Single Atom on the 2D Matrix: An Emerging Electrocatalyst for Energy Applications

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ABSTRACT: The electrochemical energy conversions play an essential role in the production of sustainable and renewable energy. However, the performance is not up to the mark due to the absence of highly efficient and stable electrocatalysts. Recently, both 2D-matrix and single-atom catalysts (SACs) are two intense research topics in the field of electrocatalysis due to the high activity and stability and to maximize the utilization efficiency. Engineering the materials from 3D to 2D and modification from nanoparticles to single atoms have created a significant enhancement in the electrocatalytic activity. Hybridizing both the 2D matrix and SACs (2DM@SACs) creates a new electronic state in the materials, and that bequeaths with enhancing potentials toward the electrocatalytic activity. The strong covalent interaction between the 2D matrix and SACs tunes the intrinsic activity of the electrocatalysts. In this mini-review, we have discussed the different synthesis methods of 2DM@SACs with a focus on their electrochemical energy applications such as hydrogen evolution, oxygen evolution, oxygen reduction, and carbon dioxide reduction. This mini-review appraises the contribution to the rational proposal for the synthesis of perfect 2DM@SAC catalysts with their electrochemical properties toward energy conversion applications.

1. INTRODUCTION

The exhaustion of fossil fuels and increasing environmental concern demand a sustainable and clean energy technology but remain a significant challenge. For the past few decades, considerable progress has been made to produce a clean and sustainable energy cycle. Among them, electrochemical energy conversion (EEC) is considered as the most promising and environmentally friendly energy cycle.1,2 In EEC, the natural sources such as water, oxygen, methanol, and carbon dioxide are converted into fuels, and it is crucial for many advanced technologies such as fuel cells, metal air batteries, water electrolyzers, etc. EEC required highly efficient, active, and stable catalysts such as Pt, Ir, Ru, etc. However, the high cost and scarcity of these catalysts hamper the widespread use of EEC technology.3 Significant effort has been made for developing and designing catalysts by adapting a different amazing strategy. Reducing the particle size is the most efficient method for maximizing the catalytic activity.4 For noble metal catalysts, reduction of size is the critical factor for enhancing the electrocatalytic activity. By reducing the particle size from bulk materials to single-atom catalysts (SACs) via nanoparticles or nanoclusters, the catalytic activity increases subsequently.5 Reducing the particle size enhances the exposed surface atoms, modifies the surface electronic and atomic structure, and creates the defects. All these activities also offer excellent potential for electrocatalytic activity. The catalytic efficiency of Pt nanoparticles is increased from 9.5 to 26% by reducing the size from 11.7 to 3.9 nm.6 Reducing the particle size enhances the electrocatalytic activity and reduces the use of precious noble metal catalysts. By decreasing the particle size, the surface energy will increase; as a result, aggregation takes place, and the particle becomes unstable. Small size particles like clusters and SACs are unstable at room temperature. Thus, to synthesize stable clusters and SACs, solid support materials having high surface area are required, and they play an important role.

SACs also exist in nature and play a vital role in the natural catalytic process. For example, Mg single atoms present in chlorophyll involve photosynthesis reactions, and other single metal atoms like Fe, Mo, Zn, and Cu, etc. are present in the enzyme and are involved in the biocatalytic process.7–9 Very recently, SACs are a very emerging and hot research topic in the field of electrocatalytic applications. The SAC consists of an isolated specific atom coordinated or firmly anchored with surface atoms of the support materials, and it is different from conventional electrocatalysts. SACs provide an alternative path for maximizing the utilization efficiency of the expensive noble
metal catalysts and tuning the intrinsic catalytic activity of the inert support catalysts. The intrinsic catalytic activity of the support materials is increased in the presence of SACs. The catalytic performance of SACs depends on size, distributions, interaction with support surface atoms, and structural modification. Moreover, its tunable atomic size modifies the energy level (HOMO—LUMO gap), and homogeneous distributions increase the surface effect and change the physicochemical property. Their strong chemical interactions transfer the electron from d-orbital to adjacent surface atoms of the support materials and modulate the structural and electronic property. All these unique properties of SACs have attracted attention as highly efficient and active catalysts for electrochemical applications.\textsuperscript{1,2,10,11} Support materials also play an important role in enhancing the electrocatalytic applications. Recently different support materials such as a carbon matrix, metal oxides, metal sulfides, metal nitrides, metal—organic frameworks (MOFs), etc. are used. Among the different support materials, a 2D matrix such as graphene, graphitic carbon nitride (g-C\textsubscript{3}N\textsubscript{4}), transition metal dichalcogenides (TMDs), layered double hydroxides (LDHs), Mxene, and 2D metal—organic frameworks (MOFs), etc. are most auspicious.\textsuperscript{12—15} 2D matrices are the most promising and widely used materials in the fields of electrocatalysis, and this is due to their unique structural and electronic properties, strong interaction with metal atoms, and tunable physicochemical properties. Additionally, the 2D matrix is a perfect catalyst for analyzing the catalytic activity and understanding the surface mechanism by both experimental and theoretical methods.\textsuperscript{1,2} Thus, both the 2D matrix and SACs are the frontier research topics in the field of electrocatalysis and have been rapidly developed in the last couple of years. The hybridization of both the 2D matrix and SACs (2DM@SACs) will give unique electrocatalysts with high catalytic activity and stability. Due to the strong covalent interaction of single atoms and the coordination environment of the 2D matrix, SACs will be stabilized in 2D-matrix support. The strong interactions will create a new electronic state, and unsaturated coordinations will generate new active sites in the catalysts.\textsuperscript{1,11} In this mini-review, we discuss the several recent novel synthetic strategies of novel SACs on 2D-matrix catalysts. Then, their electrochemical energy conversion applications such as hydrogen evolution reaction (HER), oxygen evolution reaction (OER), oxygen reduction reaction (ORR), and carbon dioxide reduction reaction (CO\textsubscript{2}RR) are discussed. The method of synthesis and energy applications of 2D-matrix-confined SACs are illustrated in Figure 1. Finally, we highlight the major challenges and opportunities of SAC electrocatalysts for future research.

2. SYNTHESIS OF CATALYSTS

Synthesizing and controllable fabrication of stable and highly dispersed 2DM@SAC catalysts is a quite tricky and challenging task because of the thermodynamic instability and aggregation tendency during the synthesis process. There is a strong tendency of a single metal atom agglomerate to form clusters or nanoparticles. To prevent the agglomerations, the metal atom and 2D-matrix support interaction is the vital factor. Recently, a number of synthetic processes have been developed for the fabrication of SACs on the 2D matrix, and these are atomic layer deposition (ALD), acid leaching, photochemical, ball milling, wet chemical, solvothermal, impregnation method, electrodeposition, and MOF-derived method. The most adopted synthesis methods are discussed here.

#### 2.1. Atomic Layer Deposition (ALD)

Atomic layer deposition (ALD) is a gas-phase chemical deposition technique and is used for the fabrication of atomic layer thin-film catalysts with the atomically precise design and control. The major features of the ALD technique are its self-limiting control to forming materials in a layer-by-layer mode. So, in the ALD technique, it is easy to control the development of exact layers of materials to form composites.\textsuperscript{16} Thus, ALD methods have been used for synthesizing precise control and homogeneous distribution of SACs on the 2D matrix. The size, morphology, and loading amount of the SACs are precisely controlled by the number of ALD cycles. By increasing the number of ALD cycles, there is a possibility for the formation of a cluster or nanoparticle, and for SACs the ideal loading is below 2%. By using this technique, a single atom of the platinum metal group is deposited on a carbon 2D-matrix support. The size and density of the atoms are controlled by varying the number of ALD cycles. With the increasing number of cycles, the size of the atoms and atomic wt % increases. The Pt-SACs are single crystalline, and its structure is cubic close-packed (CCP). The ALD method is highly precise in controlling the formation of SACs, but it is not suitable for large-scale production of the catalysts due to the high cost of the instrument and scalability issues.

#### 2.2. Electrodeposition Method

SACs can be easily synthesized on the catalyst support by the electrodeposition method from the metal ions dissolved in electrolyte solutions. The slow diffusion rate of metal ions is favorable for the growth of isolated atoms on the catalytic support, and the rate of diffusion can be controlled by varying the concentration of the metal ion precursor. The size and density of distributions can be precisely controlled by optimizing the deposition time and concentration of metal ions. For the deposition of Pt single atoms on the catalytic supports, Pt foil is used as a metal source instead of the Pt precursor. Pt foil can be oxidized and dissolved in the electrolyte under strong electrochemical environments. When a high oxidative potential is applied to the Pt counter electrode in a three-electrode system, Pt is oxidized and dissolved in the electrolyte. The continuous potential cycles redeposited the Pt as a single atom or cluster on the surface of catalytic support.\textsuperscript{12,17,18} The dissolution and redeposition of Pt are most significant in the acidic medium in comparison to the...
3. ENERGY APPLICATIONS

In the past few years, 2D-matrix-supported SACs have been used for electrocatalysis and photocatalysis and chemical and environmental applications and so forth. For the energy conversion reaction, electrocatalysts play an important role, and it is important for the production of chemicals and next-generation energy devices. For energy conversion reaction, noble metal catalysts such as Pt, Pd, Ir, and Ru are the benchmark catalysts because of their high intrinsic catalytic activity and stability, but scarcity and high cost limit their practical applications. The best method is synthesizing the 2D-matrix-supported SACs of these noble metals to overcome the cost issues. The 2D-matrix-supported SACs provide excellent catalytic activity. The high density of exposed catalytic sites increases the conductivity of the surrounding atoms by transferring the electron, and strong chemical interactions that stabilize the SACs during the electrocatalytic process play a pivotal role for high catalytic activity. In this section, we have discussed the electrocatalytic activity for hydrogen evolution reaction (HER), oxygen evolution reaction (OER), oxygen reduction reaction (ORR), and carbon dioxide reduction reaction (CO₂RR). The synthesis methods and applications of recently developed 2D-matrix-supported SACs are briefly highlighted (Table 1).

| Table 1. Summary of the Synthesis Method and Application of 2D-Matrix-Supported SACs |
|---|---|---|---|---|
| single-atom catalysts (SACs) | 2D support | synthesis methods | application | ref |
| Pt | MoS₂ | hydrothermal | HER | 17 |
| Pt | Mxene | electrochemical | HER | 12 |
| Pt | N-doped graphene | ALD | HER | 16 |
| Pd | GDY | electrochemical | HER | 13 |
| Ru | CoFe-LDH | precipitation | OER | 21 |
| Ni, Co, Fe | NHGFs | annealing | OER | 22 |
| Ru | N-doped carbon | pyrolysis | ORR | 23 |
| Pt | N-doped carbon | pyrolysis | ORR | 19 |
| Fe | N-doped carbon | pyrolysis | ORR | 20 |
| Ni | N-doped carbon | pyrolysis | CO₂RR | 24 |
| Nb | MoS₂ | CVD | CO₂RR | 25 |

3.1. Hydrogen Evolution Reaction (HER). Electrochemical hydrogen evolution is the most efficient and sustainable process to produce high-quality molecular hydrogen. Noble metal Pt-based catalysts are the benchmark catalyst for HER; however, high cost and scarcity limit the practical application. Thus, the synthesis of Pt-SACs on catalytic support is the alternative to maximize the utilization efficiency of the Pt-Pt-SACs have been synthesized by taking different 2D-matrix catalytic support such as nitrogen-doped graphene (NG), Mxene, MoS₂, WS₂, etc. and studied the HER activity. For example, by using the ALD method, Cheng et al. synthesized isolated Pt atoms and clusters on the surface of N-doped graphene nanosheets (NGNs). Modulating the ALD cycle, the size and density of SACs are precisely controlled. With the increase in the number of ALD cycles, the size of the particle increases from the atomic level to cluster. The catalysts exhibit
size-dependent HER activity; i.e., with increasing the atomic size, HER activity decreases. SACs and clusters show much higher activity than Pt nanoparticles. The DFT calculations reveal strong interaction between nitrogen sites and Pt-SACs. That modifies the electronic state by transferring the electron to adjacent N atoms and increases the vacant 5d density of states of the Pt atoms. Therefore, it increases HER activity. Using the electrochemical deposition method, Zhang et al. synthesized Pt single atoms on Mxene support (Figure 2a). First, Mo vacancies are created by the electrochemical method, and then vacancies are filled by Pt single atoms. The HAADF-STEM image confirms the distribution and coordination of Pt single

Figure 2. (a) Schematic presentation of electrochemical synthesis of Mo₂TiC₂Tₓ−PtSA. (b) HAADF-STEM image of Mo₂TiC₂Tₓ−PtSA. (c) LSV curve of Mo₂TiC₂Tₓ with different potential cycles by Pt counter electrode. (d) HER polarization curves for different synthesized catalysts. (e) Corresponding Tafel slopes. (f) Durability test of Mo₂TiC₂Tₓ−PtSA. Reprinted with permission from ref 12.

Figure 3. (a) Schematic illustration showing the hydrolysis deposition to form Ru/CoFe-LDHs. (b) HAADF-STEM image of as-synthesized Ru/CoFe-LDHs (scale bar, 2 nm). (c) HER polarization curves of synthesized catalysts. (d) Durability test of the catalysts. Reprinted with permission from ref 14.
atoms (Figure 2b). By using Pt as counter electrode, the HER activity of Mo$_2$TiC$_2$Tx is continuously increasing up to 1000 potential cycles (Figure 2c). Pt-SAC-decorated Mxenes (Mo$_2$TiC$_2$Tx−Pt$_{5A}$) exhibit excellent HER activity and are comparable with benchmark catalyst Pt/C. The catalysts achieve the current density of 10 100 and 200 mA/cm$^2$ at the lower overpotentials of 30, 77, and 104 mV, respectively. The overpotential value of Mo$_2$TiC$_2$Tx−Pt$_{5A}$ is lower than Pt/C (Figure 2d). The mass activity of Mxene-Pt is 40 times higher than commercial Pt/C. The catalyst also exhibits long-term durability up to 10 000 cycles and 100 h (Figure 2e).

Graphdiyne (GDY) is another carbon 2D matrix having sp$^2$ carbon atoms that are of rings bonded to sp carbon atoms of diacetylenic groups. The presence of unhybridized orbitals of carbon has a strong interaction with SACs. Thus, GDY is a good support material for the synthesis of SACs. The presence of unhybridized orbitals of carbon has a strong interaction with SACs. Thus, GDY is a good support material for the synthesis of SACs. By using GDY as a catalytic support, Li and co-workers synthesized Pd-SACs.$^{13}$ The synthesized catalysts exhibit excellent catalytic activity toward HER, and catalytic activity is comparable with commercial Pt/C. The catalyst also exhibits long-term durability up to 10 000 cycles and 100 h (Figure 2e).

The DFT calculation suggests that the Pt atom is active for modifying the chemisorption of H atoms on neighboring S atoms and hence enhances the HER activity. Thus, the synthesis of the single-atom-decorated 2D matrix is the best approach to use the maximum catalytic efficiency of the noble metal catalysts and increase the catalytic activity and stability toward HER. The noble-metal-based single atom modifies the electronic arrangement of adjacent atoms and decreases the adsorption free energy of H atoms.

3.2. Oxygen Evolution Reaction (OER). Oxygen evolution reaction (OER) involves a four-step proton-coupled electron-transfer process. That makes the sluggish kinetics and needs higher overpotentials to produce O$_2$. Thus, OER needs highly efficient and robust catalysts for stepping over the energy barrier. Recently, 2D-matrix-decorated SACs have been explored for advanced OER catalysis. LDHs are considered as excellent electrocatalysts for OER among the different 2D matrices. This is due to the unique 2D structure and excellent physicochemical properties. Recently, SACs confining LDHs have been extensively studied for OER. Li et al. developed the Ru-SACs on CoFe-LDH (Ru/CoFe-LDH) support by the hydrolysis-deposition method (Figure 3a).$^{14}$ The distribution and

![Figure 4](https://pubs.acs.org/journal/acsodf)
anchoring of Ru single atoms on CoFe-LDH were confirmed by the HAADF-STEM analysis (Figure 3b). Ru/CoFe-LDH exhibits excellent OER activity and stability (Figure 3c,d). The catalysts required only 198 mV to achieve the current density of 10 mA/cm² with a smaller Tafel slope of 39 mV/dec. The presence of Ru single atoms also increased the working stability of the catalysts. The Ru/CoFe-LDH catalysts exhibit 99% retention of current density up to 24 h, whereas bare CoFe-LDH catalysts exhibit 90% retention of current density within 12 h (Figure 3d). Similarly, Zhang et al. developed Au SACs on NiFe-LDH support (Au/NiFe-LDH) by an electrodeposition method. DFT study suggests that Fe sites are highly active toward OER, and further introduction of Au SACs reduces the overpotential. Au/NiFe-LDH requires the overpotential of 237 mV to achieve the current density of 10 mA/cm² which is 26 mV lower than NiFe-LDH. Only 0.4 wt % decoration of Au atoms enhances the OER activity up to six times. The formation of oxyhydroxide during OER acts as active sites, and its formation was also confirmed by the in situ Raman study. Further, Au SACs transfer electrons to support catalysts and as a result modify the distribution of surface charge and enhance the catalytic OER activity. Along with LDH, a carbon 2D matrix such as graphene and carbon nitride is also a support catalyst for OER applications. Transition metal elements such as Ni-, Co-, and Fe-based SACs decorated on the carbon 2D matrix have been extensively studied for OER. For example, Fei et al. synthesized Ni, Co, and Fe SACs anchored on an N-doped holey graphene matrix (M-NHGFs) and studied the OER activity. Ni-NHGFs exhibit higher OER activity and achieve a current density of 10 mA/cm² at the overpotential of 331 mV in an order of activity as Ni-NHGFs > Co-NHGFs > Fe-NHGFs. In this catalyst, the M-N₄C₄ site acts as an active center for OER. Thus, different transition-metal-based single atoms such as Ru, Ir, Au, Ni, Co, Fe, etc. anchored on the surface of 2D matrix have successfully enhanced the OER activity by lowering the overpotential and increased the catalytic durability. The experimental predictions are also valid by the theoretical calculations.

3.3. Oxygen Reduction Reaction (ORR). The oxygen reduction reaction (ORR) is an important half-reaction for energy conversion devices such as fuel cells and metal-air batteries. Electrocatalytic ORR proceeds through both a two-electron and four-electron path and operates in both acidic and basic conditions. The four-electron process is highly efficient in comparison to the two-electron process because the former avoids the generation of H₂O₂ in the reaction process that causes the degradation membrane and catalyst. The paths of ORR depend on the tendency of the catalysts to break the O=O bond. The heteroatom-doped 2D-carbon matrix is verified as the best catalyst for ORR. Also, the SACs decorated on the 2D-carbon matrix conspicuously boosted the ORR activity. The heteroatom-doped 2D-carbon matrix is the best support for anchoring SACs. The strong interaction between the heteroatoms and metal ions stabilizes the SACs on the 2D matrix. The heteroatoms present on the 2D matrix act as active sites for electrocatalytic activity. Usually, atomically dispersed M−N−C species follow the four-electron path for ORR, whereas Pt-SACs follow the two pathways. By using the microporous metal−organic framework (MOFs) confined strategy, Xiao et al. synthesized a Ru−N−C single-site catalyst (Ru−SSC) and studied the ORR activity. In Ru−SSC, Ru atoms are confined with both N and O atoms of the compounds. The HAADF-STEM image confirmed the formations of a Ru single atom without the formation of Ru small clusters or nanoparticles (Figure 4a). However, by increasing the Ru content, the size of the particle continues to increase. The ICP-OES result confirms that the maximum Ru content in Ru−N−C sites is 0.4188 wt %. The ORR activity of Ru−SSC was compared with Fe−SSC, Pt/C, Ru−NC, and Ru/C (Figure 4b). Ru−SSC exhibits the half-wave potentials and Tafel slope of 0.824 V and 54.2 mV/dec, respectively, which is lower than the Pt/C and Fe−SSC. The Ru−SSC follows the four-electron pathways toward ORR.
catalyst also exhibits higher mass activity, specific activity, and turnover frequency (TOF) in comparison to the benchmark catalysts Pt/C. The Ru-SSC shows higher durability property in comparison to Pt/C. After 20,000 cycles, only 17 mV positive shifts on halfwave potentials were observed in Ru-SSC, whereas Pt/C exhibited a 32 mV positive shift (Figure 4c). The DFT study suggests that in situ generated OH species act as a ligand and modify the electronic structure of the d orbital in Ru that tailors the free energy of the adsorption—desorption reaction intermediates and enhances the ORR activity (Figure 4d). Liu et al. reported the preparation of Pt-SACs dispersed on N-doped black carbon (Pt−N/BP) of 0.4 wt %.

The as-synthesized catalyst shows excellent ORR activity with methanol tolerance. DFT calculation reveals that the coordination between Pt-SACs and the pyridinic-nitrogen atom acts as catalytic sites for ORR. Other than noble metal SACs, the transition metal SACs anchored on the 2D-carbon matrix are also extensively studied for ORR. For example, Zeng et al. invented an ORR catalyst in which Fe atomic clusters are embedded in an Fe-SAC-supported nitrogen-doped carbon matrix (FeAC@FeSA−N−C).

The synthesized catalysts exhibit higher ORR activity and lower Tafel slope than the commercial Pt/C. The Fe−N4 species is the leading active site, and the cluster boosts the activity. Thus, the ORR activity of the electrocatalysts increases from nanoparticle to SACs, and both noble and non-noble metal-based SACs having M−N4 or M−S4 species and M−N−C sites are dominant active species to increase the ORR activity and stability. 3.4. Carbon Dioxide Reduction Reactions (CO2RRs)

Electrochemical CO2 reduction is a renewable process to convert CO2 into fuels and essential organic compounds. In the presence of transition-metal-based catalysts, CO2 is converted to carbon monoxide or formate ions. However, in the presence of Cu and carbon-based catalysts, CO2 is converted to a hydrocarbon. Recently, 2D-carbon matrix-supported SACs have great potentials for CO2RR. Li et al. adopted the topochemical transamination method to produce Ni-SACs on N-doped carbon (Ni−N4−C) support (Figure 5a).

The formation of Ni−N4 species in the catalytic support helps to avoid the accumulation of Ni-SACs to Ni nanoparticles, and this is confirmed by the HAADF-STEM image (Figure 5b). The synthesized Ni−N4−C catalysts exhibit excellent electrocatalytic activity toward CO2RR. The catalysts achieve the current density of 36.2 mA cm−2 at −0.91 V, which is much higher than bare N−C catalysts (Figure 5c).

The reduction product of this reaction is CO and H2 with a larger amount of CO. The Faradaic efficiency for the CO is 90% at the wide potential window of −0.5 to −0.9 eV. At the potential of −0.81 V (vs RHE), the Faradaic efficiency is 99% with a current density of 28.6 mA/cm2 (Figure 5d). The catalysts Ni−N4−C also exhibit a long-term CO2 reduction process up to 30 h, suggesting the high durability of the catalysts. In the case of the Ni−N4−C catalyst, the Ni−N4 species act as active sites for CO2RR. The theoretical calculation reveals that the formation energy of COOH* for Ni−N4−C is lower in comparison to bare nitrogen-doped carbon (N−C). Other than the 2D-carbon matrix, 2D-metal dichalcogenide (MoS2) decorated SACs are also used for the CO2RR to form CO. Abbasi et al. synthesized Nb-doped MoS2 (Nb-MoS2) by a chemical vapor deposition method.

Nb-MoS2 shows higher CO2RR activity in comparison to bare MoS2. The catalysts achieve the CO Faradaic efficiency of 82% at a potential of −0.8 V vs RHE and produce the current density of 237 mA/cm2. The theoretical calculation reveals that the formation of CO species is beneficial in MoS2, but its removal is difficult. The introduction of the Nb atom increases the electron density around the Mo atom and reduces the binding energy of CO. The binding energy of CO also depends on the position of the Nd atom. Thus, the unique structures of SACs have revealed the exclusive performances in CO2 reductions. Ni-SACs are extensively studied for CO2RR due to their unique structural active sites. For CO2RR, the M-Nx species (M = Ni, Co, Fe, etc.) act as an active center and exhibiting a selective tendency toward the formation of CO over a wide potential range.

4. CONCLUSION AND OUTLOOK

For clean and sustainable energy applications, highly efficient and stable electrocatalysts are of great interest. SACs are a bridge between homogeneous and heterogeneous catalytic systems. Both the 2D matrix and SACs are an independent research topic in the field of catalysis and have achieved significant attention in the last couple of years. Benefiting from the unique advantage of 2D-matrix support compared to the 1D and 3D, the 2DM@SACs symbolized a unique class of electrocatalysts. The high surface area and planar surface of the 2D matrix facilitate the adsorption and dispersion of SACs, and its strong covalent interactions stabilize the SACs. The 2DM@SACs are a new emerging material with a new electronic state and homogeneously precise geometric structure that has unlimited potential applications in the field of electrocatalysis. The 2DM@SACs have been synthesized by various methods such as ALD, pyrolysis, electrodeposition, etc. by taking the 2D matrix such as N-doped graphene, g-C3N4, MoS2, WS2, LDH, Xene, graphene, etc. The characterization techniques like HAADF-STEM, EXFAS, and XANES analysis are powerful tools for analysis of 2DM@SACs.

Furthermore, to understand the relationship between the structure and electrocatalytic property of 2DM@SACs, several experimental and theoretical studies have been performed. In this mini-review, first, we have discussed the importance and development of SACs on the 2D matrix and their different synthesis procedures. In the application part, the electrochemical energy conversion reactions such as HER, OER, ORR, and CO2RR are discussed. For future research, the focus on the following point may be considered:

- 2D-carbon matrix-supported SACs, mostly N-doped carbon, are widely studied for electrocatalytic applications. However, the inadequate variety of support catalysts causes the lowering in the catalytic active sites. For N-doped carbon, M-N4 acts as the catalytic active site for SACs, and catalytic activity depends on the structure of the active sites. Thus, to increase the number of active sites or synthesize different active site structures, different heteroatoms should be doped to the 2D-carbon matrix or by synthesizing new catalytic supports.

- Until now, very minimal research articles have been reported on 2D-matrix-supported SACs for electrocatalytic applications. The 2D matrices, such as carbon-based, LDH, and TMDs, are reported so far, whereas a newly developed 2D matrix such as Xene, Xene, black phosphorus (BP), and BN-decorated SACs has not been explored so far. These 2D matrix-supported SACs are highly active toward electrochemical applications, and also theoretical calculations suggest that these catalytic supports show activity to stabilize the SACs.
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