

## Review on Application Progress of Carbon-Based Catalysts in Environmental Governance

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(Received May 9, 2022; Accepted July 5, 2022)

**ABSTRACT.** In recent years, carbon-based catalysts have become a research hotspot in environmental governance applications. Carbon-based catalysts have large surface areas, porous structures, multi-surface functional groups and excellent electron transfer capabilities, and can synergistically exhibit adsorption and catalytic performance. This article reviews the research progress of carbon-based catalysts in environmental governance, mainly including its application in wastewater treatment, exhaust gas purification and soil remediation. In view of the current difficulties in the research of carbon-based catalysts, the development prospects are proposed. We hope that this review will provide convenience for new entrants and researchers intending to employ carbon-based catalysts for the remediation of contaminated environment.

**Key words:** Carbon-based catalysts, Wastewater, Exhaust gas, Contaminated soil, Environmental governance

### INTRODUCTION

The synthesis and application of carbon materials has a long history. Black carbon made from wood has been used for ink and water purification for more than 3,000 years.<sup>1,2</sup> In the 20th century, the successive discoveries of fullerenes and carbon nanotubes opened up a door to the research of nano-carbon materials.<sup>3-5</sup> Carbon-based materials are usually used as carriers and modified to prepare carbon-based catalysts. Carbon-based catalysts have large surface areas, porous structures, abundant surface functional groups, excellent electron transfer capabilities, and other unique physical and chemical properties, which make them have superior adsorption and catalytic performances, and show outstanding properties in the field of environmental governance.<sup>6-8</sup>

In recent years, many studies have been devoted to the modification and activation of carbon-based materials, including chemical impregnation, low-temperature plasma treatment, heteroatom doping, and metal loading, etc., to change the surface and internal structure of carbon-based materials, thereby further improving adsorption and catalytic performance of carbon-based materials. The modified carbon-based catalysts have exerted excellent performance in environmental treatment applications, including activation of persulfate to degrade organic pollutants in water, removal of heavy metal ions in water, low-temperature selective catalytic reduction of NO<sub>x</sub>, catalytic oxidation of H<sub>2</sub>S, adsorption-photocatalysis oxidation of organic waste gas, soil

treatment, etc.<sup>9-11</sup> In terms of environmental governance, carbon-based catalysts are green and efficient catalysts that are expected to replace metal catalysts. They have the advantages of integrating adsorption and catalytic performance, low cost, no secondary pollution and reusability.

In this review, we discuss the latest research progress of carbon-based catalysts in terms of waste water treatment, exhaust gas purification and soil treatment around different carbon-based materials, and prospects for the future development of carbon-based catalysts.

### TYPES OF CARBON-BASED MATERIALS

According to the properties, carbon-based materials can be divided into three categories, which are traditional activated carbon, nano-carbon and biochar. An overview of these three carbon-based materials is shown in *Table 1*.

### MODIFICATION AND ACTIVATION OF CARBON-BASED CATALYSTS

Modification and activation of carbon-based materials can change the pore structure of carbon-based materials, increase surface functional groups and improve electrical conductivity. Carbon-based catalysts obtained after activation and modification can exhibit more excellent adsorption and catalytic performance. Commonly used modification activation methods include chemical impregnation, low-

**Table 1.** Overview of several carbon-based materials

Types	Definition	Features	Reference
Traditional activated carbon	It is obtained by high temperature carbonization and processing of organic raw materials, usually divided into powder activated carbon (PAC), granular activated carbon (GAC) and activated carbon fiber (ACF)	Simple preparation, low cost, superior adsorption performance	[12]
Nano-carbon	The dispersed phase is a carbon material with at least one dimension less than 100 nm, including carbon nanotubes (CNTs) and graphene (GO)	Larger specific surface area, high mechanical strength, strong thermal and electrical conductivity, and has properties that some traditional carbon materials do not have	[2,13,14]
Biochar	Pyrolysis and conversion of waste organic materials such as municipal sludge and straw at high temperature	Rich in functional groups and metal components that can serve as active sites	[1,9,15]

**Table 2.** Comparison of several technologies for the modification and activation of carbon-based catalyst

Methods	Definition	Advantages	Disadvantages	Reference
Chemical impregnation	Immerse the carbon-based material in a certain concentration of acid or alkali solution to change its pore structure and increase surface functional groups	The required functional groups can be obtained by changing the impregnating liquid and adjusting the pH value, the appropriate carrier can be selected to provide the required physical structure characteristics of the catalyst	The synthesized particles are unevenly distributed, and the subsequent roasting process will cause exhaust gas pollution	[70]
Low-temperature plasma technology	Use the instant high-energy generated by high-frequency discharge to attack carbon-based materials, change the carbon network structure and increase surface functional groups	High efficiency, environmentally friendly, no secondary pollution, more controllable, and will not damage the physical surface properties of the material	The equipment is expensive, the technical parameters are complex, and the mechanism research of its modified materials is not perfect	[71,72]
Atomic doping	Introduce heteroatoms to change the internal structure of the carbon network	Can change the internal structure of the material, enhance the electrical conductivity, and provide active sites	The design calculations and mechanism analysis involved are more complicated, and it is difficult to determine the best doping elements	[60]
Metal loading	Using carbon-based materials as the carrier, and the metal or metal oxide is supported on the carrier	Metal can act as the active component of the catalytic material to transfer electrons, thereby greatly improving the activity of the catalyst	Some precious metals are expensive, and metal-loaded materials used for water treatment can easily cause the metal to dissolve and cause secondary pollution	[61,73]

temperature plasma technology, atomic doping and metal loading. *Table 2* compares the advantages and disadvantages of these methods in application.

### APPLICATION OF CARBON-BASED CATALYSTS

Compared with ordinary carbon materials, carbon-based catalysts have both catalytic performance and can degrade environmental pollutants. This section focuses on the unique adsorption and catalytic performance of carbon-based catalysts, and discusses the application progress of

carbon-based catalysts from three aspects of wastewater, exhaust gas and contaminated soil treatment.

#### Wastewater Treatment

The use of activated carbon to purify water has a long history. The principle is to use porous solid surfaces to absorb organic or toxic substances to purify water. However, its treatment effect is easily affected by the polarity and molecular size of organic matter, and there are problems such as incomplete purification. Carbon-based catalysts have both adsorption and catalytic performance, which can better remove organic pollutants in water. At present, in the research of

wastewater treatment applications, carbon-based catalysts are mainly used to activate persulfate (PS; usually divided into peroxymonosulfate (PMS) and peroxydisulfate (PDS)) to remove organic pollutants and to remove heavy metal ions.

**Activation of Persulfate for the Removal of Organic Pollutants:** Advanced oxidation technology (AOT) based on activating PS to generate sulfate radicals ( $\cdot\text{SO}_4^-$ ) and hydroxyl radicals ( $\cdot\text{OH}$ ) to degrade organic pollutants is currently a research hotspot in the environmental field.<sup>16</sup> Commonly used methods to activate PS include ultraviolet light activation and transition metal activation. The former technology consumes high energy and the reaction conditions are severe, while the catalysts used in the latter technology are prone to poisoning and deactivation and causes secondary pollution when the metal is eluted. In contrast, carbon-based catalysts, with excellent adsorption and catalytic properties, are highly efficient and green catalysts for PS activation with wide sources, low cost and no secondary pollution.<sup>17</sup> The mechanism of carbon-based catalyst activating PS to remove organic pollutants is shown in *Fig. 1*. *Table 3* summarizes the literature data of using carbon-based catalysts to activate PS to remove organic pollutants in recent years.

Carbon-based catalysts can cooperate with PS to reduce the activation energy of catalytic reaction to effectively remove organic pollutants in water. Yang and his groups carried out earlier research in this area.<sup>18,19</sup> In their work, the modified activated carbon / peroxymonosulfate (GAC / PMS) system showed a synergistic effect on the degradation of acid orange 7 (AO7) in aqueous solution, which was better than GAC

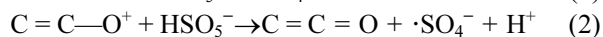
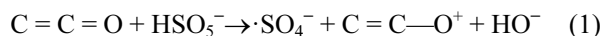
adsorption and PMS catalysis alone. The addition of GAC significantly reduced the activation energy of the reaction. Lee et al.<sup>20</sup> founded that the activation energy of perfluorooctanoic acid (PFOA) oxidized by PS was reduced from 668 kJ / mol to 261 kJ / mol by adding AC, and the removal rate of PFOA by AC / PS system was 10 times higher than that by PS alone.

The porous structure, multi-surface functional groups and internal carbon network structure of the carbon-based catalyst can promote the activation of PS to generate free radicals. Based on this, the ideal carbon-based catalysts can be designed to efficiently remove organic pollutants in water. For example, Wang et al.<sup>21</sup> prepared sludge-derived biochar and combined with PMS to form a combined system. The removal rate of 4-chlorophenol could be as high as 92.3%. The porous structure of sludge-derived biochar is conducive to the adsorption of pollutants, and the abundant functional groups and amorphous iron on its surface can be used as active sites to activate PMS. The electron-rich ketone and quinone groups on the surface of reduced graphene oxide (rGO) can also activate PMS to produce  $\cdot\text{SO}_4^-$  and  $\cdot\text{OH}$  to degrade pollutants. In addition, Liu et al.<sup>22</sup> prepared N and S co-doped multi-walled CNTs (CNT<sub>S</sub>-COOH) by thermal decomposition for activation of PMS, which could completely degrade 0.01 g/L benzophenone-4 (BP-4) within 30 minutes, while the degradation rate of BP-4 by PMS alone was only 8% within 1 hour. The co-doping of N and S introduced pyrrole N, pyridine N and thiophene S atoms, which destroyed the original chemical inertia of the carbon network and produced positively charged carbon. These carbons could act as active sites to promote the adsorption of

**Table 3.** Literature data of PMS activation on carbon-based catalysts the removal of organic pollutants

Catalysts	Pollutants	Concentration	PH	Time	Removal efficiency (%)	Reference
GAC	AO7	20 mg/L	2.5	5 h	85	[14,15]
AC	PFOA	120.6 $\mu\text{M}$	3.8	12 h	88.9	[20]
SDBC	4-CP	0.039 mM	6.3	100 min	92.3	[21]
CNTs-COOH	BP-4	1.000 g/L	7.0	30 min	100	[22]
CNT	Phenol	0.1 mM	7.0	60 min	100	[24]
FeN/C	Bisphenol F	10 mg/L	7.0	90 min	97.1	[26]
Co-WDC	BPA	0.02 g/L	7.0	6.0 min	100	[27]
NCNTs	BPA	25 mg/L	-	30 min	100	[28]
SMC-K	Phenol	20 mg/L	3.3	20 min	100	[29]
CMK-3	Phenol	20 mg/L	-	60 min	100	[30]
N-G (N-doped GO)	Phenol	50 ppm	-	30 min	100	[31]
C <sub>N</sub> -1000-1	Phenol	20 mg/L	3.3	5.0 min	100	[32]
CNTs	2,4-DCP	0.031 mM	6.5	30 min	95.9	[33]
NiZn@NG-900	BPA	20 mg/L	6.5	20 min	93.8	[35]
NG	BPS	50 mg/L	7.0	20 min	97	[37]

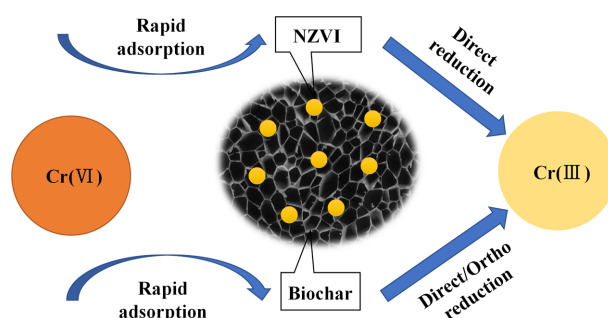
$\text{HSO}_5^-$  and destroy the O-O bond ( $\text{HO}-\text{SO}_4^-$ ) to activate PMS to produce  $\cdot\text{SO}_4^-$  and  $\cdot\text{OH}$  to participate in the oxidation reaction. The formation of radical pathway over carbon-based catalysts are summarized by the following equations:<sup>23-25</sup>



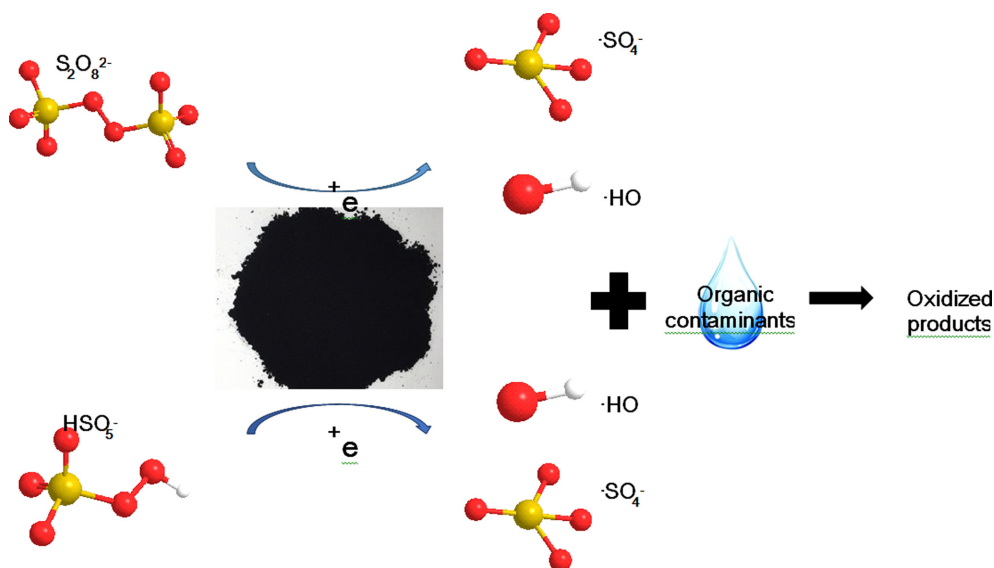
In addition to free radical pathways, carbon-based catalysts can also activate PMS through non-radical pathways.<sup>26-30</sup> The presence of C=O bonds in carbon-based catalysts can enhance the activation of PMS, generate strong oxidizing singlet oxygen ( $^1\text{O}_2$ ), and induce non-radical pathways.<sup>31,32</sup> In the experiment of using carbon-based catalyst to activate PMS to degrade phenol,  $^1\text{O}_2$  was quenched by furfuryl alcohol (FEA) and sodium azide ( $\text{NaN}_3$ ). With the increase in the amount of quencher, the degradation rate of phenol was observed to decrease continuously, suggesting that the carbon-based catalyst could also degrade phenol by activating PMS to generate  $^1\text{O}_2$ .<sup>32</sup> Similar findings were reported by Cheng and co-workers, the process of 2,4-dichlorophenol degradation over PS/CNTs catalyst produced electrophile  $^1\text{O}_2$  to participate in the redox reaction.<sup>33</sup> Interestingly, this non-radical pathway often occurs on N-doped carbon-based catalysts, because they contain more C=O bonds. In addition, the carbon grid structure is beneficial to induce another non-radical pathway, namely the direct electron transfer pathway. For instance, porous N-doped nanospheres (PNC) with positively charged sites adsorb PMS and produce electron transfer intermediates, which can help electrons trans-

fer directly from pollutants to PMS.<sup>34-36</sup> The activation of PS through non-radical pathway has many advantages, such as preventing self-quenching of generated free radicals, high selectivity to organic pollutants, thereby reducing the influence of matrix ions and natural organic matter in the water body, and being stable in a wider pH range.<sup>37</sup>

**Removal of Heavy Metal Ions:** Nano zero-valent iron (NZVI) has high reactivity to remove heavy metal pollutants, but it is prone to agglomeration in engineering applications, resulting in reduced activity. As a typical carbon-based material, biochar has a good pore structure and a large specific surface area, and can disperse NZVI well.<sup>38,39</sup> Fig. 2 shows the mechanism that biochar promotes the oxidation of Cr (VI) by facilitating the dispersion of NZVI. Therefore, using biochar as a carrier to construct a carbon-based catalyst can efficiently remove heavy metal ions in water. Qiu et al.<sup>40</sup> prepared a carbon-based catalyst with NZVI on biochar by a liquid-phase reduction method. Under the



**Figure 2.** Schematic diagram of biochar promotes the reduction of Cr (VI) by facilitating the dispersion of NZVI.



**Figure 1.** Schematic diagram of carbon-based catalyst activated persulfate for removal of organic pollutants.

operating conditions (C:Fe = 5:1, PH = 4.5, T = 25 °C, the initial reaction time = 120 minutes), the removal rate of Cr(VI) in the hexavalent chromium (Cr(VI)) solution with a concentration of 50 mg/L could reach 96.8%, which was 35.9% higher than the removal rate by NZVI alone under the same conditions. Biochar effectively disperses NZVI and overcomes its shortcomings of easy agglomeration. In addition, Xu et al.<sup>41</sup> processed cow manure into biochar at 350 °C and loaded NZVI. The adsorption of Cu, Zn, and Cd in the aqueous solution by the obtained carbon-based catalyst followed the Freundlich model, and the maximum adsorption capacity could be 48.4, 31.6 and 31.9 mg/g, respectively.

### Exhaust Gas Purification

#### Low Temperature Selective Catalytic Reduction of NO<sub>x</sub>

Selective catalytic reduction (SCR) technology is often used in the exhaust gas treatment of steel and power industries to reduce NO<sub>x</sub> emissions. V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub>/TiO<sub>2</sub> is the most widely used commercial catalyst, and its optimum operating temperature is about 400 °C. However, in order to avoid catalyst poisoning caused by ash and SO<sub>2</sub>, the SCR treatment unit is usually located after the dust removal and desulfurization treatment device, and the temperature of the treated exhaust gas is usually lower than 200 °C.<sup>42</sup> This usually requires an additional heat source to heat the exhaust gas to improve the NO<sub>x</sub> removal efficiency, which greatly increases the processing cost. In order to solve this problem, it is particularly important to develop catalysts with high activity at low temperatures. Carbon-based catalysts have developed pore structure, large specific surface area and abundant functional groups, and have superior adsorption and catalytic capabilities for NO<sub>x</sub> and NH<sub>3</sub>. The supported carbon-based catalysts formed by using carbon materials as carriers and supporting transition metals (Fe, Cu, Mn) or

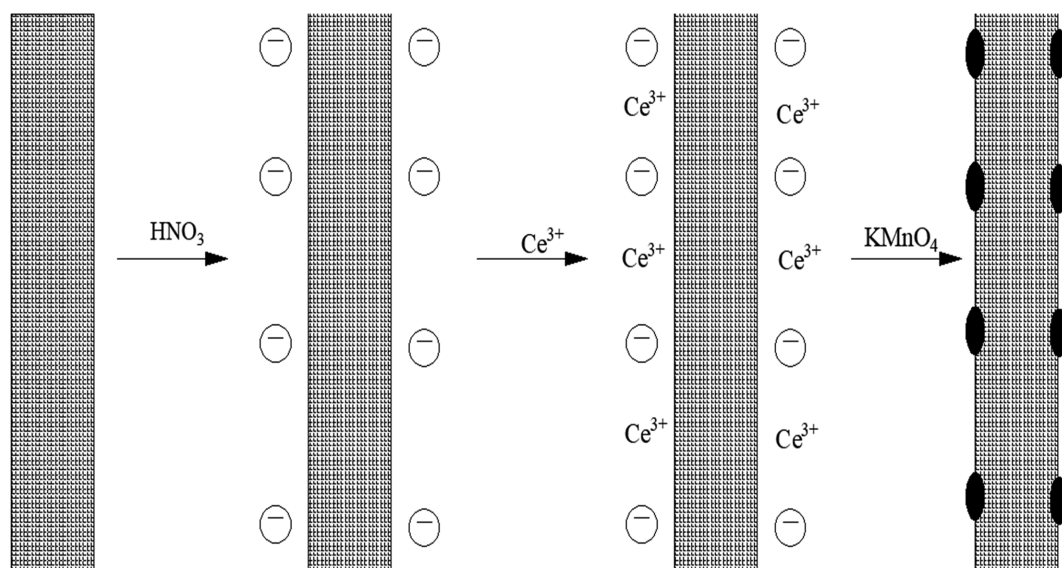
rare earth metals (Ce) exhibit superior denitrification performance at low temperatures and have broad application prospects.<sup>43</sup> Table 4 summarizes the literature data of low-temperature selective catalytic reduction denitrification using carbon-based catalysts in recent years.

In the above-mentioned supported carbon-based catalysts, metals often act as active components or assistants because they have variable valence and excellent electron mobility during the reaction process. Wang et al.<sup>44</sup> loaded Fe on a commercial active semi-coke to remove NO<sub>x</sub>. The introduction of Fe greatly improved the denitrification performance of the catalyst. In-situ infrared spectroscopy proved that Fe can transform between Fe<sup>3+</sup> and Fe<sup>2+</sup>, which improved the redox capability of carbon-based catalysts. Zhu et al.<sup>12</sup> supported CeO<sub>2</sub> on ACF modified by nitric acid, and the removal rate of NO by 9% CeO<sub>2</sub>/ACFN carbon-based catalyst at 180 °C could reach 95%. Ce loading increases the oxygen vacancy concentration of the carbon-based catalyst and provides more Brønsted acid sites, which promotes the adsorption of oxygen and the adsorption and oxidation of NO.

Bimetal or even multimetal supported carbon-based catalysts can improve the efficiency of low-temperature flue gas denitrification through synergistic effects.<sup>45</sup> Yang et al.<sup>46</sup> loaded pyrolganite (mainly composed of MnO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub>) on AC to produce AC-P10. At 150 °C, the NO removal rate was 74.2%, which was significantly higher than the 50% and 47.2% of Fe and Mn loading under the same reaction conditions. In this catalyst, the formation of a bimetallic structure and the enhanced electron transfer capability improve the low-temperature denitrification performance. Mn-Ce mixed oxide has high low-temperature SCR activity and strong SO<sub>2</sub> resistance, and CeO<sub>2</sub> can also improve the dispersibility and oxygen storage capacity of MnO<sub>x</sub>, and change the valence of Mn.<sup>47</sup> On this basis, Wang et al.<sup>48</sup> used a simple liquid phase

**Table 4.** Literature data of selective catalytic reduction of NO<sub>x</sub> over carbon-based catalysts at low temperatures

Catalysts	Reaction conditions	Temperature (°C)	NO removal efficiency (%)	Reference
CuO/AC	[NO]=2000 ppm, Ar balance GHSV=20000 h <sup>-1</sup>	230	>90	[43]
9%CeO <sub>2</sub> /ACFN	[NO]=[NH <sub>3</sub> ]=1000 ppm, [O <sub>2</sub> ]=5%, Ar balance GHSV=11000 h <sup>-1</sup>	180	94	[45]
AC-Pyrolusite (Fe-Mn/AC)	[NO]=500 ppm, [NH <sub>3</sub> ]=550 ppm, [O <sub>2</sub> ]=5%, N <sub>2</sub> balance GHSV=1000 h <sup>-1</sup>	150	74.2	[46]
4%MnO <sub>2</sub> /CNTs	[NO]=[NH <sub>3</sub> ]=500 ppm, [O <sub>2</sub> ]=5%, N <sub>2</sub> balance WHSV=108000 ml/g <sub>cat</sub> /h	180	89.5	[47]
Mn-CeO <sub>x</sub> /CNT	[NO]=[NH <sub>3</sub> ]=500 ppm, [O <sub>2</sub> ]=5%, N <sub>2</sub> balance GHSV=30000 h <sup>-1</sup>	80-180	85-100	[48]
4%MnO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> -CeO <sub>2</sub> -Ce <sub>2</sub> O <sub>3</sub> /CNT	[NO]=[NH <sub>3</sub> ]=400 ppm, [O <sub>2</sub> ]=5%, N <sub>2</sub> balance WHSV=210000 ml/g <sub>cat</sub> /h	120-180	90-100	[49]



**Figure 3.** Schematic diagram of synthesis process of Mn-CeO<sub>x</sub>/CNT.

method to prepare Mn-CeO<sub>x</sub>/CNT catalyst (as shown in Fig. 3). The catalyst exhibited superior low temperature SCR activity, with a conversion rate of up to 85% for 500 ppm NO at 80 °C and complete conversion could be achieved at 180 °C. Moreover, the ternary MnO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>-CeO<sub>2</sub>-Ce<sub>2</sub>O<sub>3</sub>/CNT catalyst synthesized by Zhang et al. with a one-step method had a maximum NO conversion rate of 99% at 120 °C. The excellent catalytic activity is attributed to the abundant surface O and the multivalent state of metal ions.<sup>49</sup> In summary, bimetal or even multimetal supported carbon-based catalysts have great potential in low-temperature SCR denitrification applications.

It is worth noting that the presence of SO<sub>2</sub> in the flue gas will reduce the efficiency of low-temperature selective reduction denitrification. This is because SO<sub>2</sub> will react with NH<sub>3</sub> to form ammonium nitrate, which inhibits the denitrification process. Existing studies have tried to design suitable carbon material carriers to reduce the negative impact of SO<sub>2</sub>. The unique properties of CNTs help reduce the stability of ammonium sulfate and promote its decomposition, while GO can slow down sulfur poisoning, thereby improving the stability of carbon-based catalysts.<sup>50</sup> Therefore, carbon-based catalysts can be prepared with CNTs or GO as carriers to solve the problem of SO<sub>2</sub> poisoning in the process of low-temperature flue gas denitrification. Tang et al.<sup>51</sup> prepared a three-dimensional nanosheet structure catalyst Mn<sub>2</sub>CoO<sub>4</sub>@rGO. When the catalyst is poisoned by SO<sub>2</sub>, ammonium sulfate can be removed by washing to restore activity, which improves the treatment efficiency and prolongs the service life of the carbon-based catalyst.

**Removal of H<sub>2</sub>S:** The removal of H<sub>2</sub>S from natural gas refining, petroleum refining and coal combustion is a major environmental challenge. H<sub>2</sub>S is toxic, harmful and has a foul odor. It is also easy to cause corrosion of equipment pipelines and catalyst poisoning during treatment. The most common industrial method of treating this gas is to oxidize it into elemental sulfur. For high concentration H<sub>2</sub>S, the Claus process (2H<sub>2</sub>S + SO<sub>2</sub> → (3/N)S + 2H<sub>2</sub>O) is often used for processing, and the conversion rate of H<sub>2</sub>S in this process can reach 97%-98%. Then the selective catalytic oxidation process is used to treat the remaining low concentration H<sub>2</sub>S and discharge it after reaching the emission standard. N-doped carbon-based catalysts are highly active for H<sub>2</sub>S catalytic oxidation, and the generated S is easier to recycle. The development of metal-free carbon-based catalysts to replace the conventional metal catalysts for H<sub>2</sub>S catalytic oxidation has the advantages of greenness and cost-effective.

Sun et al.<sup>52</sup> developed a nitrogen-rich mesoporous carbon (NMC) catalyst. N-doping introduced abundant Lewis basic sites, which made the catalyst have good activity for selective oxidation of H<sub>2</sub>S at low temperatures. Its sulfur capture capacity can reach 2.77 g<sub>sulfur</sub>/g<sub>catalyst</sub> in a single cycle, and the regeneration of catalyst and the recovery of S could be achieved through CS<sub>2</sub> washing or thermal sublimation. Li et al.<sup>53</sup> prepared an N-doped 3D mesoporous carbon/carbon nanotube (NC/CNT) catalyst, which had excellent desulfurization activity, stability and selectivity (81.6% sulfur selectivity), and the performance of the catalyst was better than the most advanced Fe<sub>2</sub>O<sub>3</sub>/SiC catalyst. In addition,

the S formed on the catalyst can be removed by simple heat treatment under He gas flow conditions to restore the desulfurization activity, which has broad prospects for practical application.

**Adsorption-Photocatalytic Degradation of Organic Waste Gas:** The treatment technologies of organic waste gas include adsorption, condensation, membrane separation, biodegradation and photocatalysis.<sup>54,55</sup> However, the application of single technology is often inefficient, while the combined treatment technology is more potential. Adsorption-photocatalysis is one of the most promising combined treatment technologies, which has the advantages of high removal efficiency, low cost and environmental friendliness. Carbon material itself has excellent adsorption performance, when used as a photocatalyst carrier, it can synchronously achieve adsorption and photocatalysis, so as to efficiently remove organic waste gas.<sup>56</sup> When An et al.<sup>57</sup> studied the photocatalytic removal of styrene, they found that the modified CNTs could prolong the adsorption equilibrium, making styrene fully in contact with TiO<sub>2</sub>/CNTs, and improving the photocatalytic efficiency. Because of the inherent porous structure and large specific surface area, carbon materials are ideal materials for dispersing and immobilizing nano photocatalysts. Miao et al.<sup>58</sup> found that CNTs could uniformly disperse the active component MnO<sub>2</sub> and improve the removal efficiency of formaldehyde over the catalyst through adsorption-photocatalysis. In addition, the excellent electrical conductivity of carbon materials can also play the role of electron transfer, reducing the electron-hole pair recombination ratio of photocatalyst, thus improving the photocatalytic activity.

In summary, the carbon-based catalysts have the following advantages in the removal of organic waste gas: (1) provide adsorption sites to enrich the organic waste gas from the gas phase to the solid phase; (2) disperse and stabilize photocatalysts, (3) reduce electron-hole pair recombination rate.

### Soil Remediation

Carbon-based catalysts, such as biochar, can be used as soil modifiers to improve soil and increase crop yields (as shown in Fig. 4). The porous structure of biochar can conserve water and nutrients, reduce soil density and facilitate gas exchange, etc. Biochar can also be used as a source of nutrients such as organic carbon, total nitrogen, potassium and phosphorus in soil.<sup>59</sup> Hafez et al.<sup>60</sup> reported that in the field experiment, the addition of modified biochar significantly increased the height, number of leaves, chlorophyll concentration and relative water content of barley

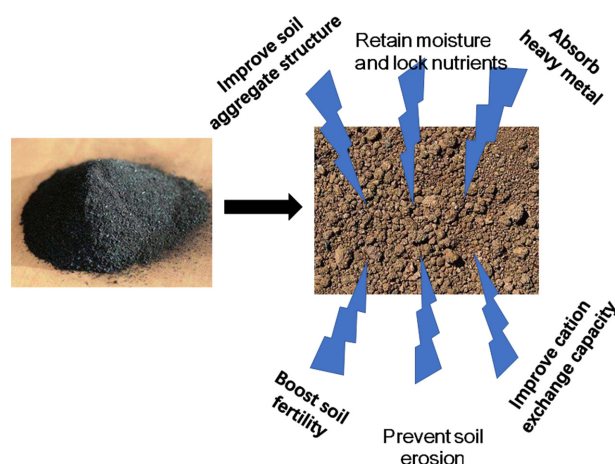


Figure 4. Schematic diagram of soil improvement by biochar.

plants, and could resist the stress of drought on the growth of barley.

In addition, biochar also plays an important role in remediation of soils contaminated by heavy metals. Biochar can reduce the content of heavy metal ions in soil through ion exchange, electrostatic attraction, precipitation and redox. Li et al.<sup>61</sup> pointed out that biochar had a high cation exchange capacity and could release Ca<sup>2+</sup> and Mg<sup>2+</sup> to exchange heavy metal ions. A study using biochar to improve the soil of a shooting range in South Korea found that biochar could reduce the bioavailability of Pb at 75.9%. Tan et al.<sup>62</sup> found that oxygen-containing functional groups, especially carboxyl groups, on the surface of biochar with low mineral content could fix heavy metals through surface complexation, and Si, S and Cl in biochar could bind heavy metals and reduce their fluidity in the soil. Biochar modified by zero-valent iron (nZVI@BC) has a strong adsorption on Cr (VI), which accelerates the aggregation rate of Cr (VI) on the surface of Fe, and can react with Cr (VI) to generate Cr (III) precipitation, thus greatly reducing the content of Cr (VI) in the soil.<sup>63</sup> Modified biochar has the advantages of low cost and high efficiency in remediation of contaminated soil.

### Other Applications

Carbon based catalysts also have huge application potential in organic synthesis, electrochemical catalysis and CO<sub>2</sub> reduction. The doping of nonmetallic atoms in the carbon matrix causes charge delocalization, thereby regulating its electronic structure to a metal-like structure, which helps to provide excellent catalytic activity like metal catalysts.<sup>64,65</sup> Based on this, Gao et al.<sup>66</sup> prepared carbon-based catalysts with adjustable concentration of P doping and lattice defects through the polymerization and carbonization of phytic

acid, which showed excellent catalytic activity, selectivity and stability in the hydrogenation of nitroaromatic hydrocarbons. N-doped GO and CNTs are more active as catalysts for oxygen redox reaction (ORR) in the cathode chamber of fuel cells than commercial Pt/C catalysts, promising to solve the high cost, toxicity and dissolution problems faced by platinum-based catalysts.<sup>13,67,68</sup> In addition, Zhang et al.<sup>69</sup> prepared 3D hierarchical polyethylenimine functionalized N-doped graphitized CNTs for reducing CO<sub>2</sub> to formates. Under the optimal conditions, the FE content of formate could reach 85% and the maximum current density could reach 9.5 mA/cm<sup>2</sup>.

## SUMMARY AND OUTLOOK

Carbon-based catalysts obtained after the modification and activation of the carbon-based materials have large surface areas, porous structure, and rich functional groups. They have both adsorption and catalytic performance, which make them play a unique advantage in the removal of environmental pollutants. They can be widely used in wastewater, waste gas and polluted soil treatment. In some fields, carbon-based catalysts are even expected to replace metal catalysts, which have the advantages of high efficiency, low cost, no secondary pollution, and reusability. It is of great ecological benefit and economic value to study and popularize carbon-based catalysts. In view of the existing problems in the application research of carbon-based catalysts, the following prospects are given:

(1) Most of the studies on the catalytic removal of environmental pollutants by carbon-based catalysts remain in the laboratory stage, and the mechanism of the removal of environmental pollutants still needs to be further studied. In addition, existing studies often emphasize the removal effect of single pollutant, while in practical application, the efficient and cooperative removal of multiple pollutants is the basis and key to the design and optimization of carbon-based catalysts.

(2) Metal-supported carbon-based catalyst can treat wastewater efficiently, but they are easy to cause secondary pollution due to metal dissolution. To solve this problem, future studies can try to coat the carbon-based catalyst with a layer of non-metallic materials, such as silica gel and silica layer, to improve their stability, reduce the amount of metal dissolution and extend their service life.

(3) Carbon-based catalysts do not completely degrade pollutants and may produce toxic by-products. Considering the economics of carbon-based materials, in practical applications, carbon-based catalysts can be used to

pre-treat wastewater or exhaust gas, and then combined with advanced oxidation, catalytic combustion and other processes to achieve advanced treatment effects.

### Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Acknowledgements.** The project is supported by the National Natural Science Foundation of China (61871409). And the publication cost of this paper was supported by the Korean Chemical Society.

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