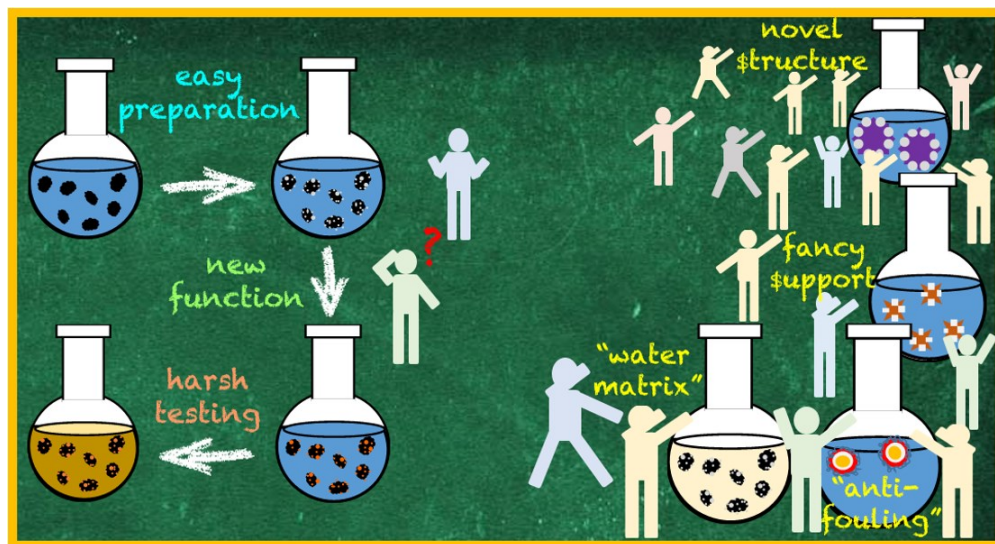


Catalytic Reduction of Water Pollutants: Knowledge Gaps, Lessons Learned, and New Opportunities

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Abstract

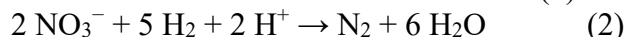
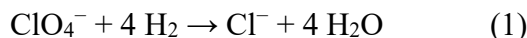
In this perspective paper, we discuss the previous advances, current challenges, and future opportunities for the research of catalytic reduction of water pollutants. We present five case studies on the development of palladium-based catalysts for nitrate, chlorate, and perchlorate reduction with hydrogen gas under ambient conditions. We emphasize the realization of new functionalities through the screening and design of catalytic metal sites, including (i) platinum group metal (PGM) nanoparticles, (ii) the secondary metals for improving the reaction rate and product selectivity of nitrate reduction, (iii) oxygen-atom-transfer metal oxides for chlorate and perchlorate reduction, and (iv) ligand-enhanced coordination complexes for substantial activity enhancement. We also highlight the facile catalyst preparation approach that brought significant convenience to catalyst optimization. Based on our own studies, we then discuss directions of the catalyst research effort that are not immediately necessary or desirable, including (1) systematic study on the downstream aspects of under-developed catalysts, (2) random integration with hot concepts without a clear rationale, and (3) excessive and decorative experiments. We further address some general concerns regarding using H_2 and PGMs in the catalytic system. Finally, we recommend future catalyst development in both “fundamental” and “applied” aspects. The purpose of this perspective is to remove major misconceptions about reductive catalysis research and bring back significant innovations for both scientific advancements and engineering applications to benefit environmental protection.

Keywords

Palladium, rhodium, ruthenium, rhenium, molybdenum, nitrate, chlorate, perchlorate, bromate, ligand, support, hydrogen

1. Introduction

Since the first report (Vorlop and Tacke, 1989), catalytic reduction of water pollutants has been extensively studied for over 30 years (Chaplin et al., 2012; Yin et al., 2018; Heck et al., 2019). The target pollutants include toxic oxyanions [e.g., nitrate (NO_3^-), nitrite (NO_2^-), bromate (BrO_3^-), chlorate (ClO_3^-), perchlorate (ClO_4^-), chromate (CrO_4^{2-})], organic halides (e.g., various brominated, chlorinated, or fluorinated hydrocarbons and functional molecules), and nitro- and nitroso- compounds (e.g., TNT, RDX, and NDMA, Fig.1). For water treatment, hydrogen gas (H_2) is an ideal electron source because the byproduct is H_2O :



The activation of H_2 (into $2 e^- + 2 \text{H}^+$) at ambient temperature (e.g., 20 °C) and pressure (1 atm) is enabled by heterogeneous catalysts, which typically contain platinum-group metal (PGM) nanoparticles on high-surface-area support (e.g., activated carbon C, γ -alumina Al_2O_3 , and porous silica SiO_2). The PGMs include ruthenium (Ru), osmium (Os), rhodium (Rh), iridium (Ir), palladium (Pd), and platinum (Pt).

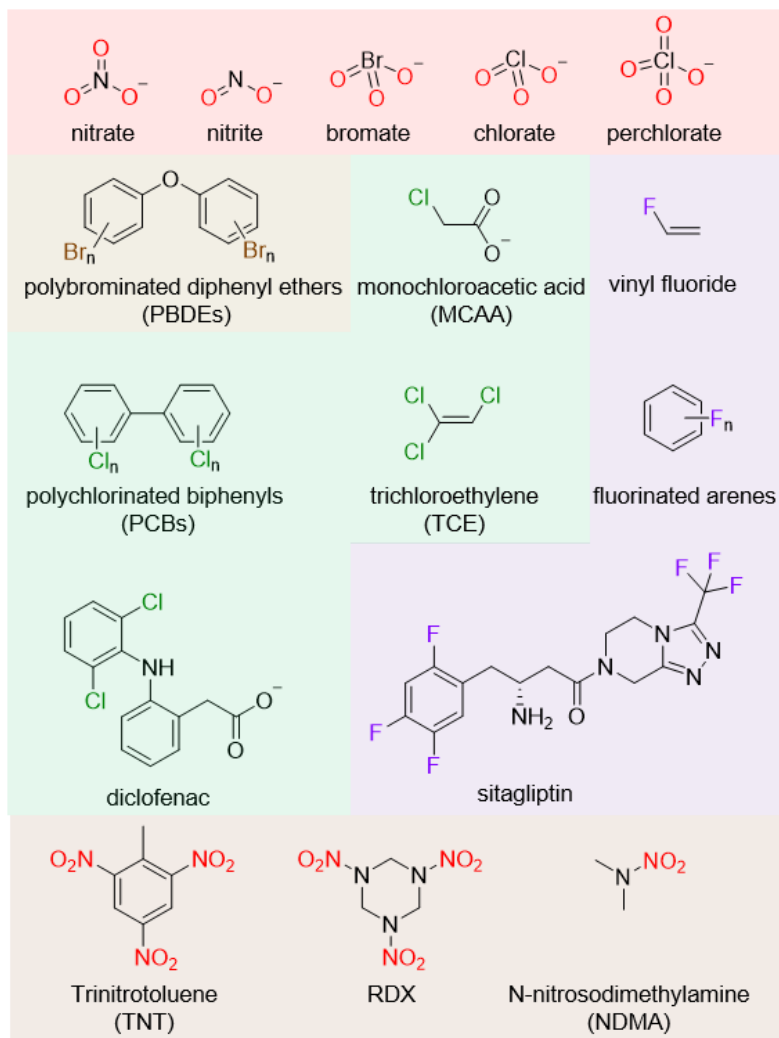


Fig.1. Representative pollutants reported to be degraded by reductive catalysis.

Despite the unique advantages of reductive catalysis, especially (i) the use of H₂ as a clean electron source, (ii) the completion of pollutant treatment under ambient conditions, and (iii) the simplicity of catalyst preparation, reactor setting, and result interpretation, the topic of reductive catalysis for water pollutant treatment has been recently vanishing from the academic research focus. However, this trend is not caused by the technology maturity that leaves no opportunity for further innovation. It is also not caused by the development of other technologies showing better cost-effectiveness. While some criticize the use of PGM (costly) and H₂ gas (flammable), the recent upsurge of electrochemical reduction of nitrate (NO₃⁻) into ammonia (NH₃) excludes both PGM and H₂ as negative factors. In those rapidly emerging studies since 2020, various PGMs are used on the electrode (Li et al., 2020; Lim et al., 2021; Chen et al., 2022), and the electrochemical systems also produce H₂ as an undesirable byproduct. Thus, the dramatic shift of research interest triggers curiosities, such as (i) what has been achieved and (ii) why the direction is now considered obsolete. Moreover, young researchers are more interested in (i) what knowledge gaps need to be filled, (ii) what misconceptions and pitfalls need to be avoided, and (iii) what new opportunities are in this “mistakenly abandoned” direction.

This perspective paper will first provide a brief review of oxyanion reduction catalyst development, then discuss the lessons learned and knowledge gaps identified. It highlights past advances (in terms of overcoming technical challenges rather than generating “academic hotspots”) and proposes new research opportunities. The discussion focuses on PGM catalysts using H₂ as the electron source. Although the electrochemical/electrocatalytic reduction systems are not in the scope of this paper, the two approaches have close similarities in design rationales and working mechanisms (Werth et al., 2020). References are cited to support the authors’ perspectives. Readers can find excellent comprehensive literature reviews of this field in the references (Chaplin et al., 2012; Yin et al., 2018; Heck et al., 2019).

2. Case Studies of Advances in Reductive Catalysis

2.1 Nitrate Reduction Catalysts Toward Dinitrogen (N₂)

The reduction of NO₃⁻ was the original motivation for developing oxyanion reduction catalysts. This case study shows the rapid development of various aspects of a catalytic system. In stark comparison, 30 years later, the pace of catalyst innovation has been substantially slower. This phenomenon is worth reflection among the environmental catalysis research community.

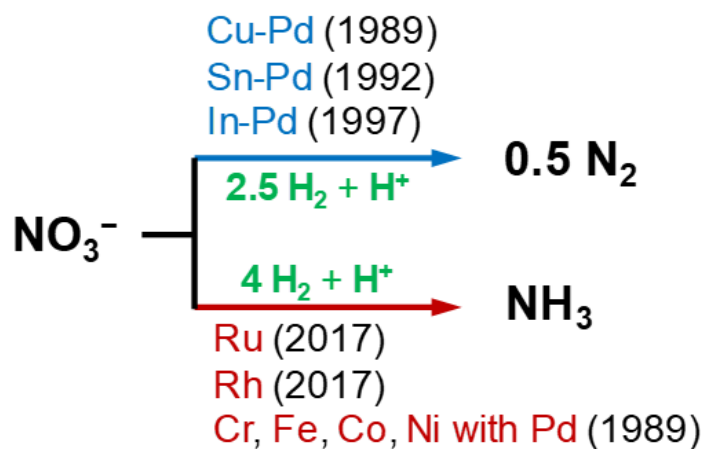


Fig.2. Major catalysts for nitrate reduction.

The first report (Vorlop and Tacke, 1989) initiated the development of PGM catalysts to reduce NO_2^- and NO_3^- . It explicitly pointed out that although NO_3^- in drinking water can be removed by ion exchange, electrodialysis, and reverse osmosis, the concentrated oxyanions required degradation treatment for disposal. It also noted the rapid catalytic treatment of NO_3^- compared to microbial reactors. The earliest report confirmed the activity of both Pd/ Al_2O_3 and Pt/ Al_2O_3 for NO_2^- reduction. Doping various secondary metals such as copper (Cu), nickel (Ni), chromium (Cr), cobalt (Co), and iron (Fe) to Pd/ Al_2O_3 enabled NO_3^- reduction (Fig.2). While most secondary metals converted NO_3^- into NH_3 , Cu allowed a faster rate of NO_3^- reduction and a lower selectivity toward the toxic NH_3 . In the following report (Vorlop et al., 1992), the product selectivity (i.e., N_2 versus NH_3) was attributed to metal content, support materials, and solution pH. This work also identified tin (Sn) as another secondary metal for NO_3^- reduction. In the third report (Tacke and Vorlop, 1993), the Cu–Pd/ Al_2O_3 catalyst powder was further encapsulated in alginate beads. A fluidized pilot reactor was operated for 100 days without catalyst deactivation. Detailed experimental data mentioned in the above reports in German were compiled in another paper in English (Hörold et al., 1993), which was often considered the “first report” of catalytic NO_2^- and NO_3^- reduction. In 1997, Prüsse, Hörold, and Vorlop (Prüsse et al., 1997) identified indium (In) as an even better option than Cu and Sn for both NO_3^- reduction kinetics and product selectivity toward N_2 . Systematic investigations of In–Pd, Sn–Pd, and Cu–Pd were reported in 2000 (Prüsse et al., 2000) and 2001 (Prüsse and Vorlop, 2001).

The studies of various aspects by Vorlop and colleagues built the framework for oxyanion reduction catalyst development in the following three decades: (i) the use of Pd as the primary choice of metal, (ii) the integration with a second metal to enable the reaction with challenging substrates, (iii) product selectivity (i.e., pathway control) and the influencing factors, and (iv) catalyst longevity and robustness. Around 400 papers have cited each of those publications (Hörold et al., 1993; Prüsse et al., 2000; Prüsse and Vorlop, 2001). The three bimetallic formulations also dominated the following research on NO_3^- reduction toward N_2 . A quick search of the most recent publications between 2016 and 2022 found meticulous advanced studies. Examples include spectroscopic characterization and theoretical simulations of In–Pd nanostructures (Guo et al., 2018), boosting the reaction kinetics and deactivation resistance of In–Pd by gold (Au) (Guo et al., 2022), immobilization of In–Pd onto sustainable and scalable natural fibers (Durkin et al., 2018), immobilization of Sn–Pd onto red mud (Hamid et al., 2018) and coal fly-ash-derived zeolites (Park et al., 2019). Notably, the electrochemical NO_3^- reduction toward N_2 also adopted similar design rationales. For example, Sn–Pd was electrochemically deposited on stainless steel mesh (Su et al., 2020); the Cu–Pd was directly used as a suspension in an electrochemical chamber (Zhang et al., 2016; Chen et al., 2019).

In short, the development of nitrate reduction catalysts had rapid growth at the beginning. The first report had already included various aspects that could be covered by multiple research articles as of today. The Cu–Pd, Sn–Pd, and In–Pd formulations were first reported in 1989, 1992, and 1997, respectively. After that, the following studies have significantly improved the catalyst formulation and mechanistic understanding of the three formulations instead of identifying new metal species.

2.2 Nitrate Reduction Catalysts Toward Ammonia (NH_3)

The original studies aimed to convert NO_3^- and NO_2^- into N_2 rather than into the toxic NH_3 (Vorlop and Tacke, 1989). Both the Drinking Water Ordinance of Germany in 1989 (Vorlop and

Tacke, 1989) and the new Standards for Drinking Water Quality issued by the Ministry of Environmental Protection of China in 2022 (Standardization Administration of China, 2022) set the limit for NH_3 at 0.5 mg/L. NH_3 in source waters is a highly challenging pollutant (Ye et al., 2022). However, in 2020, the goal of electrochemical conversion of NO_3^- suddenly switched from N_2 to NH_3 because the latter is reconsidered as a value-added product. This switch is more or less astounding because it reversed the efforts made in the past three decades (1989–2019) when the production of NH_3 was considered a failure of catalyst development.

The discussion of the environmental significance of producing N_2 versus NH_3 is not in the scope of this perspective. However, the metal-dependent functionality is noteworthy. The initial selection of Pd as the primary PGM was from a single test during the original exploration (Hörold et al., 1993). Five metals, Pd, Pt, Ru, Ir, and Rh, on Al_2O_3 support were screened by NH_3 production from NO_2^- . Pd/ Al_2O_3 showed a distinctly low NH_3 production, so it was further used to prepare bimetallic catalysts for NO_3^- reduction. Interestingly, most subsequent studies on the reduction of NO_3^- and other pollutants kept using Pd as the sole PGM for more than two decades. This situation motivated us to re-examine the five PGMs (Os is highly toxic and unsuitable for water treatment) on carbon and Al_2O_3 supports (Chen et al., 2017). To our surprise, both Ru/C and Ru/ Al_2O_3 showed high activity of NO_3^- reduction without using any secondary metal. The following study further confirmed nearly 100% selectivity to NH_3 by Ru catalysts (Fig.2) (Huo et al., 2017; Kong et al., 2022). Notably, Ru is also used in recent electrochemical systems for NH_3 synthesis from NO_3^- (Li et al., 2020; Chen et al., 2022). Because electrochemical methods do not require a PGM to extract electrons from H_2 , many other electrode materials only contained the first-row transition metals such as Fe, Co, Ni, and Cu (Chen et al., 2020; Wang et al., 2020; Wu et al., 2021; He et al., 2022; Li et al., 2022), which are consistent with the initial findings (Vorlop and Tacke, 1989; Hörold et al., 1993).

In short, the switch of PGM metal (e.g., from Pd to Ru) and the secondary metal (e.g., from In/Sn/Cu to Fe/Co/Ni) can dramatically switch the reaction pathway from yielding >70% N_2 to ~100% NH_3 . Despite the emerging confusion about the product preference, the two upsurges of NO_3^- reduction technology in the early 1990s and the early 2020s clearly suggest abundant opportunities for catalyst innovation, including the reactivity, pathway, and functionality, from a rational selection of PGMs and the secondary metals.

2.3 Chlorate and Perchlorate Reduction Catalysts

The 2022 new Standards for Drinking Water Quality of China set the concentrations of BrO_3^- , ClO_3^- , and ClO_4^- at 0.01, 0.7, and 0.07 mg/L, respectively (Standardization Administration of China, 2022). BrO_3^- is a carcinogen and can be generated from Br^- under natural and engineered oxidation (Chen et al., 2017; Gao et al., 2021). ClO_3^- is a common toxic byproduct of chlorine disinfection or electrochemical oxidation (Ren et al., 2020). ClO_4^- is an endocrine-disrupting pollutant from energetic materials. Beyond the Earth, it is also a rich component in the Martian soil (Ren et al., 2021a). Detailed literature for the background information of these anion pollutants can be found in the cited research reports. Using Pd and Cu–Pd catalysts to reduce BrO_3^- and ClO_3^- can be traced back to a patent filed in 1994 (Becker et al., 1998). Among the three oxyanions, BrO_3^- is the most labile substrate and can be rapidly reduced by various Pd-only catalysts reported since 2010 (Chen et al., 2010; Wang et al., 2014; Cerrillo et al., 2021; Gao et al., 2021). In comparison, ClO_3^- is much more recalcitrant than BrO_3^- . While the chloralkali process has developed Rh (Van Santen) and Ir (Kuznetsova et al., 2012) catalysts to reduce ClO_3^- , which is an

undesirable byproduct in the concentrated brine, academia seldom worked on ClO_3^- reduction. The limited attempts confirmed the challenge of ClO_3^- to Pd-only catalysts (Liu et al., 2015a; Ye et al., 2018).

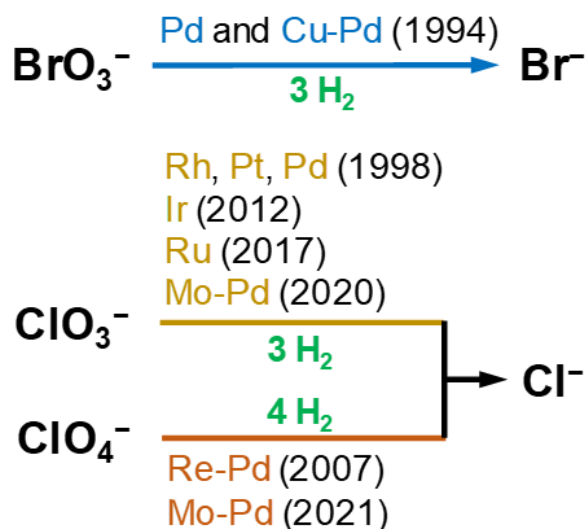


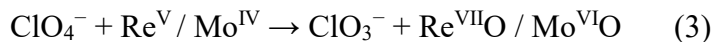
Fig.3. Major catalysts for bromate, chlorate, and perchlorate reduction.

Again, the enhanced degradation of recalcitrant oxyanions could be achieved by introducing specific metal species (Fig.3). For example, we recently found that the immobilization of molybdenum (Mo) into Pd/C accelerated ClO_3^- reduction by 55 times (Ren et al., 2020). The source of Mo is the common fertilizer, sodium molybdate (Na_2MoO_4) or ammonium molybdate $[(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}]$. Under the reducing condition of Pd+ H_2 at room temperature, the Mo^{VI} precursor is reduced to a mixture of Mo^{II} , Mo^{III} , Mo^{IV} , and Mo^{V} oxides. At pH 3.0, the $\text{MoO}_x\text{-Pd/C}$ catalyst showed comparable activity to the much more expensive Rh catalysts. A more attractive feature of $\text{MoO}_x\text{-Pd/C}$ is the much higher resistance to concentrated salts (e.g., SO_4^{2-} and Cl^- at mol/L levels) than Rh. Interestingly, tungsten (W) in similar mineral compositions, such as sodium tungstate (Na_2WO_4 and $\text{Na}_6\text{W}_{12}\text{O}_{39}$), showed no activity enhancement.

As for the most recalcitrant ClO_4^- , the activity of $\text{MoO}_x\text{-Pd/C}$ catalyst was too low to provide a satisfying reaction rate. Before we added organic ligands to enhance the ClO_4^- reduction by $\text{MoO}_x\text{-Pd/C}$ (see below) (Ren et al., 2021a), the technical solution had been dominated by rhenium (Re)-based $\text{ReO}_x\text{-Pd}$ catalysts since 2007 (Hurley and Shapley, 2007). The reductive immobilization of perrhenate salts (e.g., KReO_4) in Pd/C yield a mixture of Re^{I} , Re^{III} , and Re^{V} oxides (Choe et al., 2010; Choe et al., 2014). At room temperature, the reduced Re species can directly reduce ClO_4^- .

Using oxometallate species of Group 6 (Mo (Kolthoff, 1921; Haight Jr and Sager, 1952) and W (Haight Jr, 1954)), Group 7 (Re) (Abu-Omar and Espenson, 1995), and Group 8 (Os (Crowell et al., 1940)) metals to reduce ClO_3^- and ClO_4^- can be traced back to as early as 1921. However, the early systems required concentrated acids (e.g., 1–10 M HCl or H_2SO_4) and toxic reducing agents (e.g., HBr, SnCl_2 , and H_3PO_2). Water treatment engineering requires knowledge transfer from those theoretical studies in homogenous solutions to the heterogeneous catalytic systems using H_2 as the clean reductant (Fig.4). But as summarized above, common W^{VI} oxometallate salts did not work with the Pd/C+ H_2 platform. We also excluded osmate (OsO_4^{2-}) as

a candidate due to the high cost and high toxicity of Os and the limited activity observed in our preliminary tests with $\text{OsO}_x\text{-Pd/C}$. On the Pd/C+H_2 platform, reduced oxophilic metal species (e.g., Re^{V} , Mo^{IV}) trigger the stepwise reduction of ClO_4^- via a new mechanism, oxygen atom transfer (OAT) (Holm, 1987):



Although ClO_3^- and ClO_2^- products can be directly reduced by PGM+H_2 , the reduction of ClO_4^- requires the OAT mechanism and is usually the rate-limiting step. The primary role of PGM+H_2 is to reduce the oxidized OAT metal back to the reduced state, thus forming the catalytic cycle:

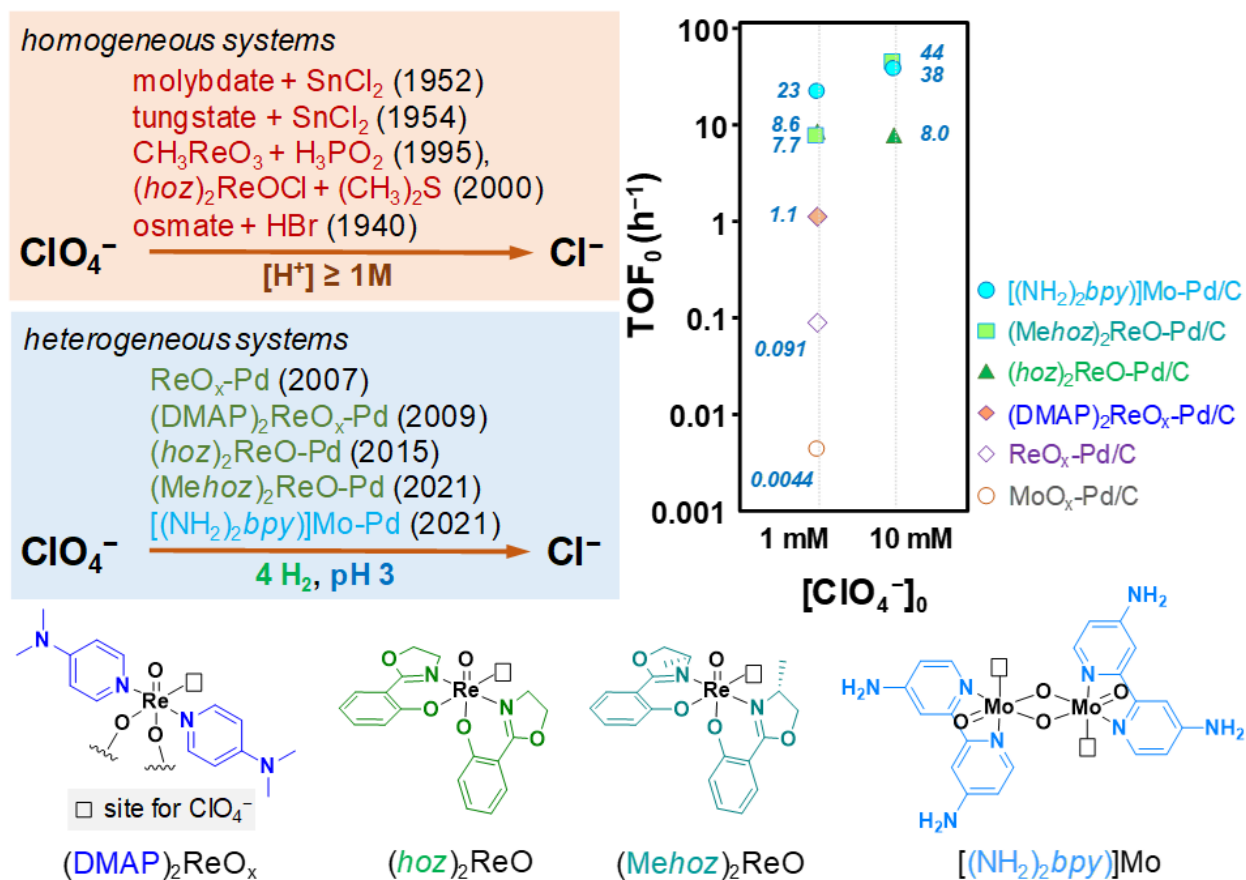
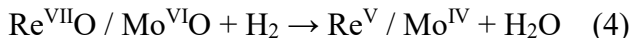


Fig.4. Catalytic systems for perchlorate reduction and the proposed or determined structures of organic ligand-coordinated Re^{V} and Mo^{IV} metal sites on the carbon surface.

Before the ligand enhancement was systematically studied, the original $\text{ReO}_x\text{-Pd}$ catalyst was directly applied to treat the waste brine from the regeneration of ion-exchange resins (Liu et al., 2013). For practical application of pollutant degradation technologies, rapid removal of oxyanions from contaminated drinking water by ion exchange is always necessary. The resin regeneration typically uses concentrated NaCl to liberate ClO_4^- and NO_3^- from the resin capture sites (e.g., $-\text{NR}_3^+$ functional groups). Therefore, concentrated ClO_4^- and NO_3^- need to be degraded in the presence of concentrated Cl^- and SO_4^{2-} (also captured from the groundwater). In general, one would expect the metal catalysts to be more or less inhibited by concentrated salts, but ClO_4^-

reduction by $\text{ReO}_x\text{-Pd/C}$ was surprisingly enhanced by concentrated NaCl (Liu et al., 2013). A probable explanation is the enhanced activity of H^+ (i.e., $\{\text{H}^+\} > [\text{H}^+]$, activity coefficient $\gamma > 1$) in the presence of concentrated salts. Because each dissolved Na^+ and Cl^- are theoretically solvated by six and two H_2O molecules, respectively, the dissolution of >1 M NaCl would significantly reduce the H_2O molecules available for H^+ solvation. As ClO_4^- reduction is assisted by H^+ (an acidic pH such as 3.0 is usually required), the enhanced activity of H^+ due to reduced solvation might accelerate the reaction. A systematic discussion of the higher $\{\text{H}^+\}$ in concentrated salt solutions can be found in the supporting file of the report (Liu et al., 2013).

Interestingly, although $\text{ReO}_x\text{-Pd/C}$ could also rapidly reduce NO_3^- (NH_3 was the primary product), the activity for ClO_4^- reduction was shut down by the NO_3^- co-contaminant. To solve this challenge, we added $\text{In-Pd/Al}_2\text{O}_3$ to reduce NO_3^- before using $\text{ReO}_x\text{-Pd/C}$ to reduce ClO_4^- . This sequential process design successfully avoided $\text{ReO}_x\text{-Pd/C}$ deactivation by NO_3^- .

In short, integrating a functional metal can help the PGM catalyst reduce challenging oxyanions. The addition of an oxometallate precursor of Group 6–8 metals utilizes the new OAT mechanism. The bimetallic system has the following advantages. First, the incorporation of the OAT metal is realized by an *in situ* reduction of the common mineral salt. Second, the substantial activity enhancement saves PGM while ensuring the same catalytic activity. Third, the rate-limiting reaction at the OAT metal site is not severely inhibited (e.g., $\text{MoO}_x\text{-Pd/C}$) or even accelerated (e.g., $\text{ReO}_x\text{-Pd/C}$) by concentrated salts.

2.4. Ligand-Enhanced Perchlorate Reduction

Although $\text{ReO}_x\text{-Pd/C}$ showed unique ClO_4^- reduction activity as a heterogeneous catalyst, the reaction rate was still much lower than that of BrO_3^- reduction by Pd-only catalysts or ClO_3^- reduction by $\text{MoO}_x\text{-Pd/C}$. In general, the catalyst activity can be estimated by the following primary parameters: half-life of the oxyanion reduction (min or h), initial concentration of the oxyanion (mM), catalyst loading (g/L), and metal content in the catalyst (wt%). Although the rigorous approach is to calculate the initial turnover frequency (TOF_0 , Fig.4) by considering the number of available metal atoms at the catalyst surface, the comparison of those kinetic parameters provides a quick estimation. The comparison is often fair because (i) the catalyst developers are responsible for maximizing the utilization of PGM, and (ii) many studies did not provide metal dispersion data to calculate TOF_0 . For the reduction of 1 mM ClO_4^- , the use of 2.0 g/L of $\text{ReO}_x\text{-Pd/C}$ (5 wt% Re, 5 wt% Pd) showed a half-life between 2.5 and 6 h, depending on the batch of commercial Pd/C (Liu et al., 2013). In comparison, for the reduction of 1 mM ClO_3^- , the use of 0.2 g/L of $\text{MoO}_x\text{-Pd/C}$ (5 wt% Mo and 5 wt% Pd) showed a half-life of <10 min (Liu et al., 2013). Apparently, the ClO_4^- reduction activity on the catalyst surface had great room for improvement.

Ligand-enhanced catalysis was motivated by the comparison with a molecular $\text{Re}(\text{O})(\text{hoz})_2\text{Cl}$ complex (Fig.4), which contains one oxo ligand, one chloro ligand, and two N,O-bidentate ligands [$\text{L}_{\text{O-N}}$, $\text{hoz} = 2\text{-(2'-hydroxyphenyl)-2-oxazoline}$] (Abu-Omar et al., 2000). This complex showed rapid ClO_4^- reduction in a homogeneous system, where acetonitrile was the solvent and dimethylsulfide was the oxygen acceptor:



The immobilization of the $\text{Re}(\text{O})(\text{hoz})_2\text{Cl}$ complex onto Pd/C achieved rapid ClO_4^- reduction by H_2 . Using the same metrics of comparison, 0.5 g/L of $\text{Re}(\text{O})(\text{hoz})_2\text{-Pd/C}$ (5 wt% Re and 5 wt% Pd) shortened the half-life of 1 mM ClO_4^- to ~15 min. Therefore, in comparison to $\text{ReO}_x\text{-Pd/C}$, the use of 1/4 of the catalyst loading and >10x faster reaction suggest a >40x activity enhancement by the coordination of Re with two *hoz* ligands. The design rationale, mechanistic elucidation, and stability improvement of the $\text{Re}(\text{O})(\text{LO-N})_2\text{-Pd/C}$ catalyst family (Zhang et al., 2011; Liu et al., 2015a; Liu et al., 2015b; Liu et al., 2016a; Liu et al., 2016b; Liu et al., 2017; Ren and Liu, 2021) are not in the scope of this paper. The concise point is that tuning the ligand structure could bring in substantial enhancement of the catalyst activity and stability at the scale of 1–2 orders of magnitude. The ligand effect is much more pronounced than other approaches for catalyst development, such as changing the catalyst support material.

Although the $\text{Re}(\text{O})(\text{hoz})_2\text{Cl}$ complex is air-stable and can be immobilized onto Pd/C by adsorption, its multi-step synthesis from KReO_4 and irreversible decomposition affected the potential application. Therefore, the *in situ* formation of active Re sites from the KReO_4 precursor and free organic ligand is an alternative route. The direct addition of *hoz* ligand (*hoz* : Re = 2:1) into $\text{ReO}_x\text{-Pd/C}$ achieved merely 4x faster ClO_4^- reduction kinetics, but the addition of the monodentate pyridine ligands (e.g., 4-dimethylaminopyridine) (Hurley et al., 2009) showed even better results (up to 12x) (Liu et al., 2015b). It appeared that ligand selection is the key factor for activity enhancement.

A similar attempt on the $\text{MoO}_x\text{-Pd/C}$ catalyst resulted in a major breakthrough. Without the addition of organic ligands, the catalyst showed literally no activity by reducing <4% of 1 mM ClO_4^- at a loading of 2.0 g/L after 8 h. However, various N,N-bidentate ligands significantly accelerated the reaction (Ren et al., 2021a). The best ligand was 4,4'-diamino-2,2'-bipyridine $[(\text{NH}_2)_2\text{bpy}]$ (Fig.4). With the addition of $(\text{NH}_2)_2\text{bpy}$: Na_2MoO_4 at 1:1, the $[(\text{NH}_2)_2\text{bpy}]\text{MoO}_x\text{-Pd/C}$ catalyst at 0.2 g/L loading shortened the half-life of 1 mM ClO_4^- to ~15 min. The coordination of the $(\text{NH}_2)_2\text{bpy}$ ligand with the Mo^{IV} site thus led to a >6,200x enhancement of the reactivity with ClO_4^- . Interestingly, in the case of Mo catalysts, monodentate pyridine ligands resulted in very limited enhancement. The ligand adaptability for $\text{MoO}_x\text{-Pd/C}$ and $\text{ReO}_x\text{-Pd/C}$ showed opposite trends for monodentate N versus bidentate N–N ligands. Currently, the selection of organic ligands for ClO_4^- reduction catalysts is still empirical rather than rational. This is understandable as most research resources have been spent on other directions, such as the synthesis of nanostructured metal particles and support materials (Chaplin et al., 2012; Yin et al., 2018; Heck et al., 2019), rather than the molecular design of coordinated metals.

The $[(\text{NH}_2)_2\text{bpy}]\text{MoO}_x\text{-Pd/C}$ catalyst was further evaluated under a series of harsh conditions (Fig.5) that simulated real waste brine treatment applications, where (1) concentrated salts (e.g., Cl^- , SO_4^{2-} , NO_3^-) and natural organic matters (NOM) are present, (2) the catalyst is under extended exposure to H_2 , (3) the catalyst is under excessive oxidative stress by concentrated ClO_4^- in brine and O_2 during the handling in air (Ren et al., 2022). Similar to the $\text{ReO}_x\text{-Pd/C}$ catalyst, the $[(\text{NH}_2)_2\text{bpy}]\text{MoO}_x\text{-Pd/C}$ was deactivated by NO_3^- but the use of $\text{In-Pd/Al}_2\text{O}_3$ to reduce NO_3^- could solve the issue. This phenomenon broke our initial expectation because (1) nitrate was considered more labile than perchlorate to reduce, and (2) common nitrogen products such as NO , N_2O , or NH_3 were not expected to inhibit either Re or Mo catalysts. Such an interesting issue in selectivity and inhibition indicated our shallow understanding of coordination chemistry and great scientific promise for future studies. The $[(\text{NH}_2)_2\text{bpy}]\text{MoO}_x\text{-Pd/C}$ showed high stability against multiple spikes of 100 mM ClO_4^- , air exposure, and up to 50 mg/L of humic

acid. Although the prolonged ligand hydrogenation lowered the activity by 90% after three weeks, a simple pH adjustment to 12.0 could remove all Mo species. The Pd/C could thus be reused with a new batch of Mo and (NH₂)₂bpy ligand. The [(NH₂)₂bpy]MoO_x-Pd/C appears to be competent for practical applications.

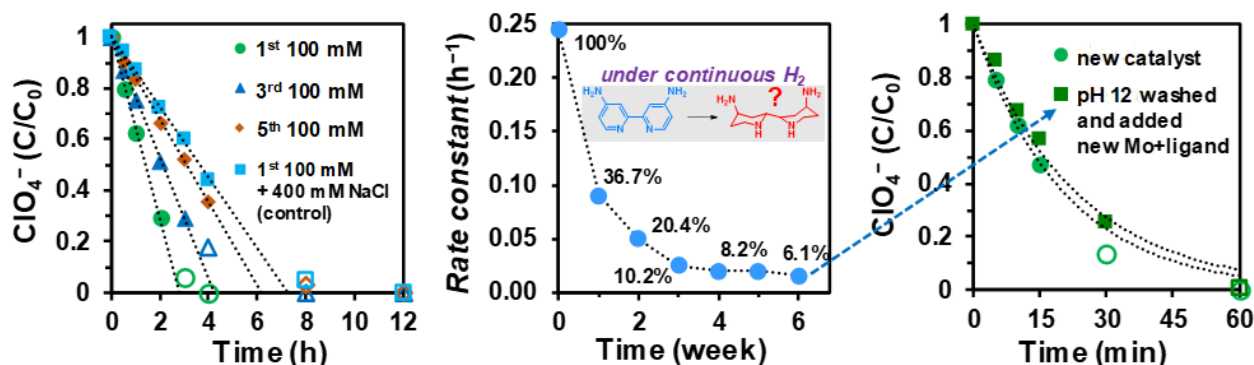


Fig.5. Examples of robustness tests of the [(NH₂)₂bpy]MoO_x-Pd/C catalyst: continuous treatment of highly concentrated ClO_4^- ; long-term exposure to H_2 ; and Pd/C reuse after the deactivation of Mo species. The data have been reported in ref. (Ren et al., 2022) and shown here with modified displays.

In short, coordinating selected organic ligands with the OAT metal (e.g., Mo and Re) substantially enhanced activity, more than three orders of magnitude, for reducing the most recalcitrant ClO_4^- . The above examples showcase the importance of (1) utilizing alternative reaction mechanisms by new metal elements and (2) harnessing the power of coordination chemistry to advance environmental catalysis. These two directions are much less explored compared to the tuning of nanostructured particles and supports of Pd-only catalysts.

A common feedback on adding organic ligands to accelerate the reaction is that the catalyst becomes more complicated than the ligand-free (or “totally inorganic”) system. To divert such concerns, we can compare it with the natural systems, which fully rely on various organic-metal complexes in enzymes to degrade pollutants. However, it is also worth comparing the usually neglected but substantial “organic footprint” from the preparation of “inorganic” nanostructures. For example, the synthesis of PGM nanocrystals and nanostructured supports consumed organic polymers (e.g., polyvinylpyrrolidone and poloxamers) and organic solvents (e.g., ethanol and tetrahydrofuran). The nitrogen doping on the support material uses urea, melamine, etc. The functionalization of inorganic oxides used 3-aminopropyltriethoxysilane and so on. The formation of ordered pore structures required surfactant templates such as cetyltrimethylammonium bromide, which was later burnt in oven or washed away by organic solvents. The synthesis of inorganic oxides started from organic reagents such as tetraethyl silicate and tetrabutyl titanate. Even the single-atom catalytic sites could use organometallic complexes as the precursor. While citations are not included here, the readers can readily find a handful of reports with detailed information. After comparison, the advantage of the ligand-enhanced catalysis would be overwhelming in terms of simplicity and performance, all attributed to the amazing power of coordination chemistry.

2.5 Lowering Technical Barriers for Catalyst Development

Despite the evolution of catalyst formulations and functionalities, a frequently encountered challenge is the cost of PGM. In a majority of reports, the Pd content was 5 wt%. While 5 wt% Pd on carbon, alumina, and silica supports are commercially available, the reason for this specific value and the suitability for water pollutant treatment is unknown. However, as most supported Pd catalysts were prepared by multi-step protocols that usually involve drying, calcination, and reduction with heated H_2 flow in specialized ovens and furnaces, the effect of Pd content was not investigated in fine detail. We recently developed an “instant” all-*in-situ* preparation method to prepare supported Pd catalysts with any metal content (Gao et al., 2021). The working principle was the high reactivity of Pd^{II} species with H_2 . In both the aqueous phase and pure solid, $\text{Na}_2\text{Pd}^{\text{II}}\text{Cl}_4$ can be rapidly reduced to Pd^0 by 1 atm H_2 . Therefore, after near-complete adsorption of Pd^{II} from water onto the porous carbon support within 5 min, the following exposure to 1 atm H_2 at room temperature for another 5 min yielded Pd^0/C (Fig.6).

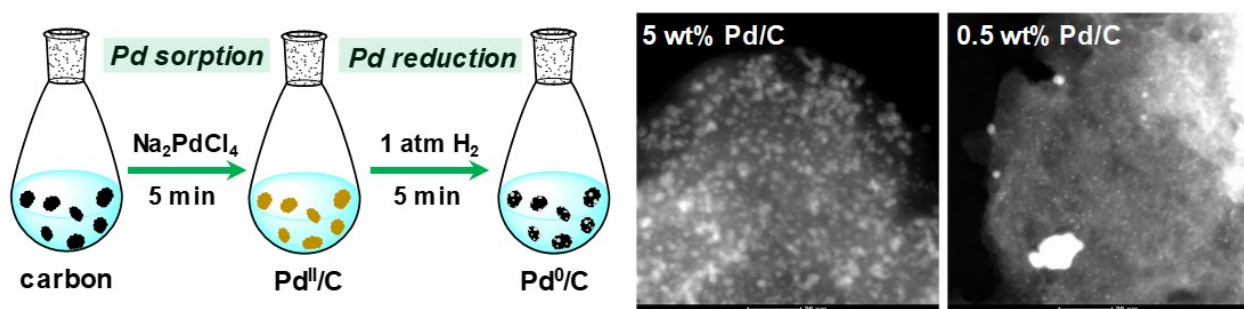


Fig.6. Facile preparation of Pd/C catalysts and the scanning transmission electron microscopy (STEM) imagings of 5 wt% Pd/C and 0.5 wt% Pd/C. The two images are reproduced from ref. (Gao et al., 2021) with permission. Note that some large Pd particles are present with the expected small ones. This is a common phenomenon (but often not shown in literature for a “good size control”) and similar to the commercial Pd/C catalyst (see Fig.7).

Microscopic characterization and kinetic testing using BrO_3^- , ClO_3^- (by Pd/C and $\text{MoO}_x\text{-Pd/C}$) and ClO_4^- (by $\text{ReO}_x\text{-Pd/C}$) found no significant difference between the prepared Pd/C and commercial Pd/C. This new and convenient approach allowed wide screening of Pd contents from 0.1 wt% to 10 wt% on the same support material. The result was surprising because the optimal Pd content on the carbon support seemed to be around 0.5 wt%, just 1/10 of the prevalently used 5 wt%. Although the reaction rate by 0.5 wt% Pd/C was lower than 5 wt% Pd/C, the decrease in reaction rate was not in proportion to the decrease in Pd content. In other words, at higher Pd contents, more Pd atoms do not participate in the catalysis. With the same solid catalyst loading, the activity of 0.5 wt% Pd/C was about half of that of 5 wt% Pd/C. Therefore, by doubling the catalyst loading, the catalytic activity remained the same while saving 80% of Pd. This simple optimization of Pd content is equivalent to increasing the catalyst activity by four times (Gao et al., 2021). Our ongoing studies have found that multiple catalyst formulations (for both PGM and OAT metals) can be further lowered from the arbitrary 5 wt%.

It is worth mentioning again that $\text{MoO}_x\text{-Pd/C}$, $\text{ReO}_x\text{-Pd/C}$, and $[(\text{NH}_2)_2\text{bpy}]\text{MoO}_x\text{-Pd/C}$ were all prepared by directly adding the components (Na_2MoO_4 , KReO_4 , and free $(\text{NH}_2)_2\text{bpy}$ ligand) into Pd/C suspension (Fig.7) (Choe et al., 2010; Ren et al., 2020; Ren et al., 2021a). Under 1 atm H_2 and room temperature, the catalytic species were assembled spontaneously from these

precursors. In other words, one can rapidly prepare the catalysts from scratch— a porous material (e.g., carbon, alumina, silica, etc.), a PGM precursor (e.g., Na_2PdCl_4), an OAT metal precursor (e.g., Na_2MoO_4 , KReO_4), and an organic ligand enhancer, without any heating equipment or specialized synthesis technique. The simplicity and reproducibility are based on the use of dissolved molecular components, while the variance of performance would be primarily attributed to the heterogeneous support material.

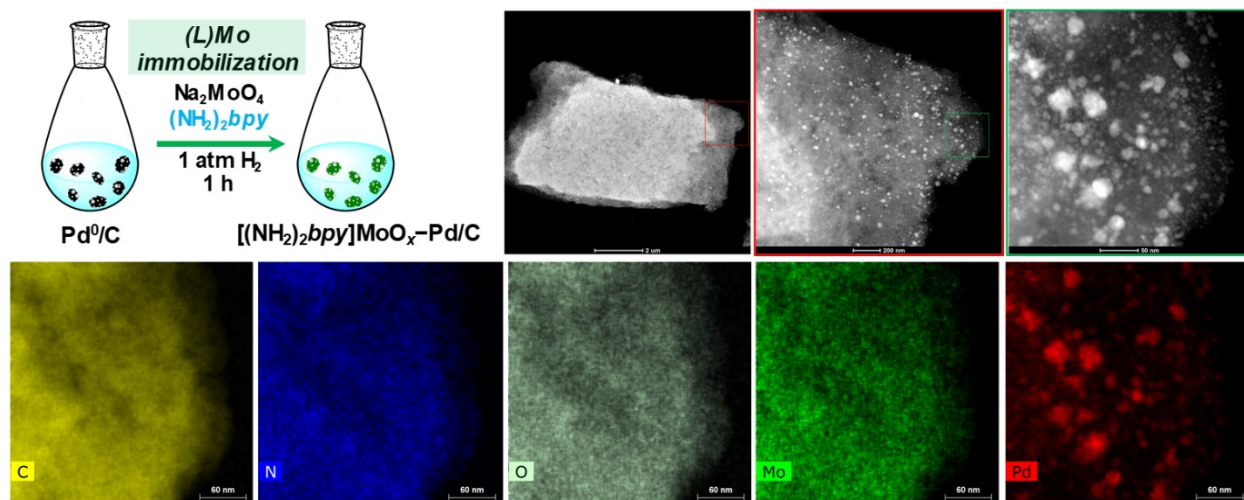


Fig.7. Facile preparation of the $[(\text{NH}_2)_2\text{bpy}]\text{MoO}_x\text{-Pd/C}$ catalyst and STEM–energy dispersive X-ray (EDX) elemental mapping of a $\sim 10\ \mu\text{m}$ sized catalyst particle. Note that the Pd particles shown here in a commercial 5 wt% Pd/C have a wide size distribution. But this Pd/C showed very similar catalytic performance as the 5 wt% Pd/C prepared by the all-*in-situ* method in Fig.6.

3. Perspectives for Catalyst Development Research

3.1 Lessons Learned from Early Efforts

While the five case studies above illustrate the core missions of catalyst development— new functionality, high activity, high stability, and low cost, there have been many other constructive efforts of catalyst development. This perspective cannot summarize all such works, but it is essential to also discuss some directions we feel are not the priority of catalyst development. To be accurate and fair, we use our own studies as examples:

1. *Systematic study of performance loss of a catalyst that is still under development.* Evaluating the loss of performance is crucial for applications. However, this downstream effort is meaningful only when the catalyst has been adequately developed and researchers are confident to move forward to the application aspects. Suppose a catalyst in the initial development phase holds various intrinsic limitations. In that case, priority should be given to better catalyst design that can overcome such limitations rather than a comprehensive measurement of how the original catalyst fails. For example, the first $\text{Re}(\text{O})(\text{hoz})_2\text{-Pd/C}$ catalyst tended to irreversibly decompose into ReO_4^- and two free *hoz* ligands (Liu et al., 2015b). After the general decomposition mechanism was found, a viable solution was to modify the ligand structure to improve stability (Liu et al., 2016a; Ren and Liu, 2021) rather than meticulously measure the effects of water matrices (e.g., 10 mM of Cl^- , Br^- , I^- , SO_4^{2-} , H_2PO_4^- ; Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Mn^{2+} , Fe^{2+} ; pH 2,3,4,5,6; $[\text{ClO}_4^-]_0 = 0.01, 0.1, 1, 10\ \text{mM}$; etc.) to the original catalyst (Liu et al., 2015a). For comparison,

after the $[(\text{NH}_2)_2\text{bpy}]\text{MoO}_x\text{-Pd/C}$ was developed, our evaluation of its application potential used a much more challenging and realistic set of metrics (concentrated salts, five spikes of 100 mM ClO_4^- , air exposure, etc.) in greater motivation and confidence (Fig.5) (Ren et al., 2022). After we became more encouraged to challenge the catalysts with extreme conditions, we also found that the Pd/C catalyst was not inhibited by 2 M Cl^- or 1 M SO_4^{2-} for BrO_3^- reduction at pH 7 (Gao et al., 2021).

2. *Anti-fouling catalyst designs.* Although sulfide and NOM are known fouling species to PGM catalysts (Chaplin et al., 2012), there are instant methods to remove them. Sulfide can be rapidly oxidized into inert SO_4^{2-} using hydrogen peroxide, sodium/calcium hypochlorite, and ferrous/ferric salts (Gao et al., 2021). NOM can be readily removed by coagulation. It is important to point out that the catalytic process is less likely to be integrated into the drinking water treatment process. Hence, a long exposure to trace sulfide and NOM in flowing drinking water seems not a realistic scenario. Instead, treating the concentrated oxyanions after ion-exchange resin regeneration would be important. Therefore, using common oxidants or coagulants to prevent catalyst fouling, rather than cleaning fouled catalysts with oxidants or alkaline chemicals, is a more realistic strategy for the application. The use of reverse osmosis membranes requires various pre- and post-treatment modules (e.g., microfiltration, chlorination, dechlorination, pH adjustments, etc.). Therefore, additional treatment steps to protect the central process is a well-established approach. The PGM catalyst is not designed as an independent technology to stand all water matrix challenges. Even if the catalyst is severely fouled by unexpected species, the PGM can be recycled by established chemical extraction protocols (Fontana et al., 2018; Nogueira et al., 2019; Fotouhi-Far et al., 2021).

3. *Use of novel support materials for known metal species.* There have been numerous studies on using various novel materials to support Pd nanoparticles for the reduction of BrO_3^- and chlorinated organics. In particular, novel electronic properties demonstrated in other disciplines (e.g., graphene for electronic devices) were hypothesized to enhance the supported Pd catalysts. However, there has been no significant activity improvement by such effort yet. This is not surprising because the interaction between PGM particles and the support material is not well understood. A systematic comparison of conventional support materials (e.g., carbon and alumina for different Pd precursors) has been conducted very recently (Cerrillo et al., 2021). How the support can impact the interaction between the PGM particles and pollutant molecules is not well elucidated, either. Although no arbitrary recommendation could be made for this direction, most published data have suggested that the benefits of changing the support material are far less pronounced than altering the metal speciation and reaction pathway. We prepared a “hierarchical” nanostructure, where Pd nanocrystals were immobilized outside an amino-functionalized silica sphere and then encapsulated by a mesoporous silica (mSiO_2) layer (Wang et al., 2014). Surprisingly, the BrO_3^- reduction activity of the mSiO_2 -coated catalyst was $>10\times$ higher than the exposed Pd catalyst. The substantial enhancement was explained by Langmuir-Hinshelwood kinetic model. Probably, this finding may also be attributed to the recently introduced “nanoconfinement” effect. However, even with the mSiO_2 coating, the BrO_3^- reduction activity was only 1/40 of a commercial Pd/C (Chen et al., 2017). The explorations of novel support materials may reveal novel insights, but they are not closely relevant to practical application. The further point is that if the practical application is not the goal, the research should focus on the structure-activity relationship. Under such circumstances, the “application evaluation” under hypothesized scenarios (i.e., water matrix effects as requested by most environmental technology journals) is unnecessary.

In short, the three aspects above are not the technical priority of catalyst development. Similar thinking logic may be applied to other research topics beyond this paper.

3.2 Clarifications of Some Misconceptions

There have been a series of technical points that may need clarification to enhance the researcher's interest or confidence in developing catalytic treatment systems. Representative ones are addressed below:

1. *Hydrogen gas consumption.* In many research reports, a rapid H₂ flow rate of 0.1 or 0.2 L/min was used in a ≤ 200 mL solution containing ≤ 1 mM pollutant. However, such a vigorous H₂ supply was not required by the reaction kinetics. In many cases, this value was adapted simply because the lowest reading on the standard gas flowmeter is 0.1 L/min. This setting not only wasted H₂ gas but also blew away the water. The solution volume might be reduced to a significant extent, adversely concentrating the pollutant. Although the H₂ mass transfer is a limiting factor in high-volume systems, for batch reactions less than 200 mL, it is only needed to maintain a positive pressure of H₂ to prevent air backflow. This condition is achieved by allowing one H₂ bubble from the gas supply needle tip every 1–2 seconds. An H₂ balloon attached to the reactor is also a common approach to maintain the positive reactor pressure (Wu et al., 2012). In short, for small-volume reactions, a vigorous H₂ flow is not necessary. The concern about using an H₂ gas cylinder may be addressed by using an H₂ generator. Nevertheless, H₂ and other flammable hydrocarbon gases have been commonly used in microbial reactors for reductive pollutant degradation (Chung et al., 2007; Zhao et al., 2011; Lai et al., 2021), whereas the heterogeneous catalysis design has been frequently challenged by H₂ safety concerns. While ventilation is essential, using N₂-H₂ mixed gas can be an additional measure to reduce the safety risk further.

2. *PGM loss from the catalyst.* There have seldom been bench-scale studies reporting Pd leaching at room temperature. In most reports, the dissolved Pd was below the detection limit. Although significant PGM leaching may be possible from long-term applications, the lack of leaching during the short-term tests indicates the promise of short-term application (i.e., hours to days). Such a scenario is possible because the treatment of ion-exchange regeneration waste is an intermittent operation. However, it is essential to note that concentrated ligands (organics, chloride anion, etc.) can promote the dissolution of Pd^{II} upon oxidation of Pd⁰ particles. Pd leaching from heterogeneous catalysts during organic catalysis has been well documented (Webb et al., 2007), but those applications typically involve concentrated organics, oxidative mechanisms, and elevated temperatures. Because the application of PGM catalysts for water treatment is still far from mature, the knowledge regarding metal leaching under practical applications is still lacking. Nevertheless, the use of oxidants to clean the “sulfide-fouled” Pd catalyst is not recommended due to the potential oxidative dissolution of metal nanoparticles (Howe and Mercer, 1925; Clem and Huffman, 1968).

3. *High cost of PGM.* A very common criticism for applying PGM catalysts is the high price of metals. This viewpoint must be addressed by the reality that most chemical treatment processes are not for integration into large-scale drinking water treatment trains. Thus, exposing PGM catalysts to giant volumes of drinking water flow is not a realistic scenario. Modern ion-exchange resins have high selectivity toward ClO₄[−]. After several months, the resins can be regenerated by as small as one bed volume of the regeneration solution (Gu et al., 2007). Therefore, the waste brines with concentrated ClO₄[−] have a minimized volume and may not even need

continuous treatment operations. As discussed above, chemical innovations in catalyst formulation can significantly improve cost-effectiveness. If the optimized $[(\text{NH}_2)_2\text{bpy}]\text{MoO}_x\text{-Pd/C}$ (0.5 wt% Pd and 3 wt% Mo) (Ren et al., 2022) is applied to treat 1 m^3 of the waste brine (after the ion-exchange purification of $>50,000\text{ m}^3$ of drinking water), a quick estimation of Pd and Mo needed for a typical 1 g/L (or 1 kg/m^3) catalyst loading would be 5 g Pd and 30 g Mo . Moreover, the catalyst is to be reused many times. For comparison, the catalyst converter in a typical gasoline vehicle contains $2\text{--}5\text{ g}$ of Pd. Hence, there is no unique economic barrier to applying PGM catalysts for water treatment applications.

3.3 New Research Opportunities

Based on the discussions above, the field of reductive catalysis for pollutant degradation has not been adequately developed for multiple reasons. The innovation of catalyst formulation, including the rational choice of metal elements, metal speciation, and reaction pathway, is far from mature. To date, limited successes include the use of (i) Cu, Sn, and In to allow NO_3^- reduction, (ii) Ru and Rh to achieve novel functions that Pd does not have, and (iii) OAT metals (e.g., Re and Mo oxides and complexes) to enable the reduction of highly recalcitrant ClO_4^- . Due to the limit of our research experience and the length of this paper, we have not discussed PGM-catalyzed dehalogenation. Here we just briefly note that the switch from Pd (highly active in dechlorination) (Grittini et al., 1995; Lowry and Reinhard, 2000,2001; Zhuang et al., 2011) to Rh enabled hydrodefluorination from fluoroarenes (Baumgartner and McNeill, 2012; Baumgartner et al., 2013; Yuan et al., 2021), vinyl fluoride (Yu and Chiu, 2014), and fluorinated pharmaceutical pollutants (Fig.1) (Park et al., 2020). As the majority of previous catalyst development have been focusing on novel support materials and nanostructure controls, we envision that the re-allocation of the research effort will substantially expand the scope of the catalyst formula and uncover various functionalities toward pollutant degradation.

We also hope that the examples, lessons, and clarifications in this paper can largely remove the concerns and misconceptions regarding reductive catalysis research. The high activity can be achieved through both rational design and extensive screening. The experimental approach is not necessarily “advanced” or “complicated”. At least, most examples shown in this paper do not involve the multiple-step construction of hierarchical nanostructures. Instead, the one-pot and *in-situ* preparation methods (Figs.6 and 7) are ideal for engineering applications. The conceived inhibition by water matrix components is not necessarily true for all catalysts. Even if some are identified as strong fouling species, they can be removed before using the catalyst.

Below are three “fundamental” questions we consider valuable for future research efforts:

- 1) What new functions can the single-metal (beyond Pd) or multi-metal formulations (beyond the reported ones) provide for water pollutant degradation?
- 2) With the existing metal selections, how to further improve the activity through simple design (e.g., using additives) rather than complicated and costly procedures?
- 3) How to improve the robustness and stability of catalysts by tuning the intrinsic properties of catalyst components?

Below are five “applied” questions we consider worth doing for future research efforts:

1) What is the performance of the sufficiently developed catalyst formulation (i.e., no more optimization is necessary) under the most challenging conditions relevant to the real applications?

2) For the final catalyst, how to maintain the activity and minimize the fouling issues through process design?

3) How to apply the powder catalyst in the pilot-scale process?

4) How to capture the leached metals and recycle the catalyst materials?

5) Where to use these catalysts beyond the drinking water treatment contexts? One emerging need is the degradation of oxyanion co-contaminants during the treatment of per- and polyfluoroalkyl substances (PFAS). For example, NO_3^- is a confirmed inhibiting species for UV-sulfite degradation of PFAS (Ren et al., 2021b). ClO_4^- is a common byproduct of the electrochemical degradation of PFAS (Schaefer et al., 2015). A comprehensive treatment of waste streams will need to address the toxic oxyanions and other organic halides. Therefore, reductive catalysis may become a key component of the treatment train system.

3.4 Extended Recommendations

Because the prior goals of this research field are still achieving more active, stable, and realistic catalysts and reactors for engineering application, we also recommend reducing some efforts that may adversely exhaust the researchers' interest, patience, and belief:

1) Avoid excessive morphology control, instrument characterization, and theoretical calculation/simulation during the initial stage of catalyst development. Serious mechanistic studies are undoubtedly imperative for both fundamental understanding of conventional catalyst structures (Cerrillo et al., 2021) and technology advancement of new catalyst structures with novel functions (Choe et al., 2014; Chu et al., 2021; Ren et al., 2021a). However, one could not deny that the core mission of water treatment technology research remains methodology development. How much earlier efforts in the advanced mechanistic investigation have contributed to the improvement of catalyst performance remains a question. Whether those efforts primarily played a decorative role is an open topic for debate. In practice, the aggravating trend of mixing methodology development and mechanistic elucidation in every single work on heterogeneous catalyst development has become a heavy burden for researchers. Many publications seem comprehensive but insufficient in either aspect. Furthermore, the obsession with complicating theoretical explanations has triggered warnings from top-tier journals of both nanotechnology (Nature Nanotechnology Editorial Board, 2022) and physics (Mazin, 2022). For a stark comparison, the field of homogeneous Pd catalysis for organic synthesis prioritizes the rate, yield, condition, and scope of reactions for applications (e.g., pharmaceuticals, organic materials, etc.) without too much burden on mechanistic elucidation. Systematic mechanistic understandings are often achieved on the most promising catalyst families at a later time (Singh et al., 2002; Shekhar et al., 2006; Strieter and Buchwald, 2006; Barder and Buchwald, 2007b,a). Readers can check these references to find how many previous methodology studies supported an adequate mechanistic investigation. We (and many peer researchers) believe that reducing unnecessary effort is the key to efficiently advancing catalyst research.

2) Avoid simply immobilizing known metal species on various "popular" supporting materials, especially when the materials are not commercially available but require laborious steps

to synthesize or have no clear rationale to enhance the catalyst performance. If one has the resource to conduct such experiments, this paper has shown many alternative efforts that can be more rewarding in terms of advancing environmental technology.

3) Avoid conducting “symbolic engineering testings” that only include one “representative” concentration of Cl^- , SO_4^{2-} , and NOM, or running 3–5 quick recycles when the catalyst has not been fully developed for real application. For instance, the result of 20% inhibition by 10 mM Cl^- cannot help evaluate the catalyst when 100 mM or more concentrated Cl^- is present. The premature recycling/reuse demonstration has been disputed by the catalysis community (Scott, 2018), although such a trend still continues for unknown reasons. As such demonstrations have been primarily decorations in most publications, there is no need to keep following them. Because not all catalysts are developed for direct application in real water, any scientific advance made by proof-of-concept is highly valuable for the research community. For catalysts developed for practical application, we have provided an example of systematic engineering evaluations and technical solutions to all the identified challenges (Ren et al., 2022). Such work can be separated from the proof-of-concept studies.

4) Avoid comparing the cost and sustainability while the catalyst has not been adequately developed and optimized. The premature conclusions, especially negative ones, would not hold long after better (or significantly better) catalysts are developed.

4. Conclusions

Toxic oxyanions, organic halides, and other oxidized pollutants remain realistic challenges in various environmental protection scenarios. While reductive catalysis for water pollutant degradation is not a very hot topic at this moment, we have discussed the history, analyzed the current status, summarized examples of advances in the catalyst functionality and preparation method, and pointed out the knowledge gaps, lessons, misunderstandings, and pitfalls of catalyst development research. The facts and reasoning suggest that this research field is far from mature but has great promise for innovation and application. New design rationale, re-allocated research effort, and the necessary escape from the decorative experimental frameworks are three key factors for the continued success of this research direction.

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Notes

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