao, X., Xiong, X., Guo, X., Li, X., & Sun, H. J. P. C. S. (2026). An explainable hyperparameter-optimized genetic algorithm-backpropagation (GA-BP) neural network model for medical

- software cost estimation. *Peer Journal Computer Science*, 12, e3477. <https://doi.org/10.7717/peerj-cs.3477>
- Li, Z., Sun, H., Chen, X., Peng, P., Sun, H., Chen, S., & Luo, Y. (2025). Integrated multiomics elucidates glutathione metabolic regulation in a marine aromatic probiotic yeast *Meyerozyma guilliermondii* GXDK6 under salt stress. *ACS Omega*, 10(41), 48965-48975. <https://doi.org/10.1021/acsomega.5c07376>
- Liu, X., Sun, Y., Liu, Y., Chen, J., Isaac, S. H. G., Zada, A., & Dang, A. (2026). Atomic-scale doping of rhenium on Ti₃C₂ MXene for noble-metal-free electromagnetic enhancement and ultra fast charge transfer resonance. *ACS Sensors*, 11(5), 4110-4120. <https://doi.org/10.1021/acssensors.6c00769>
- Maatki, C., Bilal, M., Ahmad, N., Ahmad, F., Alshammari, B. M., & Kriaa, K. (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>
- Madani, S. S., Habibi-Yangjeh, A., Asadzadeh-Khaneghah, S., Chand, H., Krishnan, V., & Zada, A. (2021). Integration of Bi₄O₅I₂ nanoparticles with ZnO: impressive visible-light-induced systems for elimination of aqueous contaminants. *Journal of the Taiwan Institute of Chemical Engineers*, 119, 177-186. <https://doi.org/10.1016/j.jtice.2021.01.020>
- Mao, Z., Liu, S., Lin, S., Qi, K., Zada, A., & Chai, S-P. (2026). Photocatalytic degradation of tetracycline and antibacterial performance by S-Scheme Bi₂WO₆/TiO₂ heterojunction. *Chemical Research in Chinese Universities*, 1-11. <https://doi.org/10.1007/s40242-026-5284-0>
- Mohammad, M., Maitra, S., Ahmad, N., Bustam, A., Sen, T., & 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>
- Muhammad, S., Sun, H., Zahoor, S., Khan, S., Ullah, R., Fu, B., Ullah, S., Isimjan, T. T., Azizi, S., & Yang, X. (2026). Advancing MOFs for electrocatalytic ORR, UOR, and CO₂RR: From fundamentals to device integration and deployment challenges. *Materials Science and Engineering: R: Reports*, 171, 101248.
- Muhsin, R. M. M., Abd Manan, T. S. B., Bidai, J., Mangat, M. S. A., Hanafiah, Z. M., Gohari, A., & Kamal, N. L. M. (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>
- Nath, G. (2024). Development of Sn/SnO₂ hard carbon composites via solvothermal synthesis as anode material for sodium-ion and lithium-ion batteries. <https://doi.org/10.26083/tuprints-00029999>
- Nelwamondo, A. M., Maaza, M., & Mohale, K. C. J. (2024). Symbiotic nitrogen fixation and nutrient acquisition of three groundnut genotypes exposed to different concentrations of magnesium oxide and calcium carbonate nanoparticles. *Biocatalysis and Agricultural Biotechnology*, 59, 103246. <https://doi.org/10.1016/j.bcab.2024.103246>
- Noukelag, S. K., Mewa-Ngongang, M., Ngqoloda, S., Kotsedi, L., Razanamahandry, L. C., & Ntwampe, S. K. (2023). Influence of synthesis method on structural, morphological, magnetic, and antimicrobial properties of Fe-Ag nanoparticles. *Journal of Inorganic and Organometallic Polymers and Materials*, 33(1), 159-169. <https://doi.org/10.1007/s10904-022-02493-9>
- Muhsin, R. M. M., Abd Manan, T. S. B., Bidai, J., Mangat, M. S. A., Hanafiah, Z. M. (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>
- Ryan, S. (2023). Solvent-Engineered Tin (II) Oxide for Applications in Energy Storage Devices. For the degree of Doctor of Philosophy in Chemistry, Trinity College, The University of Dublin.
- Saleh, S., Ibrahim, A., & Mohamed, S. (2016). Structural and optical properties of nanostructured Fe-doped SnO₂. *Acta Physica Polonica*, 129(6), 1220-1225.
- Sun, Y., Qian, K., Sun, S., Cui, J., Li, X., & Han, D. (2025). Loofah sponge-templated synthesis of multilayered mesoporous SnO₂ with excellent NO₂ detection performance at low temperatures. *Sensors and Actuators B: Chemical*, 441, 137991. <https://doi.org/10.1016/j.snb.2025.137991>
- Pervaiz, S., Afridi, A., Shah, S. W. H., Jadoon, M., Zada, A., & Azizi, S. (2025). Clove oil and surfactant-based green synthesis and characterization of nano calcium hydrates for application in stone conservation. *Applied*

- Physics A*, 131(12), 1-17. <https://doi.org/10.1007/s00339-025-09064-y>
- Rehman, A. U., Humayun, M., Khan, A., Zada, A., Jing, L. J. T., & Chemistry, E. (2016). Effect of biocides on the precipitation of calcium fluoride in the presence of anionic copolymeric inhibitors. *Toxicological & Environmental Chemistry*, 98(7), 748-758. <https://doi.org/10.1080/02772248.2015.1124107>
- Schwan, J., Nava, G., & Mangolini, L. (2020). Critical barriers to the large-scale commercialization of silicon-containing batteries. *Nanoscale Advances*, 2, 4368-4389. <https://doi.org/10.1039/D0NA00589D>
- Shah, A., Sun, H., Qiao, Z., Khan, M. U., Ali, N., Gao, C., & Kashif, M. (2024). Synthesis of iron oxide nanoparticles and its antimicrobial, anticancer, anti-inflammatory, wound healing, and immunomodulatory activities-A Review. *Phytopharmacology Research Journal*, 3(3), 1-28. <https://www.ojs.prjn.org/index.php/prjn/article/view/75>
- Shah, J., Sun, H., Qiao, Z., Sharif, T., & Gul, M. J. B. J. o. S. (2024). Enhanced degradation of methylene blue dye using hydrothermally synthesized Nickel-doped Strontium oxide catalysts. *Brazilian Journal of Science*, 3(12), 13-27. <https://doi.org/10.14295/bjs.v3i12.663>
- Shah, M., Hameed, A., Kashif, M., Majeed, N., Muhammad, J., Shah, N., & Khan, A. (2024). Advances in agar-based composites: a comprehensive review. *Carbohydrate Polymers*, 346, 122619. <https://doi.org/10.1016/j.carbpol.2024.122619>
- Shah, S. A., Nazir, M. S., Mustafa, F., Irfan, S., Ahmad, N., Ahmad, F., 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>
- Shah, S. I. A., Anwar, M., Ahmad, W., Ateeq, M., Zada, A., Shah, N. S., & Han, C. (2026). Photocatalytic CO₂ reduction: Fundamental principles, mechanistic pathways and material-specific kinetic insights. *Chemical Engineering Journal*, 175981. <https://doi.org/10.1016/j.cej.2026.175981>
- Sun, H., Ciska, M., Makki, M., Tenllado, F., & Canto, T. (2024). Adaptive substitutions at two amino acids of HCPro modify its functional properties to separately increase the virulence of a potyviral chimera. *Molecular Plant Pathology*, 25(6), e13487. <https://doi.org/10.1111/mpp.13487>
- Sun, H., Del Toro, F., Makki, M., Tenllado, F., & Canto, T. (2022). Adaptation of a potyvirus chimera increases its virulence in a compatible host through changes in HCPro. *Plants*, 11(17), 2262. <https://doi.org/10.3390/plants11172262>
- Sun, H., Gul, M., Khan, A., Liaqat, Z., Aleena, S., & Ali, A. (2026). Engineering disorder in high-entropy metal oxides for advanced functional applications. *Brazilian Journal of Science*, 5(8), 38-51.
- Sun, H., Sohail, A., Shah, A., Liaqat, Z., & Gul, M. J. P. R. J. (2025). From precursors to performance: Diverse synthesis strategies for cerium oxide nanoparticles. *Phytopharmacology Research Journal*, 4(2), 28-42. <https://ojs.prjn.org/index.php/prjn/article/view/82>
- Sun, H., Yang, B., Ji, D., Ma, C., Pang, R., Yuan, B., & Zhang, M. (2024). Bioinspired aerogels: ingenious structure, remarkable performance, and versatile applications. *Journal of Materials Chemistry A*, 12(21), 12358-12380. <https://doi.org/10.1039/d4ta00851k>
- Sun, Y., Li, T., Liu, X., Han, Y., Liu, Y., Zada, A., & Dang, A. (2024). Modulating oxygen vacancies in MXene/MoO_{3-x} smart fiber by defect engineering for ultrahigh volumetric energy density supercapacitors and wearable SERS sensors. *Chemical Engineering Journal*, 494, 152911. <https://doi.org/10.1016/j.cej.2024.152911>
- Sunjaya, N. B. P., Yulianti, R. T., Hanifah, A., Fadila, S., Indriyati, I., Priyono, S., Indayaningsih, N., Setiawan, J., Effendi, M., & Yudianti, R. (2026). Structural and synergistic effect of SnO₂-carbon interfaces for improved lithium-ion battery anode performance. *Surfaces and Interfaces*, 83. <https://doi.org/10.1016/j.surfin.2026.108502>
- 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, S., 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>
- Ullah, K., Abrar, M., Uddin, S., Ahmad, M., Ali, A., Ahmad, P., Rahman, N., Iqbal, N., Tirth, V., Algahtani, A., & Zaman, A. (2025). Structural, optical, and dielectric Properties of Sr^{2+} substituted $\text{Ba}_{1-x}\text{Sr}_x(\text{Co}_{1/2}\text{W}_{1/2})\text{O}_3$ ceramics for wireless application. *Ceramics International*, 51(5), 5923-5929. <https://doi.org/10.1016/j.ceramint.2024.12.039>
- Wang, Y., Yu, Z., Wang, Y., You, J., Du, C., & Cheng, S. J. I. J. o. E. S. (2025). Hybrid $\text{SnO}_2/\text{MoS}_2@ \text{C}$ nanocomposites as anode materials for high-performance lithium-ion batteries. *International Journal of Electrochemical Science*, 20(10), 101145. <https://doi.org/10.1016/j.ijoes.2025.101145>
- Yan, G., Wang, F., Liu, J., Zhou, H., Lei, X., & Wu, Z. (2026). Contact interfaces in anodes with large volume strain for high-performance lithium-ion storage. *Energy & Environmental Science*, 19, 2420-2491. <https://doi.org/10.1039/d6ee01264g>
- Wang, J., Fazil, P., Shah, M. I. A., Zada, A., Anwar, N., Zain, G. G., & Ateeq, M. (2023). Surface plasmon assisted photocatalytic hydrogen generation with Ag decorated g-C $_3$ N $_4$ coupled SnO_2 nanophotocatalyst under visible-light driven photocatalysis. *International Journal of Hydrogen Energy*, 48(57), 21674-21685. <https://doi.org/10.1016/j.ijhydene.2023.03.048>
- Wang, W., Gao, R., Zhang, L., Dong, Y., Du, Y., Dai, Q., & Sun, W. (2026). Precisely targeting cardiac remodeling nanomachine for restarting healthy heartbeat. *Advanced Healthcare Materials*, 15(3), e03478. <https://doi.org/10.1002/adhm.202503478>
- Welegers, G. G., Gebretinsae, H., Girmay, M., Sindelo, A., Tedla, A., Nuru, Z., & Nyokong, T. (2025). Plasmonic silver (Ag) supported mesoporous CuO nanocomposites for photodegradation of methylene blue in water. *Catalysis Letters*, 155(8), 275. <https://doi.org/10.1007/s10562-025-05100-x>
- Yan, G., Wang, F., Liu, J., Zhou, H., Lei, X., Wu, Z., Du, W., & Zhong Y. (2026). Contact interfaces in anodes with large volume strain for high-performance lithium-ion storage. *Energy & Environmental Science*, 19(8), 2420-2491. <https://doi.org/10.1039/d6ee01264g>
- Yan, J., Zhou, C., Wang, L., Zhuang, Y., Zhong, M., Zhang, J., Lei, Y., Shen, W., & Guo, S. (2022). Effects of pulverization and dead Sn accumulation in SnO_2 nanorods grown on carbon cloth on their electrochemical performances as the anode in lithium ion batteries. *ACS Applied Energy Materials*, 5(3), 3536-3544. <https://doi.org/10.1021/acsam.1c04074>
- Yasmeen, H., Zada, A., Li, W., Xu, M., & Liu, S. (2019). Suitable energy platform of Bi_2WO_6 significantly improves visible-light degradation activity of g-C $_3$ N $_4$ for highly toxic diuron pollutant. *Materials Science in Semiconductor Processing*, 102, 104598.
- Ye, F., Li, T., Chen, J., Liu, Y., Wu, S., Zada, A., & Dang, A. (2024). Fabrication of high-performance graphene fiber: Structural evolution strategy from a two-step green reduction method. *Ceramics International*, 50(22), 48575-48582. <https://doi.org/10.1016/j.ceramint.2024.09.205>
- Zada, A., & Azizi, S. (2026). Synergistic advanced oxidation and physicochemical treatment strategies for antibiotic removal and resistance mitigation in water. *Asia-Pacific Journal of Chemical Engineering*, e70265. <https://doi.org/10.1002/apj.70265>
- Zahoor, S., Muhammad, S., Kashif, M., Shahzad, N., Liu, Y.-c., Celik, C., Azizi, S., & Wen, C. (2026). Advances in mesoporous nanomaterials for photocatalytic degradation of pollutants: fundamentals, material classifications, challenges and future prospects. *Coordination Chemistry Reviews*, 549(1), 217239. <https://doi.org/10.1016/j.ccr.2025.217239>
- Zeng, X., & Sun, H. (2025). Enhancing the understanding of complement protein changes in RVO: Insights and Suggestions. *Journal of Inflammation Research*, 18, 2781-2782. <https://doi.org/10.2147/JIR.S522685>
- Zhang, B., Zhang, H., Zhu, L., Weng, X., & Sun, H. (2026a). Complex research review on environmental risk management of soil microplastic contamination: Treatment technologies and global perspectives. *MSI Journal of Multidisciplinary Research*, 3(4), 01-34. <https://doi.org/10.5281/zenodo.19660481>
- Zhang, B., Zhang, H., Zhu, L., Weng, X., & Sun, H. (2026b). Microplastics in the human gastrointestinal system:

- A comprehensive study of metabolic risks and digestive toxicity. *Msi Journal of Multidisciplinary Research*, 3(4), 1-31. <https://zenodo.org/records/19660158>
- Zhang, Z., Zada, A., Cui, N., Liu, N., Liu, M., Yang, Y., Jiang, D., Jiang, J., & Liu, S. (2021). Synthesis of a loaded ZnO/BiOCl with high photocatalytic performance for the removal of antibiotic pollutants. *Crystals*, 11(8), 981. <https://doi.org/10.3390/cryst11080981>
- Zhao, P., Sun, H., & Han, Q. (2025). Development and application of an intelligent platform for automated recognition of surgical instruments in laparoscopic procedures: a multicenter retrospective study. *International Journal of Surgery*, 111(10), 7379. <https://doi.org/10.1097/JS9.0000000000002726>
- Zheng, X., Mejia-Centeno, K. V., Khan, M. D., Cabot, A., & Sun, Q. (2026). From printed architectures to functional batteries: printing technologies, post-processing, and sintering. *Advanced Materials Joining*, 1. <https://doi.org/10.1007/s44500-026-00002-3>
- Zhu, H., Sun, H., Dai, J., Hao, J., & Zhou, B. (2024). Chitosan-based hydrogels in cancer therapy: Drug and gene delivery, stimuli-responsive carriers, phototherapy and immunotherapy. *International Journal of Biological Macromolecules*, 282(2), 137047. <https://doi.org/10.1016/j.ijbiomac.2024.137047>
- Zia, R., Nazir, M. S., Rouf, H., Ahmad, N., Ahmad, F., Ali, Z., & Hassan, S. U. J. I. J. o. B. M. (2025). Modified lignin etched sulphur-doped graphitic carbon nitride for electrochemical sensing of cypermethrin in drinking water: *Experimental and Theoretical Insights*. 146503.

Funding

Not applicable.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Copyrights

Copyright for this article is retained by the author(s), with first publication rights granted to the journal.

This is an open-access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).