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Research Progress on Catalyst Supports for the Oxygen Evolution Reaction in Water Electrolysis

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Abstract. The oxygen evolution reaction (OER) is the slow half-reaction of water electrolysis, and its kinetics largely set the ceiling on the energy efficiency of green hydrogen production. In a supported electrode, what the support does is easily overlooked. It controls the dispersion of active components, the efficiency of electron transport, and the lifetime of the electrode; on these three counts rests the practicality of any catalyst. Support design has therefore grown into a central topic of OER research. This review summarizes recent progress on catalyst supports for the OER in water electrolysis, grouping them by the pH window in which they operate: supports common under alkaline OER (carbon materials and metal oxides), supports common under acidic OER (doped tin oxides, titanium-based oxides and suboxides, and conductive carbides and borides), and pH-universal supports (titanium suboxide Ti_4O_7, doped TiO_2, and tungsten carbide). For each family we introduce representative materials, recent preparation strategies, and the performance reached in typical studies, and then compare the advantages and limitations of the different support families in a single table. The review ends with a summary of the field, a point-by-point discussion of current challenges, and the prospects that follow from them, in the hope of providing a workable reference for the rational design of OER catalyst supports.

Keywords: oxygen evolution reaction, catalyst support, water electrolysis, conductive oxide, support–metal interaction

1. Introduction

Carbon reduction policies keep tightening across major economies, and hydrogen keeps drawing attention as a consequence: high gravimetric energy density, and no carbon emitted where it is used. Making it cleanly is the hard part. Coal gasification and natural gas reforming are mature processes, but their carbon emissions and pollution cannot be avoided; the bill simply arrives elsewhere. Drive water electrolysis with clean electricity instead, and the whole chain from hydrogen production to end use turns nearly carbon-free. This is the core of the "green hydrogen" concept, and water electrolysis is regarded as its key technological pathway [1, 2].

Water electrolysis consists of two half-reactions: the cathodic hydrogen evolution reaction (HER) and the anodic oxygen evolution reaction (OER). Kinetics on the hydrogen side are relatively straightforward. The oxygen side is another story. Water molecules must adsorb onto the catalyst

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surface, O–H bonds must cleave, several oxygen-containing intermediates form one after another, and O_2 finally desorbs from the surface. Each step has its own barrier; the total is high, the rate slow, and the energy consumption of electrolysis rises accordingly while overall efficiency falls [1]. How to accelerate the OER has therefore stood at the center of efforts to improve electrolysis efficiency.

Industry currently runs three main electrolysis routes. Alkaline water electrolysis (AWE), built on a liquid alkaline electrolyte, is the most mature and the cheapest to build, and it holds the largest share of installed capacity; carbon materials or metal oxides dominate its anode supports. Proton exchange membrane (PEM) electrolysis swaps the liquid for an acidic solid membrane. The strongly acidic internal environment permits fast dynamic response and high current density, which suits intermittent renewables such as wind and solar, but materials and components cost roughly an order of magnitude more; its anode supports lean on titanium-based oxides, tin-based oxides, or carbides. Anion exchange membrane (AEM) electrolysis, built on a solid alkaline membrane, promises AWE economics with PEM-like flexibility, yet it remains at the demonstration stage—the long-term durability of its membrane and electrodes still has to be proven [3-6].

Research on OER catalyst supports has moved quickly in recent years. Lin et al. reviewed the mechanism, catalyst classification, and enhancement strategies of the acidic OER in 2023 and stressed the decisive role of the support in keeping noble-metal active components stable [7]. The following year, Zaman et al. surveyed advanced electrocatalyst supports for proton exchange membrane water electrolyzers and singled out support engineering as a lever for cutting iridium loading [8]. Zhao et al., also in 2024, constructed regulable supports through non-stoichiometric engineering that stabilize ruthenium nanoparticles for pH-universal water splitting—clear evidence that a support can take part in catalysis instead of merely holding the metal in place [9]. On the alkaline side, Smiljanić et al. traced recent progress in advanced support materials for electrocatalysis [3], and Ye and Yuan reviewed the electrochemical applications of Magnéli phase Ti_4O_7-based materials [10]. Building on these advances, this review classifies OER supports by their operating pH window and connects material progress across alkaline, acidic, and pH-universal conditions.

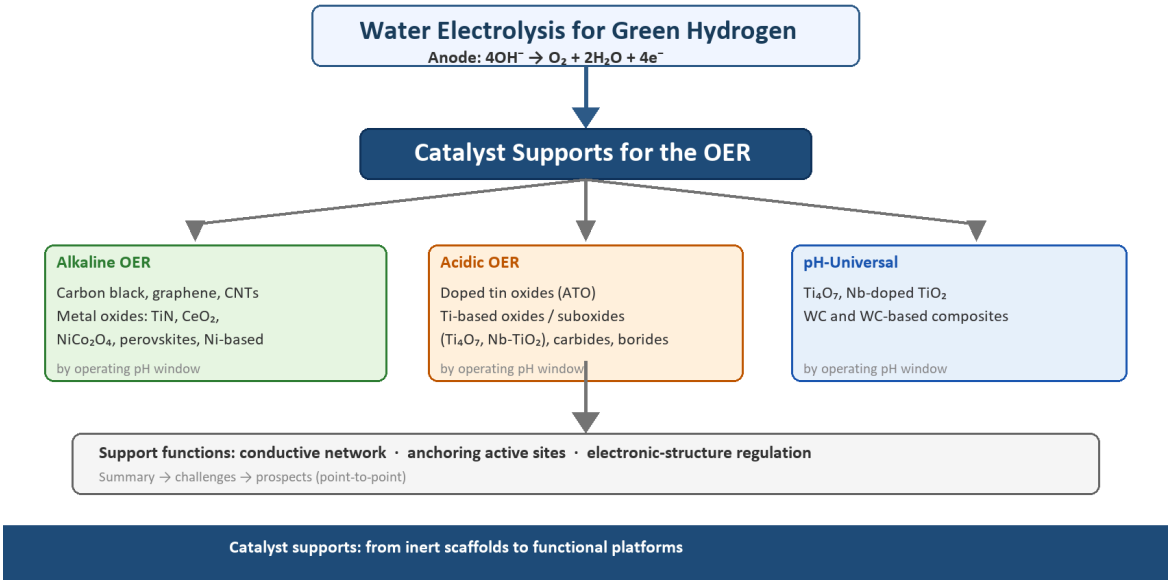

Figure 1. Classification of catalyst supports for the oxygen evolution reaction in water splitting

The classification used here is deliberately simple: three groups, sorted by the pH environment in which each support operates. For each group, the material characteristics, the recent research progress, and the challenges still open are examined in turn.

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2. Common supports for alkaline OER

2.1. Carbon materials

Carbon materials are the supports most widely applied in alkaline OER systems, and the reasons are not hard to find: good conductivity, high specific surface area, and relatively low cost. Three of them are in common use—carbon black, graphene, and carbon nanotubes.

Carbon black offers a large specific surface area and a pore network that spans the meso-to-macropore range; catalyst nanoparticles load into this network while electrolyte diffuses in and O_2 escapes [11]. Its behavior under anodic polarization worried researchers early on. Working with Vulcan XC-72R in 2018, Pérez-Rodríguez et al. showed that the corrosion rate at high anodic potentials is tied closely to the type and content of surface oxygen-containing functional groups, and that oxidative treatment, whatever it improves, also accelerates carbon weight loss [11]. A year later, Filimonenkov et al. separated the OER current from the carbon corrosion current on a rotating ring disk electrode (RRDE); their data leave little room for optimism about the stability of carbon black under OER operating conditions [12].

Graphene, a two-dimensional honeycomb of sp^2-hybridized carbon atoms, conducts well and exposes a large specific surface area. Loading active phases such as NiFe-LDH onto the sheets reduces particle agglomeration and tightens the interfacial coupling between support and active component [13]. Yin et al. reported in 2018 an oxygen evolution catalyst built from interconnected NiFe-LDH and carbon nanodomains [13]. Six years on, Liu et al. constructed a face-to-face combination of exfoliated NiFe-LDH nanosheets with monolayer rGO, and the numbers were strong: an overpotential of only 241 mV at 30 mA cm^{-2}, a Tafel slope of 62.1 mV dec^{-1}, and overall water splitting driven at 1.68 V at 10 mA cm^{-2} [14]. Pristine graphene, however, offers few surface anchor sites, which is why reduced graphene oxide (rGO), whose retained oxygen-containing functional groups bind active components better, has largely replaced it in practice [13].

Carbon nanotubes are essentially graphene rolled into tubes—high aspect ratio, low resistance, good conductivity. Defect sites and the π-electron structure of their walls interact with metal catalysts, so the tubes regulate the electronics of whatever they carry; they are functionalized supports, not passive carriers [15]. Chen et al. made use of this in 2023, realizing room-temperature synthesis of carbon-nanotube-interconnected amorphous NiFe-LDH for boosting the OER [15].

For all their conductivity, carbon-based supports corrode oxidatively at elevated anodic potentials. Once the carbon structure is damaged, electrode integrity declines and the catalyst detaches. Smith et al. analyzed the thermodynamics of carbon corrosion in alkaline water oxidation in 2024 and reached a sobering conclusion: the protective carbon shells themselves corrode under OER conditions, which makes carbon degradation essentially unavoidable [16]. The next year, Fan et al. systematically reviewed strategies for mitigating carbon oxidation—graphitization, surface functionalization, corrosion-resistant coatings, and non-carbon alternatives among them [17]. How to keep carbon supports alive under high-current operation remains an open question .

2.2. Metal oxides

Metal oxides hold up well under strongly alkaline conditions and high anodic potentials, and they form strong electronic interactions with active components. Their weakness is electronic conductivity, which stays well below that of carbon and restricts development. The main families used as alkaline OER supports are transition metal oxides, perovskite-type oxides, and metallic nickel.

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Mou et al. fabricated CoO/TiN nanowire arrays as a self-supported OER catalyst in 2020; the conductive TiN framework delivered acceptable activity and stability, with the current density holding above 90% of its initial value after a 15 h chronoamperometric test [18]. Cerium dioxide draws attention for a different reason: an oxygen-vacancy-rich surface and outstanding oxygen storage capacity, with the Ce^{4+}/Ce^{3+} redox couple serving as a buffer. Rajapriya et al. doped CeO_2 with heteroatoms (B, P, N, and S) in 2021; the doping enriched oxygen vacancies, improved electron transfer and hydroxide transport, and strengthened the alkaline OER performance [19].

Spinel-type oxides such as $NiCo_2O_4$ combine high intrinsic activity with acceptable conductivity. Wang et al. coupled molecularly ultrathin NiFe-LDH sheets on $NiCo_2O_4$ nanowire arrays for highly efficient overall water splitting back in 2017 [20], and returned in 2021 with inverse spinel $NiCo_2O_4$ embedded in N-doped carbon nanofibers, activated via Fe substitution for bifunctional oxygen electrocatalysis [21]. Yang et al. took another path in 2024, supporting Ir clusters on ultrathin $NiCo_2O_4$ nanosheets; the catalyst reached 10 mA cm^{-2} at a 238 mV overpotential and ran stably for 100 h at 100 mA cm^{-2} [22]. Perovskite-type oxides (ABO_3) possess intrinsic OER activity and a tunable electronic structure. Soltani and Wu integrated ultrafine Ni-Fe clusters with $CaTiO_3$ interfaces in 2026, achieving robust hydrogen and oxygen evolution at low overpotentials, with support and active phase operating as "dual active centers" [23]. What holds perovskite supports back is their usually low specific surface area and, in several systems, poor conductivity.

In alkaline systems nickel rarely serves as a support on its own; it usually appears alongside another metal oxide or carbon. Li et al. realized the ultrafast room-temperature synthesis of self-supported NiFe-LDH as a large-current-density OER electrocatalyst in 2022 [24], and Wang et al. followed the NiFe-LDH literature in 2024 with a review covering catalytic mechanism, electrode design, and stability [25]. A telling result came from Wu et al. in 2025. They constructed a NiFe-LDH/Ni_4Mo heterojunction in which the Ni_4Mo alloy worked as an "oxygen pump" to promote lattice oxygen regeneration; durability stretched from 10 h to more than 60 h, and the corresponding AEM water electrolyzer operated stably for over 150 h at 100 mA cm^{-2} [26]. In such designs the metallic component holds two jobs at once—conductive network and active phase .

3. Common supports for acidic OER

3.1. Doped tin oxide supports

Tin oxide doped with high-valence elements such as antimony or titanium combines high conductivity with good acid stability, and it is the most extensively studied class of acidic OER supports [8, 27]. In ATO, Sb substituting at Sn sites introduces free carriers and lifts the conductivity to the order of S cm^{-1}. Hartig-Weiss et al. supported iridium oxide on ATO in 2020 and obtained high OER activity in acidic media; a strong metal–support interaction improved mass activity and cut noble-metal consumption considerably [28]. Saveleva et al., in the same year, explained the origin of this activity and stability through in situ near-ambient-pressure X-ray photoelectron spectroscopy: oxygen spillover from the ATO support stabilizes oxidation states of the active component that would otherwise dissolve [29]. Further support came quickly. Khan et al. confirmed ATO as an efficient support for iridium-based OER catalysts in acidic media in 2023 [30]; Li et al. showed that Ti doping restrains grain growth in tin oxide and keeps the surface area high enough for electron transport [31]; and Shi et al. structured IrO_x into nanorods on a unique Sb-doped tin oxide microstructure, giving OER activity a sharp boost for PEM water electrolysis [32]. Mesoporous architectures add a further margin—they host the active component, release trapped reaction products, and suppress its peroxidative dissolution, which stretches operating lifetime.

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3.2. Titanium-based oxides and suboxides

Titanium oxide resists acid and costs little; the problem is its poor intrinsic conductivity. Two approaches have been explored. Hu et al. doped TiO_2 with niobium as early as 2014 to introduce carriers, and the resulting material served as an IrO_2 support with both corrosion resistance and moderate conductivity [33, 34]. The alternative is to abandon stoichiometry: titanium suboxides such as the Magnéli phase Ti_4O_7 reach metallic-level conductivity (on the order of 10^3 S cm^{-1}) while retaining acid resistance. Qin et al. developed an interface-engineering strategy for low-Ir water oxidation on a conductive Ti_4O_7 support in 2024; there, Ti–O–metal interfacial bonds regulate the electronic structure of the active component, stabilize lattice oxygen, and strengthen dissolution resistance [33]. Even non-conductive TiO_2 can serve as an anode support, provided a sufficiently conductive phase is deposited on its surface to form a continuous network [35, 36]. Non-stoichiometric titanium oxides go one step further and offer a platform whose composition can be tuned continuously; Zhao et al. used such non-stoichiometric engineering in 2024 to construct regulable supports that stabilize ruthenium nanoparticles for enhanced pH-universal water splitting .

3.3. Conductive carbides and borides

Where else can one find a support that conducts and survives acid at the same time? Transition metal carbides and borides have entered researchers' field of view as candidates [8, 37]. Karimi and Peppley compared metal carbide and oxide supports for iridium-based OER electrocatalysts in 2017; carbides such as TaC, NbC, and TiC remained stable in strongly acidic media with adequate conductivity, though they warned that support selection must be judged within the context of the specific catalytic system [37]. Wang et al. fabricated a nano-metal diboride-supported anode catalyst with a strongly coupled TaO_x/IrO_2 catalytic layer in 2023, and it maintained reaction rate and stability under reduced iridium loading in a PEM electrolyzer [38]. Kang et al. then supported iridium on tantalum carbide in 2026 and outperformed commercial IrO_2 in both half-cell and membrane electrolyzer tests [39]. The obstacle is manufacture: preparing carbides and borides requires high-temperature carburization or boronization, which raises cost and limits production volume. And a support that disperses the noble metal beautifully is of little use if it dissolves or loosens in service [40-43].

4. pH-universal supports

4.1. Titanium suboxide (Ti_4O_7)

Titanium suboxide (Ti_4O_7) belongs to the Magnéli phases and maintains a wide electrochemical stability window in acidic and alkaline electrolytes alike [9, 35]. The numbers explain the interest. In 0.5 M H_2SO_4 its OER potential reaches 2.9 V (vs. RHE); in 1 M NaOH it is 1.25 V, with no obvious degradation after more than 360 h of continuous alkaline operation. The passivation film measures only about 3 nm in alkaline solution but approaches 12 nm in acid, so the interfacial resistance stays low under alkaline conditions [34, 10, 35]. Ye and Yuan reviewed the electrochemical applications of Magnéli phase Ti_4O_7-based materials in 2023 and confirmed its suitability as an anode support for acidic PEMWE and alkaline water electrolysis alike [10, 44].

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4.2. Doped titanium dioxide

The intrinsic conductivity of pure TiO_2 is low, and doping is the improvement most often tried. After Nb doping, both the conductivity and the acid/alkali resistance of TiO_2 improve clearly , which is what allows Nb-TiO_2 to serve as an IrO_2 support in acidic media. TiO_2/rGO composites take a different route, adjusting the rutile-to-anatase phase ratio to improve hydroxyl-species adsorption and raise OER activity [45]. Two studies from 2025 deserve mention here. Zhen et al. discussed dopant selection and passivation-layer regulation for doped TiO_2 acidic-OER supports [45], and Ekanayake et al. investigated Ti-Nb alloys as supports for iridium oxide water oxidation electrocatalysts, finding that the vacancy-free lattice of doped TiO_2 is thermally and electrochemically more stable than reduced TiO_2 [46].

4.3. Tungsten carbide

Few non-oxide supports tolerate the full pH range; WC is one of them. Griesser et al. probed the surface chemistry of WC powder electrocatalysts in situ with NAP-XPS in 2021 [46]. The performance record, though scattered across conditions, is consistent. In 0.5 M H_2SO_4, N-doped WC nanorod arrays outperformed IrO_2 for OER [47]; in 1 M KOH, Ni/WC composites beat RuO_2, an effect attributed to electron transfer between WC and Ni [48]. Dharman et al. synthesized a WC@$Co(OH)_2$ nanocomposite by a simple hydrothermal route in 2025; the WC support regulated the electronic structure of $Co(OH)_2$, and the catalyst reached an OER potential of 1.475 V at 10 mA cm^{-2} [49]. It helps, too, that the support function of WC changes little with pH—a useful property for electrodes meant to work across media.

Table 1. Comparison of typical catalyst supports for the OER in water electrolysis

Support category	Representative materials	Main advantages	Main limitations
Alkaline—carbon	Carbon black, graphene/rGO, carbon nanotubes	High conductivity, high specific surface area, low cost, mature production	Oxidative corrosion at anodic potentials caps service life
Alkaline—metal oxides	TiN, CeO_2, $NiCo_2O_4$, perovskites, Ni-based composites	Excellent corrosion resistance in alkaline media; strong electronic interaction with active components	Conductivity generally lower than carbon; perovskites often have low specific surface area
Acidic—doped tin oxides	ATO, Ti-doped SnO_2	High conductivity (S cm^{-1} order) and acid stability; strong metal–support interaction with Ir	Complex mesoporous architectures; possible dopant leaching
Acidic—Ti-based	Nb-TiO_2, Ti_4O_7, non-stoichiometric TiO_x	Near-metallic conductivity (Ti_4O_7) with excellent acid resistance	Complex and costly synthesis of suboxides; passivation in acid
Acidic—carbides/borides	TaC, NbC, TiC, TaB_2	Combined conductivity and acid stability	High-temperature carburization/boronization raises cost and limits scale
pH-universal	Ti_4O_7, Nb-doped TiO_2, WC	Structural stability across broad pH; adaptable to AWE, PEMWE and AEM	Synthesis complexity, reproducibility and production volume still limited

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5. Summary, challenges and future prospects

5.1. Summary

One constraint runs through all three categories: conductivity, corrosion resistance, and specific surface area trade against one another, and no material wins on every count. In alkali, carbon conducts well and costs little, yet the carbon structure oxidizes at elevated anodic potential, while nickel and transition metal oxides survive alkaline media but pay for it through band-gap limits on conductivity. Acid rules carbon out entirely; there, antimony-doped tin oxide and the titanium suboxides carry the load, with carbides and borides available at higher cost. For wide-pH duty, Ti_4O_7, Nb-doped TiO_2, and WC hold their structure in acid and base alike. This review has followed these support families from carbon blacks and graphene to conductive oxides, suboxides, and carbides, together with their representative preparation strategies and achieved performance.

5.2. Current challenges

1. Evaluation gap. Most knowledge comes from bench-scale three-electrode cells. Current densities, temperatures, and electrolyte compositions there sit far from what an industrial electrolyzer sees, and the results do not transfer directly.

2. Crude interface regulation. Regulation of the support–active-component interface still relies mostly on etching, doping, and coating; control at the atomic scale has not arrived.

3. Cost-performance balance. Few supports strike a workable balance between performance and cost—particularly where noble-metal loading or high-temperature synthesis is involved.

4. Synthesis complexity. The synthesis routes of wide-pH materials tend to be complicated, and batch-to-batch reproducibility and production volume both leave much room for improvement.

5. Lack of design tools. Support selection still rests largely on trial and error, with no quantitative structure–performance relationships to guide rational design.

5.3. Future prospects

1. Device-level evaluation. Testing protocols and evaluation standards matched to industrial conditions—high current density, real electrolytes, full cells—should be established, so that laboratory results translate into electrolyzers.

2. Precise interface engineering. In situ/operando characterization and controllable surface modification should push interface regulation from etching, doping, and coating toward atomically precise construction of the support–active-component interface.

3. Low-cost routes. Scalable, low-cost preparation routes (room-temperature or combustion synthesis, for example) and earth-abundant support families should be developed to balance performance against cost.

4. Simplified scalable synthesis. The synthesis of wide-pH supports should be simplified, with explicit attention to reproducibility and scale-up.

5. Intelligent design. Machine learning and high-throughput computation could build quantitative links between defect concentration, facet orientation, and OER performance, so that supports are designed backward from the target rather than forward from habit. Beyond that, supports are expected to shed the inert-scaffold role and become active, dynamically reconstructing, even self-repairing platforms.

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