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ALUMINOSILICATE-BASED COMPOSITES WITH METAL OXIDES, SULFIDES AND SELENIDES: EMERGING HYBRID MATERIALS FOR ENERGY STORAGE, CATALYSIS AND ENVIRONMENTAL REMEDIATION

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Abstract:

Aluminosilicate-based materials have attracted extensive attention owing to their remarkable physicochemical properties, including high surface area, tunable porosity, thermal stability, ion-exchange capacity, and structural versatility. The incorporation of metal oxides, metal sulfides, and metal selenides into aluminosilicate matrices has emerged as an effective strategy for developing multifunctional composites with enhanced catalytic, photocatalytic, adsorption, sensing, energy-storage, and biomedical performances. These hybrid materials combine the stability and porosity of aluminosilicates with the unique electronic and optical characteristics of semiconductor nanostructures. Recent studies have demonstrated that synergistic interactions between aluminosilicates and transition metal compounds significantly improve charge separation, surface reactivity, and pollutant adsorption, resulting in superior photocatalytic degradation efficiencies and catalytic activities. This review comprehensively summarizes recent advances in the synthesis, characterization, properties, and applications of aluminosilicate-based composites integrated with metal oxides, metal sulfides, and metal selenides. Furthermore, the mechanisms governing enhanced performance, current challenges, and future research opportunities are critically discussed.

Keywords: *Aluminosilicates, Zeolites, Metal Oxides, Metal Sulfides, Metal Selenides, Photocatalysis, Adsorption, Nanocomposites, Environmental Remediation.*

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1. Introduction

The rapid growth of industrialization, urbanization, and population worldwide has resulted in unprecedented environmental and energy challenges. The continuous discharge of organic pollutants, toxic dyes, pharmaceuticals, pesticides, and heavy metals into aquatic ecosystems has become a major threat to environmental sustainability and public health. Simultaneously, the increasing global demand for clean energy and sustainable technologies has intensified the search for advanced functional materials capable of addressing environmental remediation, energy conversion, storage, and catalytic applications. In this context, nanostructure composite materials have emerged as promising candidates due to their tunable physicochemical properties, enhanced surface reactivity, and multifunctional performance

The growing demand for sustainable energy technologies and environmental remediation systems has stimulated the development of advanced, functional materials (1, 2). Transition metal selenides have attracted significant attention because of their remarkable electronic conductivity, tunable band structures, high catalytic activity, and diverse redox chemistry (3). Compared with transition metal oxides and sulfides, metal selenides generally exhibit enhanced electrical conductivity owing to the lower electro negativity of selenium, making them attractive candidates for electrochemical energy storage and conversion applications (4, 5).

Recent reviews have extensively summarized the roles of metal selenides in energy storage, electrocatalysis, photocatalysis, and environmental remediation. However, the tendency of nanosized metal selenides to aggregate and undergo structural degradation is a major limitation. Consequently, immobilization on porous supports has emerged as an effective strategy for enhancing stability and catalytic performance (6, 7).

Among the available support materials, aluminosilicates are particularly attractive because of their high surface area, ion-exchange capability, thermal stability, tunable porosity, and low cost. The anchoring of metal selenides onto aluminosilicate frameworks creates hybrid interfaces that facilitate charge transfer and suppresses particle agglomeration. Despite the increasing number of reports on such composites, no dedicated review has systematically summarized aluminosilicate-supported metal selenides. Therefore, this article provides a comprehensive overview of the synthesis methods, physicochemical properties, applications, challenges, and future prospects of these emerging hybrid materials (8, 9).

Despite substantial progress, several challenges remain to be addressed before the widespread commercialization of these materials can be achieved. Issues such as long-term stability, scalability of synthesis, reproducibility, toxicity concerns, and mechanistic understanding require further investigation. Moreover, the development of environmentally benign synthesis routes and the exploration of novel aluminosilicate-supported multicomponent heterostructures represent important future research directions (15-17).

Therefore, this review provides a comprehensive overview of recent advances in aluminosilicate-based composites integrated with metal oxides, metal sulfides, and metal selenides. Particular emphasis is placed on their synthesis strategies, structural and physicochemical characteristics, charge-transfer mechanisms, and emerging applications in environmental remediation, catalysis, energy conversion, energy storage, and biomedical fields. Furthermore, current challenges and future prospects are critically discussed to provide valuable insights for the rational design of next-generation multifunctional aluminosilicate-based hybrid materials.

2. Fundamental properties of metal selenides

2.1 Crystal structures

Metal selenides typically crystallize in hexagonal, cubic, trigonal, or orthorhombic phases, with their structural characteristics determined by atomic arrangement and orbital occupancy (10). The crystal structure is primarily influenced by the metal's coordination environment, stoichiometry, and outer electron configuration. Metal selenides are broadly categorized into layered compounds (e.g., $TMSe_2$ where M = group IIIB–VIIB metals, FeSe, NiSe) and non-layered structures, typically involving group VIII metals (11). In layered metal selenides, properties are strongly dependent on the number of atomic layers due to surface-related effects (12).

Stoichiometry and phase composition significantly affect their thermal stability and electronic bandgap. Metal selenides exist in stoichiometric (e.g., MSe, M_2Se, MSe_2) and non-stoichiometric forms (e.g., Ni1-xSe, Cu_2-xSe). Among them, MSe_2 compounds commonly crystallize in two structural motifs: layered and pyrite-type. The layered MSe_2 structure features a hexagonally arranged metal layer sandwiched between two chalcogen layers, forming a structure 6–7 Å thick (13). These structures exhibit strong anisotropic properties, while pyrite-type structures with cubic symmetry display isotropic behaviour. In layered systems, interlayer interactions are governed by van der Waals forces, whereas pyrite-type crystals are stabilized by covalent bonding. Some metal selenide compounds, including FeSe, NiSe, CuSe ,SnSe and InSe, also exhibit layered structures distinct from MSe_2 in their monolayer arrangements (14). MSe_2 compounds typically exist in three polymorphs: 1T (trigonal), 2H (hexagonal), and 3R (rhombohedral), which differ in symmetry and electronic configuration (15). The 1T phase exhibits metallic behaviour due to partially filled d-orbitals, while the 2H phase is semiconducting, with fully occupied d-orbitals. Transformation from 2H to 1T phase is often utilized to enhance electrical conductivity and catalytic performance.

2.2 Electronic properties

The performance of metal selenides in making hydrogen through light is mainly determined by their structure and electronic setup. These rely on how selenium bonds with metals. Selenium has a way its electrons are arranged and can form strong bonds with certain metals. This results in different structures and electronic states. These help it work better for making hydrogen. These properties are listed in Table 1. The table also includes points for hydrogen evolution using light and electricity. Metal selenides and selenium play a role in this process (16). Their ability to form bonds with metals boosts their performance, in hydrogen production.

2.3 Common metal selenides

NiSe and $NiSe_2$: Nickel selenides and Nickel diselenides are two significant transition metal selenides, characterized by their electrical conductivity, catalytic properties, and electrochemical efficiency. They are extensively researched for uses in energy storage, electrocatalysis, sensors, and electronic devices.

$CoSe_2$: Cobalt diselenideis a transition metal selenide made up of cobalt (Co) and selenium (Se). It is among the most thoroughly researched cobalt-containing selenides due to its remarkable electrical conductivity, catalytic performance, and electrochemical characteristics. These attributes render it a favourable material for technologies related to energy storage and conversion.

$FeSe_2$: Iron diselenide is a selenide of transition metal made up of iron (Fe) and selenium (Se). It has garnered significant interest due to its advantageous electrical, optical, and electrochemical characteristics, rendering it valuable for energy storage, electrocatalysis, photovoltaic, sensors, and photocatalysis.

CuSe: Copper selenides is a chalcogenide (selenide) of transition metal made up of copper (Cu) and selenium (Se). It is a crucial semiconductor substance featuring outstanding electrical conductivity, optical characteristics, and electrochemical capabilities. CuSe has attracted considerable interest for uses in energy storage, photovoltaics, photocatalysis, thermoelectric devices, and sensors.

ZnSe: Zinc selenide is a II–VI semiconductor selenide made up of zinc (Zn) and selenium (Se). In contrast to transition metal selenides like NiSe or $CoSe_2$, ZnSe is mainly appreciated for its semiconductor and optical qualities instead of its electrical conductivity. It is extensively utilized in optoelectronics, photodetectors, lasers, solar cells, photocatalysis, and sensors.

$MoSe_2$: Molybdenum selenide is a transition metal dichalcogenide (TMD) made up of molybdenum (Mo) and selenium (Se). It is a multi-layered semiconductor boasting outstanding electrical, optical, and catalytic characteristics. Due to its two-dimensional (2D) layered configuration, $MoSe_2$ has emerged as a crucial substance for electrocatalysis, energy storage, optoelectronics, sensors, and nanotechnology.

WSe_2: Tungsten selenides is a transition metal dichalcogenide (TMD) made up of tungsten (W) and selenium (Se). It is a two-dimensional (2D) layered semiconductor exhibiting exceptional electrical, optical, and catalytic characteristics. Due to its adjustable band gap, high carrier mobility, and robust light–matter interaction, WSe_2 is extensively researched for uses in electronics, optoelectronics, energy storage, electrocatalysis, photocatalysis, and sensing.

3. Aluminosilicate supports

3.1 Zeolites

Zeolites are crystalline, microporous aluminosilicates featuring a meticulously arranged 3D structural framework. This solid structure of TO_2 tetrahedrons (with T usually being Silicon or Aluminium) forms tiny channels and cages that provide zeolites with their effective molecular sieve and ion exchange properties (18).

The microscopic framework

Molecular Sieving: The pore sizes vary from 0.3 to 1.0 nm, designed on a microscopic scale to correspond with the dimensions of small molecules. This allows zeolites to function as precise physical filters, permitting only suitably sized and shaped molecules to pass while blocking others (19).

Secondary Building Units (SBUs): The basic SiO_2 and AlO_2 tetrahedra are linked through shared oxygen atoms. These basic units combine to create intricate geometric forms such as rings and polyhedra, composing the overall structure (19).

Net negative charge: Silicon ($Si4^+$) has a +4 charge, yet when Aluminium (Al^{3+}) is isomorphically substituted in the structure; it creates a net negative charge in the lattice (21).

Ion exchange characteristics

Exchangeable cations: To counterbalance the negative charge from aluminium atoms, additional cations (like Na^+, K^+, Ca^{2+}, or Mg^{2+}) are loosely positioned within the tiny channels and voids (22).

Facile mobility: These cations are very mobile and readily exchanged with different cations in water-based solutions. Water molecules located in the spaces function as a lubricant for this motion (22).

Selectivity and Capacity: The capacity for ion exchange is directly influenced by the Silicon-to-Aluminium ratio (Si/Al); a reduced ratio indicates more Aluminium, leading to an increase in cation exchange capacity (CEC).

Zeolites display different selectivity for various ions depending on charge density, hydration size, and pore structure (23).

Heavy metal and radionuclide removal: Due to their unique structural characteristics and high cationic attraction, zeolites are widely employed to selectively eliminate harmful heavy metals and radioactive materials from industrial and nuclear effluents (23).

3.2 Bentonite and montmorillonite

Bentonite is swelling clay mainly made up of the mineral montmorillonite, which usually constitutes 70–90% of its makeup. Montmorillonite has a distinct layered configuration that draws in water, allowing the clay to take in moisture and expand considerably, frequently swelling by 10 to 15 times its original dry volume.

Stratified configurations

Both minerals belong to the smectite group and have a crystalline structure with a 2:1 layer format.

i. The 2:1 Unit: Each distinct layer (or platelet) comprises a central octahedral sheet located between two silica tetrahedral sheets.
ii. Isomorphous Substitution: In the tetrahedral and octahedral layers, lower-charge cations often take the place of higher-charge cations (e.g., Mg^{2+} substituting Al^{3+}). This establishes a lasting negative charge on the surfaces of the layers.
iii. Interlayer Region: Cations such as Sodium (Na^{+}) or Calcium (Ca^{2+}) are located in the area between the layered structures, referred to as the interlayer or gallery, to offset this negative charge Swelling Characteristics (24).

The swelling of montmorillonite (and thus bentonite) occurs in two primary, sequential phases:

1. Crystalline swelling (Inner-crystalline swelling)

i. Process: Upon contact with water, the dry clay allows water molecules to penetrate the interlayer region and hydrate the cations available for exchange.
ii. Behaviour: Water molecules arrange themselves into specific, organized layers surrounding the cations (e.g., 1 to 4 layers of water). This compels the clay platelets to gradually separate, resulting in a progressive increase in the interlayer distance.

Osmotic swelling

i. Mechanism: When the interlayer distance surpasses a specific limit, osmotic pressure prevails. The level of cations in the interlayer area is significantly greater than that in the adjacent bulk water.
ii. Behaviour: Large amounts of water flow into the interlayer region to equalize the concentration gradient. This forces the clay layers significantly apart, resulting in considerable volumetric expansion and the creation of a dispersed gel (24).

3.3 Kaolinite

Kaolinite is a dioctahedral phyllosilicate clay with a 1:1 structure and the chemical formula $Al_2SiO_2(OH)_4$. Hydrogen bonding between its tetrahedral and octahedral sheets largely determines its structural stability, whereas surface hydroxyl groups characterize its chemical reactivity and amphoteric charge.

Layer structure & structural stability

i. 1:1 Layers: Kaolinite is composed of repeated 1:1 layers. Every layer consists of a silica (SiO_2) tetrahedral sheet that shares oxygen atoms with an alumina ($AlO_2(OH)_4$) octahedral sheet.

ii. Hydrogen Bonding: The layers are connected by strong hydrogen bonds that form between the basal oxygen atoms in the tetrahedral sheet and the hydroxyl groups in the neighbouring octahedral sheet (25).

iii. Low Swelling Capacity: This extensive network of hydrogen bonds greatly limits the movement of water molecules into the interlayer regions. As a result, kaolinite shows minimal plasticity, low cohesion, and does not expand like other smectite clays (e.g., montmorillonite) (26).

iv. Thermal Stability: The configuration remains stable at room temperature; however, it experiences irreversible dehydroxylation at approximately 450°C to 600°C, converting into amorphous metakaolinite (Al_2O_3. $2SiO_2$) (27).

Surface hydroxyl groups

Kaolinite is a dioctahedral phyllosilicate clay with a 1:1 structure and the idealized chemical formula $Al_2SiO_2(OH)_4$. The structural stability is significantly influenced by hydrogen bonds connecting its tetrahedral and octahedral sheets, while the surface hydroxyl groups characterize its chemical reactivity and amphoteric charge.

Layer arrangement & structural integrity. hydroxyl groups on the surface

i. Two Main Categories: The hydroxyl groups of kaolinite are categorized based on their location within the crystal structure.

ii. Internal Hydroxyls: Found exclusively within the octahedral sheet (situated between the tetrahedral and octahedral layers). They do not engage directly with the outside environment [28].

iii. Inner-Surface (Basal) Hydroxyls: Found on the surfaces of the alumina layer, where they establish the interlayer hydrogen bonds (28).

iv. Edge Hydroxyls: At the fractured edges of the crystal, bonds end with unsaturated metal atoms, creating very reactive silanol (Si-OH) and aluminol (Al-OH) groups (29).

v. Reactivity & Charge: Hydroxyl groups on the edge and basal surfaces are amphoteric and can be protonated or deprotonated based on the pH of the adjacent aqueous solution. At low pH, they take up protons and acquire a positive charge, while at high pH, they lose protons to obtain a negative charge (29).

3.4 Halloysite nanotubes

Halloysite nanotubes (HNTs) are naturally occurring aluminosilicate clay minerals. Formed by the inward coiling of kaolin sheets, they feature a unique two-layer chemistry with a negatively charged silica outer surface and a positively charged alumina inner lumen (30).

Hollow tubular structure

HNTs are characterized by their unique, nano-scale tubular structure.

Dimensions: Generally, their length ranges from 0.2 ɥm to 2ɥm , featuring an external diameter of 40–190 nm and an internal lumen diameter of 10–100 ɥm. Selective Chemistry: The distinct chemistries of the inner and outer surfaces allow for selective functionalization—permitting the attachment of different chemical groups on the inside compared to the outside.) Mechanical Reinforcement: Due to their elevated aspect ratio and strength, they serve as outstanding "green" nanofillers for enhancing toughness, thermal stability, and tensile strength in polymer composites (30).

Nanoconfinement effects

The hollow lumen creates highly restricted, nanoscale environments that drastically alter the physical and chemical behaviour of confined substances.

i. Targeted Drug & Agent Delivery: Active agents (e.g., drugs, fertilizers, anti-corrosives) can be loaded into the inner lumen and slowly released over extended periods. Capping the tube ends with polymers allows for precise, controllable release rates.
ii. Altered Thermodynamic Properties: Confined substances—such as water molecules trapped inside the lumen—exhibit suppressed freezing points and unique hydrogen-bonding configurations compared to bulk materials (31).
iii. Catalysis and Energy: This confinement effect enables precise control over the size and morphology of catalytic metals grown inside the core, vastly improving their efficiency in energy storage devices and catalytic applications (32).

3.5 Geopolymers

Geopolymers are inorganic aluminosilicate polymers created by alkali-activating industrial by-products or natural minerals (like fly ash, slag, and metakaolin). They provide a highly sustainable, low-carbon alternative to traditional cement and excel in structural integrity, fire resistance, and durability (33).

Sustainable synthesis

The creation of geopolymers is characterized by a considerably lower environmental impact in comparison to Ordinary Portland Cement (OPC).

i. Carbon Reduction: Producing geopolymer concrete can decrease carbon dioxide (CO_2) emissions by approximately 40% to 80%, mainly because it removes the necessity for high-temperature calcination of limestone associated with conventional cement (34).
ii. Waste Valorization: Geopolymerization employs industrial waste and by-products like fly ash, blast furnace slag, silica fume, and mining tailings, which are ideally suited to circular economy frameworks (35).
iii. Energy Efficiency: The synthesis method employs low-temperature curing (typically ranging from 60° C to 80° C, or sometimes at room temperature for certain slag-blended mixtures), significantly reducing total energy usage (36).
iv. Resource Optimization: Recent advances involve employing recycled ceramic materials, glass sands, and different alkaline activators (such as sodium silicate waste) to further reduce environmental effects (37).

Mechanical Robustnes

Geopolymers are valued for their superior structural strength and durability, often surpassing OPC in mechanical stress and extreme conditions.

i. Compressive Strength: Based on the mix design and curing conditions, geopolymers can attain compressive strengths between 35 MPa and more than 100 MPa, rendering them appropriate for high-performance structural uses[38].
ii. Early Strength Development: The addition of high-calcium substances such as ground granulated blast-furnace slag (GGBS) enhances the creation of stable calcium-aluminosilicate-hydrate (C-(N)-A-S-H) gels, which contribute to substantial mechanical strength in the early stages (38).
iii. Tensile and Flexural Properties: Geopolymers exhibit remarkable sensitivity to strain rates and impressive structural durability. The direct tensile strength ratio is usually around 12% to 13.3% of the compressive strength (39).

iv. Unparalleled Durability: In addition to strength, the interconnected three-dimensional network structure offers remarkable protection against acid damage, sulfate deterioration, and freeze-thaw effects, reducing voids and stopping internal micro-cracking (40).

3.6 Fly-ash derived aluminosilicates

Aluminosilicates from fly ash convert industrial waste into useful, environmentally friendly substances. Researchers synthesize high-surface-area zeolites and mesoporous structures by leveraging the naturally occurring SiO_2 and Al_2O_3 found in coal combustion byproducts. This "waste-to-wealth" approach offers economical catalyst supports for green chemical production, biofuel creation, and environmental cleanup (41).

Why fly-ash aluminosilicates excel as catalyst supports

i. Elevated Porosity and Surface Area: By means of alkali-fusion and hydrothermal synthesis, unprocessed fly ash with low porosity is transformed into crystalline, structured zeolites (such as ZSM-5, NaX, and Analcime) that possess extensive surface areas (41).

ii. Cost Effectiveness: The estimated cost of synthesizing these porous supports from industrial fly ash is about one-fifth the expense of manufacturing commercial zeolites with pure, traditional feedstocks (42).

iii. Tunable Acid Sites: The structure of aluminosilicates derived from fly ash possesses natural Brønsted and Lewis acidic sites, essential for facilitating reactions that require proton transfer and electron-pair acceptance (43).

iv. Thermal and Hydrothermal Stability: These composites are capable of enduring extreme thermal and chemical conditions, resulting in their exceptional durability for ongoing reaction cycles (41).

4. Synthesis strategies of metal selenides

The catalytic performance of metal selenides is significantly determined by their composition, structure, and morphology, which are all greatly affected by the method of synthesis. In the last ten years, multiple synthetic approaches have emerged, encompassing wet-chemical methods like hydrothermal/solvothermal processes, electrodeposition, and colloidal synthesis, along with vapor-phase techniques such as chemical vapor deposition (CVD) and atomic layer deposition (ALD), enabling the production of materials with adjustable sizes and managed surface chemistry (44,45). These synthesis techniques establish the foundation for creating effective and long-lasting selenide-based catalysts. This segment underscores crucial synthesis methods, focusing on the regulation of morphology, electronic arrangement, and crystal phase. A summary of the synthesis strategies, emphasizing their benefits, drawbacks, safety aspects, and scalability for hydrogen production driven by solar energy, is provided in 1. (Refer to Table 2).

4.1 Hydrothermal growth

Hydrothermal synthesis enables the creation of 2D/3D structures (46). As an illustration, hydrothermal techniques have successfully produced 2D Ni–Cu–Se nanoflakes and MoSSe/MnSe nanoplate hybrids (47,48). Yang *et al.* (48) created 3D WP/$MoSe_2$/ZnCdS hybrids utilizing selenium powder, resulting in flower-shaped $MoSe_2$ featuring incorporated ZnCdS for enhanced light absorption. Template-guided methods enhance shape. Nasiri *et al.* (49) created MOF-derived Ni–Zr–Co–X (X = Se, S) through hydrothermal etching/ion exchange and subsequent selenization; the selenides exhibited enhanced redox activity owing to the lower electronegativity of Se.

Table 1: Evaluation of synthesis methods for metal selenides: Benefits, drawbacks, scalability, and appropriateness for solar-powered hydrogen generation

Synthesis strategy	Morphologies	Key advantages	Key limitations	Safety & environmental aspects	Scalability & reproducibility	Suitability for solar H_2
Hydrothermal/ solvothermal	Nanoparticles, nanorods, nanosheets	Good crystallinity; moderate temperature; tunable morphology	Long reaction times; autoclave pressure	Manageable Se precursors; closed systems improve safety	Scalable to batch level; good reproducibility	Widely used for PEC And
Colloidal (hot-injection)	Monodisperse nanocrystals, QDs	Excellent size, phase, and composition control; metastable phases accessible	Use of toxic solvents and ligands; ligand removal required	Organoselenium precursors and solvents pose safety concerns	Limited scalability; batch-to-batch variation	Ideal for model photocatalysts
Chemical vapor deposition (CVD)	Thin films, 2D selenides	High crystallinity; precise thickness control; clean interfaces	High temperature; complex equipment	Toxic Se vapor; strict ventilation required	Scalable for thin films; costly	Excellent for PEC photoelectrodes
Selenization (post-treatment)	Thin films, porous frameworks	Enables phase conversion; compatible with metal oxides/sulfides	Risk of non-uniform Se incorporation	Se vapor handling required	Industrially scalable; good reproducibility	Widely used for PEC Electrodes
Electrodeposition	Thin films, nanostructured coatings	Low cost; ambient conditions; direct growth on substrates	Limited compositional control; post-annealing often needed	Environmentally benign electrolytes possible	Highly scalable; excellent for large-area electrodes	Highly suitable for PEC hydrogen production

Template-assisted synthesis	Hollow, porous, hierarchical structures	Structural control; high surface area	Template removal steps; added complexity	Depends on template chemistry	Moderate scalability	Beneficial for light harvesting
Mechanochemical synthesis	Nanocrystalline powders	Solvent-free; fast; energy-efficient	Limited morphology control; defects difficult to tune	Environmentally friendly; minimal waste	Easily scalable	Promising for bulk HER Catalysts
Atomic layer deposition (ALD)	Ultrathin films, conformal coatings	Atomic-level thickness control; excellent uniformity	Very slow; expensive precursors	Precursor toxicity possible	Limited scalability	Ideal for model PEC studies and interfaces
Cation exchange/ anion exchange	Complex heterostructures	Preserves morphology; enables multicomponent systems	Kinetic control challenging	Moderate chemical risk	Moderate scalability	Useful for advanced
High-entropy synthesis routes	Multicomponent selenides	High configurational entropy; tunableelectronic states	Synthetic complexity; phase control challenging	Depends on route used	Under early development	Emerging strategy for

4.2 Solvothermal approaches

Solvothermal techniques consist of producing materials from reactive starting substances in a confined, heated solvent (typically above its boiling point). This method controls nucleation and growth rates to create specific morphologies—such as nanorods, nanosheets, or spheres—by accurately adjusting temperature, pressure, and solvent chemistry within a sealed container (50).

4.3 *In situ* selenium treatment

In situ selenization is a chemical conversion process in which supported metal precursors (such as metal oxides, hydroxides, or MOFs) are transformed into metal selenides. Reacting these precursors directly with a selenium source—like H_2Se gas, elemental Se vapor, or liquid precursors—generates highly active, conductive nanostructures suitable for energy storage and catalysis (51).

Table 2: Summary of recent progress of metal selenide-based photocatalysts for hydrogen production via water splitting

Photocatalyst	Light source	Sacrificial reagent	Products and activity	Efficiency	Ref.
Pt/Cr_2O_3 $(ZnSe)_x(CuGa_{2.5}Se_{4.25})_{1-x}$	300 W Xe lamp, λ > 420 nm	Pure H_2O	–	AQE: 0.54% at 420 nm	(65)
TiO_2/CdS-$(ZnSe)_{0.5}(CuGa_{2.5}Se_{4.25})_{0.5}$	300 W Xe lamp, λ > 420 nm	Pure H_2O	H_2: 12.0 μmol h^{-1}	AQE: 1.5% at 420 nm	(66)
$Pt/Zn_{0.75}Cd_{0.25}Se$	300 W Xe lamp, 420 < λ < 800 nm	Pure H_2O	H_2: 1.1 μmol h^{-1}	AQE: 0.0082% at 400 nm	(67)
ZnSe	300 W Xe lamp, λ > 400 nm	Pure H_2O	H_2: 68.7 μmol h^{-1}	AQE: 7.75% at 400 nm	(68)
Pt-CdSe-Pt	300 W Xe lamp, λ > 420 nm	Na_2SO_3/Na_2S	H_2: 63.6 μmol h^{-1}	AQE: 7.7% at 420 nm	(69)
Pt-PdS/CdSe	300 W Xe lamp, λ > 420 nm	Na_2S and Na_2SO_3	H_2: 5300 mmol g^{-1} h^{-1}	AQE: 45% at 420 nm	[70]
$CdSe/Zn_{1-x}Fe_xS$	405 nm	Triethylamine	H_2: 393 μmol mg^{-1} h^{-1}	AQE: 22.0% at 405 nm	(71)
CdSe MSC-422	300 W Xe lamp, λ > 420 nm	Ascorbic acid	H_2: 27.3 mmol g^{-1} h^{-1}	AQE: 1.79% at 420 nm	(72)
$MoSe_2$/CdSe	300 W Xe lamp, λ > 400 nm	Na_2S and Na_2SO_3	H_2: 7120.0 μmol g^{-1} h^{-1}	AQE: 27.2% at 670 nm	(73)

4.4 Ion-exchange pathways

The use of exchangeable cations in aluminosilicate structures depends on the isomorphic replacement of Al^{3+} by Si^{4+} in tetrahedral locations. This results in a net negative charge, counterbalanced by mobile extra-framework cations (e.g., Na^{+}, K^{+}, Ca^{2+}). These cations can be specifically swapped with other ions for focused industrial, environmental, and catalytic uses (41).

4.5 Synthesis with microwave assistance

Microwave-assisted synthesis utilizes electromagnetic radiation to directly warm reaction precursors, providing highly effective volumetric heating. This circumvents traditional thermal lag, creating a significant surge in localized supersaturation that compels swift nucleation while significantly reducing overall processing durations from hours to minutes (52).

4.6 Eco-friendly synthesis approaches

Eco-friendly alternatives are used in green synthesis strategies instead of toxic organic solvents and dangerous chemical reagents. This method employs biogenic reducing agents and eco-friendly solvents, which cuts down waste, lowers energy use, and generates biocompatible materials suitable for biomedical, agricultural, and environmental uses (53).

5. Interfacial engineering and structure–property relationships

5.1 Effects of nanoparticle dispersion

The dispersion of nanoparticles directly influences the active surface area of a nanomaterial. When nanoparticles are adequately dispersed, they prevent clumping and entirely reveal their large surface-to-volume ratio to the surrounding environment, generating numerous active sites for improved chemical reactions, better catalysis, and accelerated heat or mass transfer (54).

5.2 Pathways for charge transfer

Enhancing electron mobility at interfaces is an essential materials science approach for increasing the effectiveness of optoelectronic devices like solar panels, light-emitting diodes (LEDs), and transistors (55).

5.3 Synergy of adsorption and catalysis

The interaction of adsorption and catalysis in aluminosilicates consists of two phases: interfacial enrichment (adsorption), during which pollutants are extracted from dilute solutions onto the surface, and subsequent in-situ degradation. This process significantly reduces the activation energy necessary for the degradation of pollutants (23).

5.4 Structural integrity

Structural durability, especially against photocorrosion and dissolution, determines a photocatalyst's lifespan. It stops the active material from leaching into the surrounding environment (e.g., metal-ion leaching) and guarantees the semiconductor retains its structural integrity and performance over several catalytic cycles (20).

5.5 Inhibition of selenium leaching

Mitigating selenium (Se) leaching poses a significant environmental problem, especially in mining, coal burning, and dangerous waste disposal, where Se can accumulate in the food chain and turn extremely toxic to aquatic organisms. Successful mitigation necessitates a blend of source reduction and customized chemical or biological immobilization (56).

6. Applications

6.1 Degradation of organic pollutants through photocatalysis

Dyes: Intricate pigments derived from textile, leather, and printing wastewater [57].Pharmaceuticals: Residues of antibiotics and personal care items in water environments that encourage antibiotic resistance [58].Pesticides: synthetic agrochemicals and herbicides that disrupt ecosystems.. Industrial Chemicals: Enduring phenolic substances, solvents, and plasticizers (such as BPA) (59).

6.2 Hydrogen production through photocatalysis

Photocatalytic hydrogen production is a man-made photosynthesis method that utilizes sunlight to divide water H_2O into clean, storable hydrogen energy H_2. As a solar fuel technology aimed at net-zero emissions, it serves as a fundamental element of decentralized renewable energy studies (60).

6.3 Electrocatalytic processes

Electrocatalysis propels the transition to green energy by hastening slow, multi-step reactions. The Hydrogen Evolution Reaction (HER) and Oxygen Evolution Reaction (OER) are the paired half-cells involved in water electrolysis, whereas the Oxygen Reduction Reaction (ORR) serves as the essential energy-producing mechanism in fuel cells (61).

6.4 Ultracapacitors

Supercapacitors are sophisticated energy storage units characterized by the buildup of physical electrostatic charges (double-layer capacitance) and rapid surface redox reactions (pseudocapacitance) as opposed to slow, deteriorating chemical reactions (62).

6.5 Rechargeable battery packs

Lithium-ion, sodium-ion, and potassium-ion batteries are all "rocking-chair" types that produce energy by transferring ions between electrodes. Though they operate on comparable principles, their availability of raw materials, energy densities, and expenses vary greatly (63).

6.6 Environmental cleanup

Environmental remediation rehabilitates polluted ecosystems via specific decontamination methods. In wastewater treatment, this entails merging heavy metal removal techniques, like adsorption and chemical precipitation, with advanced oxidation to eliminate toxic, non-biodegradable organic substances prior to reintroducing water to the environment (64).

7. Comparative analysis

Support Material	Surface Area	Cost	Stability	Adsorption Capacity
Zeolite	High	Moderate	Excellent	High
Bentonite	Moderate	Low	Good	Very High
Kaolinite	Low	Low	Excellent	Moderate
Halloysite	Moderate	Moderate	Excellent	Moderate
Geopolymer	Variable	Low	Excellent	Moderate

8. Challenges and Future Perspectives

i. Limited understanding of aluminosilicate–selenide interfacial chemistry.
ii. Scarcity of DFT-guided mechanistic studies.
iii. Insufficient long-term stability evaluation.

iv. Potential concerns regarding selenium leaching.
v. Lack of pilot-scale demonstration.
vi. Need for machine-learning-assisted catalyst design.
vii. Integration into multifunctional energy-environment systems.

Conclusions

Composites of metal selenide anchored in aluminosilicate represent a new category of hybrid materials with considerable promise for sustainable energy and environmental applications. The combined use of conductive metal selenides with porous aluminosilicate supports enhances catalytic activity, stability, and recyclability. Future studies ought to emphasize interfacial engineering, scalable synthesis, computational design, and extensive environmental safety evaluations to expedite their practical implementation.

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