Photocatalysis is one potential solution to the energy and environmental crisis and greatly relies on the development of the catalysts. Niobium pentoxide (Nb$_2$O$_5$), a typically nontoxic metal oxide, is eco-friendly and exhibits strong oxidation ability, and has attracted considerable attention from researchers. Furthermore, unique Lewis acid sites (LASs) and Brønsted acid sites (BASs) are observed on Nb$_2$O$_5$ prepared by different methods. Herein, the recent advances in the synthesis and application of Nb$_2$O$_5$-based photocatalysts, including the pure Nb$_2$O$_5$, doped Nb$_2$O$_5$, metal species supported on Nb$_2$O$_5$, and other composited Nb$_2$O$_5$ catalysts, are summarized. An overview is provided for the role of size and crystalline phase, unsaturated Nbsites and oxygen vacancies, LASs and BASs, dopants and surface metal species, and heterojunction structure on the Nb$_2$O$_5$-based catalysts in photocatalysis. Finally, the challenges are also presented, which are possibly overcome by integrating the synthetic methodology, developing novel photoelectric characterization techniques, and a profound understanding of the local structure of Nb$_2$O$_5$.

1. Introduction

Abundant fossil resources are utilized to fulfill the growing energy and chemical requirements. However, carbon dioxide generated in these processes is inevitably released into the environment, accompanying global warming, ocean acidification, and a series of ecological problems. Moreover, the expected global energy consumption is up to 22.5 trillion watts (22.5 TW) of power demand in 2030. Notably, electromagnetic radiation power flow from the Sun on the Earth is estimated to be 120 000 TW, which is far beyond the global energy consumption without carbon emission. Learning from photosynthesis in nature, photocatalysis is potentially utilized for scalable and controlled production of fuel and diverse chemicals to alleviate the dependence on fossil fuels and the consequent environmental pollution. Nowadays, diverse semiconductors are synthesized and applied in the photocatalytic process. In principle, the electrons are motivated by the light and then transfer from valence band (VB) to conduction band (CB) in semiconductor photocatalysts, which induce subsequent redox reactions. For instance, metal oxide, metal sulfide, metal nitride, metal phosphide, and nonmetallic material, like carbon nitride, are reported in the areas of photocatalysis, such as pollutant degradation, hydrogen generation, chemical synthesis, etc. In these studies, researchers are devoted to preparing the photocatalysts that are nontoxic, eco-friendly, low-cost, and efficient, to realize reactions under mild conditions with massive desired products.

The niobium pentoxide (Nb$_2$O$_5$), a typically nontoxic solid oxide, exhibits strong redox ability and unique Lewis acid sites (LASs) and Bronsted acid sites (BASs). Previously, Ziolek’s group and Tsang’s group mentioned the photocatalytic performance of different niobium compounds and nanostructured Nb$_2$O$_5$ in 1999 and 2012, respectively. Recently, the amount of publications in Nb$_2$O$_5$ photocatalyst increased rapidly over the past decade, indicating the novel discovery and profound understanding of Nb$_2$O$_5$. Concretely, the applications of Nb$_2$O$_5$ are extended to the photocatalytic conversion of waste plastics, activation of hydrocarbon, photoreduction of CO$_2$, and selective transformation of amines and alcohols. For instance, Nb$_2$O$_5$ exhibited a higher reaction rate and selectivity than those of TiO$_2$ in the selective photooxidation of benzylamine to N-benzylidene benzylamine. Besides, inert polyethylene and waste plastics were completely degraded on Nb$_2$O$_5$ at 25 °C, while the generated CO$_2$ was further reduced to CH$_3$COOH. The selectivity of CO$_2$ to CO, CH$_4$, and other acid products is related to the distribution of LAS and BAS on the Nb$_2$O$_5$ surface. These results suggest the attractive properties of Nb$_2$O$_5$ and its potential in practical applications. However, a few review articles systematically summarize Nb$_2$O$_5$-based photocatalysts to provide the structure–activity relationship for future studies.
mainly located in Brazil, Canada, and Nigeria. Nowadays, niobium oxides are classified into two categories: i) pure Nb$_2$O$_5$ catalysts with diverse morphology, and ii) Nb$_2$O$_5$ catalysts with other species, such as metal species and other components. In the synthetic section, we summarize the method and the role of treatment and additives in the control of morphology and structure. After that, we discuss the optical and catalytic properties of Nb$_2$O$_5$-based photocatalysts (Figure 2). Except for the generation, migration, and recombination of charge carriers, acidic properties and Nb–O–metal interface are also taken into account, which can affect the interaction between substrate molecules and catalyst, the product selectivity, and reaction rate. In the end, we give the summary and outlook of Nb$_2$O$_5$-based photocatalysts.

2. The Nature of Nb$_2$O$_5$

2.1. Resource

The abundance of niobium on earth is 20 ppm.\(^\text{[9a]}\) Niobium does not exist in a pure metallic form but is often found as mixtures with other metals in minerals, which are unevenly distributed around the globe.\(^\text{[10]}\) Abundant columbic mines are mainly located in Brazil, Canada, and Nigeria.\(^\text{[9a]}\) Nowadays, niobium compounds are widely utilized in superconducting, electronic, and catalytic industries, indicating that the recovery of niobium-containing solid waste is potential strategies to produce desired niobium oxide.\(^\text{[11]}\) In the field of catalysis, niobium powders and Nb$_2$O$_5$ obtained from the minerals are the raw material for the production of niobium chloride, niobium oxide, ammonium niobium oxalate, niobium pentaborate, and other organic niobium salts, which can be utilized for further preparation of nanostructured Nb$_2$O$_5$ due to the differences in acidity, alkalinity, and solubility.\(^\text{[4a,8a,12]}\)

2.2. Physicochemical Properties

The Nb$_2$O$_5$ is an n-type semiconductor.\(^\text{[13]}\) The structure of Nb$_2$O$_5$ depends on the preparation conditions.\(^\text{[14]}\) Amorphous Nb$_2$O$_5$ can be transformed into pseudohexagonal phase (TT-Nb$_2$O$_5$), orthorhombic phase (T-Nb$_2$O$_5$), and monoclinic phase (H-Nb$_2$O$_5$) by increasing the temperature.\(^\text{[8a]}\) Unique properties are observed in Nb$_2$O$_5$. Nb$_2$O$_5$ has the bandgap energy ($E_g$) value of 3.0–3.4 eV, which is suitable for redox reaction in photocatalysis.\(^\text{[4a]}\) As shown in Figure 3a, the excited electrons and holes on Nb$_2$O$_5$ migrate to the surface under light irradiation and then interact with the substrate in the reduction process and oxidation process, respectively. Besides, LASs and BASs are observed on tetrahedral NbO$_4$ and octahedral NbO$_6$ units (Figure 3b,c), respectively.\(^\text{[14a,b,15]}\) The Nb$_2$O$_5$ exhibits high acid strength and is utilized in the dehydration reaction, hydrolysis reaction, and hydrodeoxygenation reaction.\(^\text{[8a,16]}\) Meanwhile, these structures can be distorted by decreasing the thickness of Nb$_2$O$_5$ and reduction with the formation of Nb$_2$O$_3$ and NbO.\(^\text{[15,17]}\) In addition, H$_2$O and hydroxyl groups on the Nb$_2$O$_5$ surface can be removed by post-treatment, resulting in the improvement of absorption performance.\(^\text{[18]}\) Except for the unique acidity and redox properties, Nb$_2$O$_5$ is robust in organic acid solutions. This property implies that Nb$_2$O$_5$ can be stable in acidic solutions derived from biomass and other acid products in photocatalysis. However, there are still some limitations of Nb$_2$O$_5$. An unavoidable trade-off is present between the restricted optical absorption and suitable photoredox ability of Nb$_2$O$_5$. In addition, the methods are still necessary for the large-scale production of specific morphology of Nb$_2$O$_5$-based photocatalysts. Thus, an overview is conducive to the systematic understanding and development of Nb$_2$O$_5$-based photocatalysts.

3. Synthesis of Nb$_2$O$_5$-Based Photocatalysts

3.1. Synthesis of Pure Nb$_2$O$_5$ Catalysts

The specific surface area (SSA) of commercial Nb$_2$O$_5$ (orthorhombic phase) is lower than 15 m$^2$ g$^{-1}$.\(^\text{[176]}\) This property leads to the restricted active sites and a high recombination efficiency of charge carriers on Nb$_2$O$_5$.\(^\text{[20]}\) Nowadays, the Nb$_2$O$_5$ catalysts with diverse morphologies are synthesized to solve these problems in photocatalysis.\(^\text{[8a]}\) These catalytic systems can be divided into three classes: 1D, 2D, and 3D Nb$_2$O$_5$ catalysts. Although 0D Nb$_2$O$_5$ quantum dots (QDs) were synthesized by the physical vapor deposition, the application of Nb$_2$O$_5$ QDs in photocatalysis is rarely reported.\(^\text{[21]}\) Therefore, the synthesis and applications of Nb$_2$O$_5$ QDs are not mentioned in this work.

3.1.1. 1D Nb$_2$O$_5$ Catalysts

Recently, diverse methods have been developed for the synthesis of 1D Nb$_2$O$_5$ nanorods, nanowires, and nanotubes. In 2006, the preparation of Nb$_2$O$_5$ nanotubes was reported by the atomic layer deposition (ALD) approach.\(^\text{[22]}\) Amorphous Nb$_2$O$_5$ was deposited first on the porous Al$_2$O$_3$ template with gas pulses of niobium iodide (NbI$_5$) and oxygen.\(^\text{[22]}\) Then, Al$_2$O$_3$ was removed by chromic acid/phosphoric acid solution to produce desired Nb$_2$O$_5$ nanotubes.\(^\text{[22]}\) Because of the costly apparatus and low yield of catalysts in the ALD process, other synthesis methods are necessary. The 1D T-Nb$_2$O$_5$ and TT-Nb$_2$O$_5$ nanotubes were obtained...
Figure 2. An overview of a) Nb$_2$O$_5$-based photocatalysts and b) plausible influence in photocatalysis.

Figure 3. a) The photocatalytic process on Nb$_2$O$_5$, and the local structure of b) H-Nb$_2$O$_5$ and c) T-Nb$_2$O$_5$.\textsuperscript{[8a,19]} a) Adapted with permission.\textsuperscript{[19]} Copyright 2014, Royal Society of Chemistry. b-c) Adapted with permission.\textsuperscript{[8a]} Copyright 1999, American Chemical Society.
from layered niobates. [23] First, layered \( \text{K}_x\text{Nb}_y\text{O}_{17} \) was synthesized from the solid reaction of \( \text{Nb}_2\text{O}_5 \) and \( \text{K}_2\text{CO}_3 \) under the calcination. Then, the scrolled \( \text{H}_x\text{Nb}_y\text{O}_{17} \) was prepared via the exfoliation of \( \text{K}_x\text{Nb}_y\text{O}_{17} \), with the assistance of acid and base. Finally, the \( \text{Nb}_2\text{O}_5 \) nanotubes were obtained from \( \text{H}_x\text{Nb}_y\text{O}_{17} \) by dehydration under 400–450 °C. The heat treatment was a vital process for the transformation of nanosheets to nanotubes. [23] Besides, the Kirkendall effect was applied in the synthesis of \( \text{H}_2\text{Nb}_2\text{O}_6 \) nanorods from nanorods by a two-step hydrothermal synthesis approach. [24] The TT-\( \text{Nb}_2\text{O}_5 \) nanorod arrays grew on niobium foils in the first hydrothermal process. Due to the Kirkendall effect, the outside walls of TT-\( \text{Nb}_2\text{O}_5 \) nanorods exhibited preferential nucleation and growth in the second hydrothermal process, which is accompanied by the migration of inside core composition and the formation of nanotubes. After that, a one-step hydrothermal method was reported. [23] The \( \text{Nb}_2\text{O}_5 \) powders, hydrofluoric acid (HF), hydrogen peroxide, and Ti powders were introduced into the precursor. Hydrofluoric acid acted as an etching reagent to disperse Nb powders in solution. [23,26] In addition, the evolution of nanotubes was significantly affected by the concentration of \( \text{F}^- \) ions. This phenomenon may be due to the fact that \( \text{F}^- \) anions act as a structure-directing agent to control the crystal growth. [23,26] Similarly, \( \text{T-Nb}_2\text{O}_5 \) nanotubes were obtained by the electrochemical method, which consisted of the anodization of Nb with ammonium fluoride. [27] However, toxic reagents (e.g., HF, NH\(_3\)F, or H\(_2\)O\(_2\)) are required in these processes.

Compared to the nanotubes, \( \text{Nb}_2\text{O}_5 \) nanorods can be synthesized directly from Nb probes and foils by a calcination method at \( \approx 1000 \) °C. [28] Besides, the decomposition of niobium isopropoxide was controlled to prepare the \( \text{Nb}_2\text{O}_5 \) nanorods in chemical vapor deposition (CVD) at 950 °C. [12] The synthesis methods of \( \text{Nb}_2\text{O}_5 \) nanorods were reported at lower temperatures in other studies. For instance, TT-\( \text{Nb}_2\text{O}_5 \) nanorods encased in carbon were obtained from the niobium ethoxide by calcination at 800 °C in the 3 mL autoclave under nitrogen. [29] To remove the carbonaceous residues, the as-synthetic material was further treated at 500 °C under air condition, leading to the formation of T-\( \text{Nb}_2\text{O}_5 \) nanorods. [29] Besides, the topochemical method was developed, which is composed of the i) synthesis of specific morphology of niobates, ii) ion-exchange for removal of other metal ions on niobates, and iii) calcination for the phase transformation. [30] Typically, the \( \text{K}_x\text{Nb}_y\text{O}_{17} \) nanowires were prepared by molten salts of \( \text{Nb}_2\text{O}_5 \) and KCl under 800 °C and treated with HNO\(_3\) to produce \( \text{H}_x\text{Nb}_y\text{O}_{17} \) nanorods, which were further calcinated to produce the \( \text{H}_2\text{Nb}_2\text{O}_6 \) nanorods. [30] Similarly, \( \text{CaNb}_2\text{O}_6 \) nanowires were also utilized to prepare the \( \text{H}_2\text{Nb}_2\text{O}_6 \) nanorods, which were further transformed to produce the T-\( \text{Nb}_2\text{O}_5 \) nanorods. [31] Additionally, the solvothermal approach was reported in the catalyst preparation, following the calcination treatment to prepare the \( \text{Nb}_2\text{O}_5 \) nanorods from amorphous \( \text{Nb}_2\text{O}_5 \cdot n\text{H}_2\text{O} \). The additives, like alcohol, played a key role in the hydrothermal process. [32] If alcohols are present in the solution, the \( \text{Nb}_2\text{O}_5 \) particles were observed. According to this phenomenon, TT-\( \text{Nb}_2\text{O}_5 \) nanorods were synthesized by a one-step alcohothermal method, which is contributed to the growth direction of [001] for the 1D structure under enough reaction time, temperature, and concentration of NbCl\(_3\). [32] Likewise, TT-\( \text{Nb}_2\text{O}_5 \) nanorods were obtained by introducing oleic acid and trietylamine, isopropanol, benzyl alcohol (BA), and triethylamine in the hydrothermal process. [32a,33] In addition, corrosive NH\(_4\)F and H\(_2\)O\(_2\), HF, cetyltrimethylammonium bromide, and ionic liquid are also effective additives. [34] Particularly, the rodlike structure was observed when the hydrothermal process was prolonged to 30 days without any additives. [35] Electrospinning was also utilized in the synthesis of \( \text{Nb}_2\text{O}_5 \) nanorods. [36] A mixture of \( \text{Nb(OE)}_3\), polyvinylpyrrolidone (PVP), acetic acid, and ethanol solution was prepared before the electrospinning. The complex of PVP and acetic acid in the solution acted as a template. [36] After electrospinning operation, the obtained material was treated at 550 °C to produce the \( \text{Nb}_2\text{O}_5 \) nanorods under air condition. [36] In these methods, calcination is generally utilized for the removal of carbonaceous impurities or the change in the crystallinity.

For the synthesis of \( \text{Nb}_2\text{O}_5 \) nanowires, a thermal oxidation approach was reported from the linear Nb foils under 900–1000 °C. [37] Similarly, \( \text{Nb}_2\text{O}_5 \) nanowires can be obtained from the topochemical method. T-\( \text{Nb}_2\text{O}_5 \) was synthesized from NaNbO\(_3\) nanowires under 700 °C. [38] \( \text{H-Nb}_2\text{O}_5 \) nanowires were also prepared from \( \text{Nb}_2\text{O}_5(\text{OH}) \) nanorods by calcination at 450 °C. [39] Besides, TT-\( \text{Nb}_2\text{O}_5 \) nanowires can be prepared with the assistance of reflux. [40] The refluxing is a useful approach to synthesize metal oxide nanorods with suitable additives for crystal growth, like trioctylamine, which directly affects the pH, the hydrolysis, and deposition of the precursor. [40] When the precursor solution tends to be acidic, high crystallinity of \( \text{Nb}_2\text{O}_5 \) nanowires is observed after calcination. [40] In addition, electrospinning was also reported in the preparation of T-\( \text{Nb}_2\text{O}_5 \) nanowires. [41] Furthermore, Nb foil was treated with oxygen plasma to induce the growth of \( \text{Nb}_2\text{O}_5 \) nanowires over the Nb foil. [42]

### 3.1.2. 2D \( \text{Nb}_2\text{O}_5 \) Catalysts

\( \text{Nb}_2\text{O}_5 \) nanosheets are typical 2D materials, which are attractive due to their unique structure and electronic properties. Previously, \( \text{Nb}_2\text{O}_5 \) nanosheets could be fabricated directly from the raw \( \text{Nb}_2\text{O}_5 \) and NbCl\(_3\) without any templates or organic polymers. [43] For instance, \( \approx 3–5 \) nm T-\( \text{Nb}_2\text{O}_5 \) nanosheets were produced from commercial \( \text{Nb}_2\text{O}_5 \) particles in a solution containing ethanol and urea under 130 °C for 30 days. [44] Similarly, TT-\( \text{Nb}_2\text{O}_5 \) nanosheets were also synthesized from NbCl\(_3\) in ethylenediamine solution by hydrothermal treatment and calcination. [45] In this process, the alkaline additive may be beneficial for the nanosheet evolution. [46] Especially, Wang’s group reported the synthesis of the \( \text{Nb}_2\text{O}_5 \cdot x\text{H}_2\text{O} \) nanosheets from NbCl\(_3\) by a one-step hydrothermal method and revealed the effect of additives. [47] They speculated that the alkaline NH\(_3\)·H\(_2\)O may play a key role in nanosheet synthesis. To prove the opinion, they replaced the NH\(_4\)H\(_2\)O with other alkaline additives, like the NaOH, \( n\)-butyl amine, and \( t\)-butylammonium hydroxide (TBAOH). [47] Nanosheet-like morphology is only obtained using \( n\)-butyl amine and TBAOH, suggesting the vital role of the NH\(_4\)\(^+\) ions. The ions in the \( \text{Nb}_2\text{O}_5 \) nanosheets, like \( \text{NbO}_3 \)\(^{3−}\), \( \text{NbO}_2 \)\(^{5−}\), and \( \text{NbO}_2 \)\(^{7−}\), exhibit negative charges, which show an electrostatic interaction with NH\(_4\)\(^+\) ions that act as a capping agent. This interaction can restrain the interlamination growth and avoid the formation of bulk \( \text{Nb}_2\text{O}_5 \). [47]

In addition to \( \text{Nb}_2\text{O}_5 \) and NbCl\(_3\), other 2D columbic compounds are also applied in the synthesis of \( \text{Nb}_2\text{O}_5 \) nanosheets by
the topochemical method (Figure 4a). For instance, 2D Nb$_m$X$_n$ (X = Se and S) materials were utilized to prepare the Nb$_2$O$_5$ nanosheets.[48] The Nb$^{4+}$ species in NbSe$_2$ oxidized to Nb$^{5+}$ ions with the formation of Se under calcination, leading to the generation of porous Nb$_2$O$_5$ nanosheet.[48] Besides, the Nb$_2$O$_3$F nanosheets were produced by a hydrothermal approach and further calcinated to prepare the T-Nb$_2$O$_5$ nanosheets.[49] Additionally, other niobates were also reported in the synthesis of Nb$_2$O$_5$ nanosheets.[17c,50] For instance, layered KNb$_3$O$_8$ was prepared by calcination of commercial Nb$_2$O$_5$ and K$_2$CO$_3$.[17c] After that, the layered HNb$_3$O$_8$ was obtained from the KNb$_3$O$_8$ in an acidic solution by ion-exchange.[17c] Ultimately, few-layer HNb$_3$O$_8$ nanosheets were observed by the intercalation of TBAOH.[17c] Similarly, T-Nb$_2$O$_5$ nanosheets were obtained from the layered H$_3$Nb$_6$O$_{17}$·3H$_2$O.[51]

Besides, layered templates are applied in the synthesis of Nb$_2$O$_5$ nanosheets (Figure 4b). The graphene oxide (GO), a typical 2D material, was introduced into the cyclohexane solution, following the addition of Nb(OC$_4$H$_9$)$_5$.[52] After the hydrothermal process, NbO$_x$/GO nanosheets were observed.[52] Subsequently, ≈2–4 nm Nb$_2$O$_5$ nanosheets were obtained by the removal of GO under calcination.[52] Moreover, when the calcination temperature was elevated to 750 °C, holey T-Nb$_2$O$_5$ nanosheets were observed by the utilization of GO.[53] Likewise, silica/graphene nanosheets were utilized to prepare T-Nb$_2$O$_5$ nanosheets by the hydrolysis of NbCl$_5$.[54] The silica in the template was removed by NaOH, maintaining the porous structure of Nb$_2$O$_5$.[54] These preparation methods of Nb$_2$O$_5$ nanosheets can be divided into two classes. One kind of method is to synthesize layered intermediate that contains niobium to prepare nanosheets. Another one is to afford 2D templates that are niobium-free to induce the growth of Nb$_2$O$_5$ nanosheets.

Furthermore, 2D ordered porous Nb$_2$O$_5$ were prepared with the assistance of chain ligand.[55] In 1996, Ying's group put forward a method to synthesize the mesoporous Nb$_2$O$_5$ molecular sieve with the assistance of ligands.[55] In this approach, Nb(OEt)$_5$ and tetradeclamine were utilized to produce ringed Nb$_2$O$_5$ via hydrolysis, which is controlled precisely by the volume of water, hydrolysis temperature, and time.[55] Because of the interaction between the basic amine ligand and Nb$_2$O$_5$, the residual tetradeclamine molecules were further removed by strong acid HNO$_3$/EtOH.[55] After that, block-copolymer/inorganic-salt methodology was developed.[56] The tetradeclamine can be replaced by poly (alkylene oxide) block copolymer, such as P-123.[56] Meanwhile, inorganic niobium salts, NbCl$_5$, were also utilized as a precursor in an ethanol solution.[56] The ordered mesoporous Nb$_2$O$_5$ was obtained by the formation of crown-ether-type complexes between alkylene oxide segments and inorganic ions through weak coordination bonds.[56] Especially, when inorganic Nb salts and aqueous solution were introduced simultaneously into the precursor with controlled hydrolysis, 3D mesoporous Nb$_2$O$_5$ were observed.[57] In addition to the utilization of a single hydrophilic ligand, amphiphilic block copolymers were also developed to fabricate Nb$_2$O$_5$ materials. The poly(ethylene-co-butylene)-b-poly(ethylene oxide) diblock copolymers were mixed with NbCl$_5$ in the ethanol solution, following the calcination to remove the polymers and obtain the 2D mesoporous Nb$_2$O$_5$.[58] The orientation of porous structure can be regulated by the changes in polymer hydrophilicity and hydrophobicity.[59] For instance, the polymers with different chain lengths, like
amphiphilic L64, P85, and P103, were effective in the synthesis of porous Nb2O5.\cite{59}

### 3.1.3. 3D Nb2O5 Catalysts

Generally, the porous structure is beneficial for the diffusion and transmission of substrates.\cite{60} Although the porous Nb2O5, HY-340, is supplied from the CBMM (Brazil, one commercial company), many research groups are still devoted to designing and developing novel synthetic methods of 3D porous Nb2O5 catalysts.

To date, 3D porous Nb2O5 catalysts can be synthesized from the Nb foils, niobium salts, and raw Nb2O5. The Nb foils were irradiated within a constant flux of 100 eV He ions under 500–950 °C to prepare the porous Nb2O5.\cite{61} With the increase of temperature, the pore diameter over Nb2O5 was larger, which can be up to 230 nm.\cite{62} In addition, Nb(OH)5 was obtained by the anodization of Nb foil in ethylene glycol containing 4 vol% HF and 2 vol% H2O2. Then, mesoporous Nb2O5 was obtained by the calcination of Nb(OH)5.\cite{63} In the anodization process, the porous structure was controlled by the changes in voltage, electrolyte temperature, time, and solution.\cite{64,65} Particularly, a careful cleaning process is necessary to remove the impurity on the surface of Nb foils before anodization.\cite{66} Besides, the sol–gel approach was also reported. Nb(OC2H5)5 was hydrolyzed with the assistance of the NH3·H2O solution and calcined at 300 and 650 °C to TT-Nb2O5 and T-Nb2O5, respectively.\cite{67} Similarly, wormhole-like amorphous Nb2O5, and hierarchically porous Nb2O5 were prepared from the hydrolysis of Nb salts (NbCl5 and Nb(OC2H5)5) by the addition of P-123 and surfactant (Brij 56), respectively.\cite{68,69} Other uniform templates, like polystyrene spheres and zeolites, were also utilized to prepare the porous Nb2O5. For instance, polystyrene spheres were introduced into the Nb–citric complex solution via the reaction of Nb2O5 with HF, NH3·H2O, and citric acid.\cite{70} The template was subsequently removed by the calcination with the formation of macroporous Nb2O5.\cite{71} The macropores size of Nb2O5 was greatly dependent on the diameter of the polystyrene spheres. Similarly, the ammonium niobate oxalate was deposited on the FDU-1, one type of zeolite, by an impregnation method.\cite{72} Then, the FDU-1 is removed by a diluted NaOH solution. Furthermore, T-Nb2O5 and TT-Nb2O5 were obtained with the assistance of other porous carbon materials, such as cotton.\cite{73} In these methods, the evolution of ordered porous structure mainly depended on the hydrolysis of niobium salt and the uniformity of templates.\cite{74}

Porous Nb2O5 constituted by stacked particles was also reported.\cite{75} For instance, T-Nb2O5 can be prepared by direct calcination of Nb powders.\cite{76} In addition, the hydrolysis of organic Nb salts was also applied in the synthesis of nanoparticules. Especially, Nb(OBu)5 was dissolved in toluene with different amounts of water in an autoclave under 300 °C for 2 h.\cite{77} When the amount of water was up to 30 cm3, amorphous Nb2O5 were transformed to TT-phase and grew from ≈5 to 30–60 nm, indicating that water was beneficial for the dissolution-recrystallization process on the growth of Nb–O–Nb structure.\cite{78} Instead of toluene, ethanol, triethylamine, and H2O solution were also applied in the synthesis of Nb2O5 particles.\cite{79} Besides, the NbCl5 and Nb-fluoro complex were used in the synthesis of H-Nb2O5 and TT-Nb2O5 particles, respectively.\cite{80} In the hydrolysis process, structure-directing agents were introduced, such as the lauryl amine hydrochloride and F127.\cite{81} The smaller particles of Nb2O5 were observed with the increase of pH.\cite{82} Furthermore, other methods were developed for the synthesis of Nb2O5 particles. For instance, the supercritical-CO2-assisted approach was introduced into catalyst preparation.\cite{83} The hydrolyzed mixture of NbCl5 dissolved in ethanol solution and aged in the supercritical CO2 under 80 °C for 3 h. After the calcination under 200 °C, amorphous Nb2O5 particles with a high surface area (≈340 m2 g−1) were obtained.\cite{84} In addition, the ball-milling process was reported for the low-temperature synthesis. Mixed Nb2O5 and Na2CO3 were formed by the reaction of NbCl5 and Na2CO3.\cite{85} The molar ratio of NbCl5 to Na2CO3 and calcination temperature were controlled to inhibit the generation of unwanted niobiates.\cite{86} The additives, such as urea and melamine, acted as the fuel and template to fabricate TT-Nb2O5 particles in the calcination process.\cite{87,88} Furthermore, the as-synthesized H-Nb2O5 particles can be treated under laser pulses to prepare amorphous Nb2O5, T-Nb2O5, and TT-Nb2O5, realizing the reversible transformation of crystal structures.\cite{89}

Other morphologies of Nb2O5 catalysts were also reported, such as the bulk, octahedron, hollow structure, and others.\cite{90} The synthetic methods of these morphologies were partly similar to that of Nb2O5 particles under different conditions. For instance, the Nb2O5 particles can be further calcinated to prepare the bulk counterpart.\cite{91} Besides, the resorcinol, formaldehyde, and ammonium niobate oxide were utilized in the hydrothermal process for the synthesis of Nb2O5@polymer materials, which were further calcinated to remove the polymer and obtain the hollow Nb2O5 microspheres.\cite{92}

### 3.2. Synthesis of Nb2O5 Catalysts with Other Species

#### 3.2.1. Doped Nb2O5 Catalysts

Because of the wide bandgap of Nb2O5 (≈3.0-3.4 eV), the strategies by introducing doped atoms are applied to enhance the optical absorption ability, which was confirmed by experiments and first-principles calculations.\cite{93} The synthetic methodologies can be classified into two approaches: a) synthesis from the mixture of additives and columbic precursors, and b) post-treatment of as-synthesized Nb2O5 catalysts.\cite{94} For instance, ethanol and acetic acid acted as the carbon sources and the solvent to prepare the carbon-doped Nb2O5 (C–Nb2O5) in the solvothermal process (Figure 5, path I).\cite{95} Similarly, the niobium ethoxide and NbCl5 were dispersed in a mixed solution of alcohol and nitrogenous additives in the solvothermal process, leading to the formation of nitrogen-doped Nb2O5 (N–Nb2O5).\cite{96,97} Besides, N–Nb2O5 can be obtained from the calcination of niobium salts with urea, melamine, and ammonium chloride.\cite{98,99} A series of rare-earth (Er, Eu, Pr, Tm, and Yb), Ag, Fe, Mo, Pd, Sr, W, Y, Zn, and Zr doped Nb2O5 materials were also synthesized from the calcination of the niobium oxides with other metal additives.\cite{100} Additionally, the alkali metal doped Nb2O5 materials were also fabricated by the electrochemical approach. The Nb foils were oxidized at a pulsed current while the alkali metal ions in the
electrolytes were feasible to interact with NbO₅, resulting in the generation of M–Nb₂O₅ (M = Li, Na, K, Rb, and Cs). [86]

Moreover, as-synthesized Nb₂O₅ can be further treated (Figure 5, path II). Mesoporous Nb₂O₅ and citric acid were utilized to synthesize the C–Nb₂O₅ under the calcination at 400 °C. [73] The Nb₂O₅ was treated with NH₃ gas to prepare N–Nb₂O₅ under 400–600 °C. [87] In addition, the N–Nb₂O₅ was also synthesized from the calcination of porous Nb₂O₅ with urea. [19, 50f, 88] If urea is replaced by thiourea, the generation of sulfur-doped Nb₂O₅ (S–Nb₂O₅) can be observed. [73] Furthermore, N, S codoped Nb₂O₅ was obtained when the ratio of thiourea to Nb₂O₅ increased from 0.37 to 1. [89] Other metal atoms, like Mo atoms, can be introduced into the Nb₂O₅ lattices, which were synthesized from the hydrothermal process of ultrathin Nb₂O₅ nanosheets and ammonium molybdate. [90]

3.2.2. Metal Species Supported on Nb₂O₅ (M/Nb₂O₅) Catalysts

Diverse metals, metal oxides, and metal salts are utilized in the synthesis of M/Nb₂O₅. For instance, Pt and Ag₂O powders were mixed with Nb₂O₅ to prepare the Pt/Nb₂O₅ and Ag/Nb₂O₅, respectively. [91] Accompanied by the development in nanotechnology, the size of metal particles was precisely controlled by the colloidal method, which can be further applied in the synthesis of M/Nb₂O₅. [48, 92] For instance, ≈7.0 nm Pd nanoparticles were protected by the ligand, oleylamine, or oleic acid and introduced into the Nb₂O₅ suspension with the assistance of hexanes. The ligands on the Pd species can be further removed by calcination. [92a]

Metal salts were applied in the synthesis of M/Nb₂O₅ by the wet chemistry methods. [93] The Au/Nb₂O₅, Ir/Nb₂O₅, Rh/Nb₂O₅, Ru/Nb₂O₅, Pd/Nb₂O₅, and Pt/Nb₂O₅ were synthesized by the incipient wetness impregnation method. [93] The heteroatoms in the precursor, such as nitrogen and chlorine atoms, are reasonably removed by the calcination process. [93a] Whereas, the aggregation of metal species to nanoparticles was observed, ascribed to the heat treatment. The deposition–precipitation method was also developed to produce M/Nb₂O₅, following the calcination under lower temperature (≈300 °C). [94] In the preparation of catalysts, Au⁺ ions were deposited on the Nb₂O₅ surface with the assistance of urea or ammonium hydroxide. The average diameter of Au nanoparticles was ≈5 nm after calcination. [96] The H₂ can be replaced by NaBH₄ or hydrazine, which is an effective reductant for RuCl₃ and Pd(acac)₂ to Ru/Nb₂O₅ and Pd/Nb₂O₅ without heat treatment. [94] Instead of NaBH₄ and hydrazine, the reductive electrons can be directly generated from Nb₂O₅ under UV light irradiation. [4a] The Au/Nb₂O₅, Pt/Nb₂O₅, and Pd/Nb₂O₅ were fabricated by this approach. [95] Meanwhile, the photogenerated holes were captured by sacrificial agents, such as ethanol or isopropanol. [95] Besides, the electrostatic adsorption was available to prepare the highly dispersed metal nanoparticles supported on Nb₂O₅, under room temperature, attributed to the difference in point of zero charges (PZCs) between the metal ions and Nb₂O₅ at the same pH. Thus, Ag/Nb₂O₅ can be synthesized via the interaction between the Ag(NH₃)₂⁺ and Nb₂O₅ at high pH (>5). [96]

3.2.3. Composited Nb₂O₅ Catalysts

The Nb₂O₅ can be modified by other metal oxides, metal sulfides, metal carbides, carbon materials, carbon nitride (g-C₃N₄), and black phosphorus (BP) to enhance its activity. [13, 97] As-prepared Nb₂O₅, NbC₂, NbO.F, and niobium salts were reported in the synthesis of composited Nb₂O₅ catalysts (Figure 6).

Different Nb salts were reported in the synthesis of composited Nb₂O₅ photocatalysts (Figure 6, path I). [98] The methods mentioned in the preparation of pure phase Nb₂O₅ were also applied in the composited Nb₂O₅ photocatalysts. For instance, the CVD method was utilized to fabricate Nb₂O₅/SiO₂. [98] Besides, Nb precursors, like NbCl₅, and other metal salts were cohydrolyzed and precipitated to prepare mixed metal oxide particles. [99] Especially, ≈25–51 nm Nb₂O₅ nanocrystals were observed on the surface of ZnO nanorods, while ≈3–5 nm Nb₂O₅ microspheres were fabricated on the g-C₃N₄. [99e, g] This phenomenon can be ascribed to P123, which were conducive to the stabilization and dispersion of Nb micelles in the synthesis of Nb₂O₅/g-C₃N₄. [99e]

In addition, as-prepared Nb₂O₅ can be ground directly with TiO₂, SrNb₂O₆, Bi₂O₃, and GO to prepare the TiO₂/Nb₂O₅, SrNb₂O₆/Nb₂O₅, and GO/Bi₂O₃/Nb₂O₅, respectively. [100] Further calcination was conducted to improve the interaction between the Nb₂O₅ and other components (Figure 6, path II). [101] Besides, as-prepared Nb₂O₅ was also dispersed in solutions, such as isopropanol or tetrahydrofuran, to enhance the contact with
the TiO₂, BP, and C₆₀.[97c,102] In addition, the metal salt precursors were introduced into Nb₂O₅ suspension instead of as-synthesized metal oxide or metal sulfide.[103] The ZnO/Nb₂O₅ and CdS/Nb₂O₅ were prepared from Zn(NO₃)₂ and CdCl₂ by the impregnation approach, respectively.[104] The metal precursors, like TiCl₄, were hydrolyzed by the addition of NH₃·H₂O and deposited on the Nb₂O₅ to obtain the TiO₂/Nb₂O₅.[104a] Besides, CdS/Nb₂O₅/N-GO was obtained from Nb₂O₅ by the deposition of CdS in the hydrothermal process. Especially, electrostatic adsorption was also reported to fabricate composite Nb₂O₅ catalysts.[111,105] In principle, the PZC can be utilized to screen materials that exhibit positive or negative surface charges, which are opposite to that on the Nb₂O₅ surface at the same pH value. Fortunately, SiO₂ and g-C₃N₄ as the potential candidates were reported.[111,106] Positive charges originated from amino groups that were exposed on the g-C₃N₄ surface in a pH range of 3–4. Meanwhile, the Nb₂O₅ surface is electronegative, ascribed to the presence of surface hydroxyl groups.[112] Compared to the impregnation approach, this method is available to prepare highly dispersed components on Nb₂O₅, due to the adsorption equilibrium. Excess g-C₃N₄ are possibly removed by washing and filtration, which differ from the drying treatment in the impregnation approach.[113] Furthermore, isolated species on Nb₂O₅ may be obtained by this method with precise control of precursor concentration, pH, and temperature.

Additionally, as-synthesized NbC₂ and NbO₂F were also utilized to prepare corresponding Nb₂O₅-based catalysts (Figure 6, path III). The Nb₂O₅/C/NbC and Nb₂O₅/F/Nb₂O₅ photocatalysts were obtained by one-step calcination.[97d,106] The formation of Nb₂O₅/F/Nb₂O₅ was ascribed to the decomposition of Nb₂O₅/F to Nb₂O₅ when the temperature is higher than 400 °C.[106] Similarly, the observed Nb₂O₅ supported on NbC was due to the reaction between NbC and CO₂ under 850 °C.[97d] Considering the thermal reaction, a series of composite photocatalysts with different Nb₂O₅ fractions are feasibly prepared, using the NbC, NbN, NbSe₂, NbS₂, and NbO₂F.[107]

4. Application of Nb₂O₅-Based Photocatalysts

4.1. Photodegradation of Pollutants

Nowadays, Nb₂O₅-based photocatalysts were widely reported in the photocatalytic photodegradation of pollutants (Table 1).[108] The hydrocarbons and chlorinated hydrocarbons (Table 1, Nos. 1–5), phenols (Table 1, Nos. 6–16), aldehydes (Table 1, No. 17), organic acids (Table 1, Nos. 18–26), ester (Table 1, No. 27), organic dyes, and pesticides (Table 1, No. 28–145) are oxidized on Nb₂O₅-based photocatalysts.[77,99e,109b,111] In these processes, the ultraviolet filter can be utilized to eliminate the effect of UV light. Especially, the degradation of RhB was driven under visible light over pure Nb₂O₅ without the limitation of its bandgap energy (Table 1, No. 101). This process is ascribed to the dye-sensitized photocatalysis, in which the RhB molecules adsorbed on the Nb₂O₅ surface are excited by 440 nm light irradiation.[109e,112] The electrons transfer from the highest occupied molecular orbital (HOMO) to lowest unoccupied molecular orbital (LUMO) of RhB molecules and inject into the Nb₂O₅ conduction band, which induce the generation of active species for the succedent mineralization of the organic pollutant.[112]

Furthermore, the photodegradation of textile wastewater, palm oil mill effluent, petrol station wastewater, and vinasse was also reported (Table 1, Nos. 146–155).[113] These results suggested the potential of Nb₂O₅-based photocatalysts in practical applications. In these processes, the efficiency of catalysts is important in photocatalytic performance.[50] Generally, the degradation rate is a common criterion for the comparison of activity (Table 1). However, the degradation rate is related to the ratio of the moles of organic pollutants to the mass of catalyst, temperature, and intensity of the light source. For instance, a change of reaction temperature is beneficial to the separation of photogenerated electrons and holes.[114] Increasing the intensity of the light source can improve the number of incident photons to enhance the reaction rate.[115] Thus, it is a complicated and difficult process for the comparison of the activity results. The utilization of photogenerated electrons and holes over Nb₂O₅-based photocatalysts can be used as another one criterion for the comparison of their activity. The organic pollutants can be degraded by the superoxide anions (•O₂⁻), hydroxyl radicals (•OH), and photogenerated holes (h⁺), corresponding to the path A, path B, and path D in Figure 7.[11,116] Therefore, the efficiency of electrons can be calculated by the ratio of products to the pollutants. However, the qualitative and quantitative analysis of obtained products is not always mentioned in the literature, leading to challenges in the...
Table 1. Recent advances in the photodegradation of pollutants over Nb₂O₅-based photocatalysts.

| No. | Catalysts                  | Pollutants                          | Light sources                              | Reaction temperature [°C] | Degradation rate | Refs. |
|-----|----------------------------|-------------------------------------|--------------------------------------------|---------------------------|------------------|-------|
| 1   | N-TiO₂–Nb₂O₅              | Benzene, toluene, and xylene        | 46 W black lamp                           | 25                        | 10 min⁻¹         | [108] |
| 2   | N–Nb₂O₅                   | Toluene                             | Xe lamp                                   | n.m.                      | ≈10% (60 min)    | [110a]|
| 3   | Pt/Nb₂O₅                  | Ethylene                            | Xe lamp                                   | n.m.                      | 0.94 min⁻¹       | [95b] |
| 4   | T-Nb₂O₅ nanotubes         | Trichloro-ethylene                  | UV light                                  | n.m.                      | 100% (15 min)    | [23c] |
| 5   | Nb₂O₅/TiO₂                | 1,4-dichlorobenzene                 | 150 W Xe lamp                             | n.m.                      | ≈60% (10 min)    | [118] |
| 6   | TT-Nb₂O₅ particles        | 2-chlorophenol                       | 400 W halide lamp (350–700 nm)            | 30                        | 0.13 h⁻¹         | [77]  |
| 7   | Nb₂O₅ nanorods/graphene   | 4-chlorophenol                       | 300 W Xe lamp (420–780 nm)                | n.m.                      | ≈95% (210 min)   | [119] |
| 8   | Carbon xerogel/Nb₂O₅/TiO₂ | 4-chlorophenol                       | 300 W lamp                                | 25                        | 0.0078 min⁻¹     | [120] |
| 9   | WO₃/Nb₂O₅                 | 4-nitrophenol                       | 125 W Hg lamp                             | 27                        | 4.6 s⁻¹          | [121] |
| 10  | CeO₂/Nb₂O₅                | Phenol                              | UV light                                  | n.m.                      | 90% (150 min)    | [122] |
| 11  | Nb₂O₅                     | Phenol                              | UV light                                  | n.m.                      | 14% (15 min)     | [123] |
| 12  | Nb₂O₅–Pr₆O₁₁              | Phenol                              | 6 W Hg lamp                               | n.m.                      | 2.5 × 10⁻⁴ m s⁻¹| [124] |
| 13  | Nb₂O₅–ZnS                 | Phenol                              | 8 W Hg lamp                               | n.m.                      | 58% (15 min)     | [125] |
| 14  | Nb₂O₅/ZnO rods            | Phenol                              | Sunlight                                  | n.m.                      | 100% (40 min)    | [96c] |
| 15  | Nb₂O₅/ZnO                 | Phenol                              | 15 W Hg lamp                              | n.m.                      | 100% (60 min)    | [110b]|
| 16  | Sr–Nb₂O₅                  | 2-chlorophenol                       | 400 W halide lamp (350–700 nm)            | 30                        | 0.58 h⁻¹         | [77]  |
| 17  | Nb₂O₅–TiO₂                | Acetaldehyde                        | Xe lamp (350–700 nm)                      | r.t.                      | 0.0139 min⁻¹     | [126] |
| 18  | Amorphous Nb₂O₅ particles | Acetic acid                          | 400 W Hg lamp (λ > 300 nm)                | 25                        | 53 μmol h⁻¹ g⁻¹ | [70]  |
| 19  | Pt–TiO₂–Nb₂O₅             | Ketoprofen                           | UV LEDs                                  | n.m.                      | 0.174 min⁻¹      | [110a]|
| 20  | Nb₂O₅                     | Caffeic acid                         | White LED                                 | 25                        | 55% (180 min)    | [127] |
| 21  | Pt–TiO₂–Nb₂O₅             | Diclofenac                           | UV LEDs                                  | n.m.                      | 0.446 min⁻¹      | [102a]|
| 22  | Nb₂O₅                     | Oxalic acid                         | 300 W Xe lamp                             | 25                        | 40% (240 min)    | [128] |
| 23  | Mesoporous Nb₂O₅          | Terephthalic acid                    | 400 W Hg lamp                             | 25                        | 100% (60 min)    | [129] |
| 24  | Nb₂O₅/C₃N₄                 | Tetracycline hydrochloride           | 250 W Xe lamp (λ > 420 nm)                | 25                        | 76% (150 min)    | [116] |
| 25  | g-C₃N₄–mesoporous Nb₂O₅  | Tetracycline hydrochloride           | 300 W Xe lamp (λ > 420 nm)                | n.m.                      | 76% (60 min)     | [99c] |
| 26  | Zn–Nb₂O₅                  | Caffeic acid                         | 15 W UV light                             | r.t.                      | 80% (180 min)    | [85a] |
| 27  | Fe₂O₃/Nb₂O₅               | Ethyl 4-hydroxy-benzoate            | 300 W Xe lamp (λ > 400 nm)                | n.m.                      | ≈55% (12 h)      | [130] |
| 28  | NO–Nb₂O₅                  | Indigo carmine                       | 20 W UV light                             | n.m.                      | ≈90% (90 min)    | [131] |
| 29  | Zr–Nb₂O₅                  | Indigo carmine                       | 400 W halide lamp (350–700 nm)            | 30                        | 0.52 h⁻¹         | [77]  |
| 30  | Nb₂O₅                     | Indigo carmine                       | 125 W Hg lamp                             | 30                        | 0.29 h⁻¹         | [77]  |
| 31  | TT-Nb₂O₅ particles        | Indigo carmine                       | 400 W halide lamp (350–700 nm)            | 30                        | 0.29 h⁻¹         | [77]  |
| 32  | TiO₂/Nb₂O₅ particles      | Indigo carmine                       | 36 W UV lamp (200–400 nm)                 | n.m.                      | ≈87% (120 min)   | [104a]|
| 33  | Nb₂O₅/cellulose acetate   | Indigo carmine                       | 125 W Hg lamp                             | n.m.                      | ≈99% (120 min)   | [132] |
| 34  | Nb₂O₅ hollow spheres      | Indigo carmine                       | 100 W Hg lamp                             | n.m.                      | ≈90% (80 min)    | [109a]|
| 35  | g-C₃N₄/Nb₂O₅              | Malachite green                      | 150 W white LED light                     | n.m.                      | 100% (90 min)    | [109c]|
| 36  | Amorphous Nb₂O₅ particles | Malachite green                      | 400 W Hg lamp                             | 25                        | 0.014 min⁻¹      | [85a] |
| 37  | Ag/TiO₂/Nb₂O₅             | Malachite green                      | Visible light                             | 25                        | 100% (20 min)    | [929] |
| 38  | TT-Nb₂O₅ particles        | Orange G                             | 400 W halide lamp (350–700 nm)            | 30                        | 0.13 h⁻¹         | [77]  |
| 39  | Sr–Nb₂O₅                  | Orange G                             | 400 W halide lamp (350–700 nm)            | 30                        | 0.20 h⁻¹         | [77]  |
| 40  | TT-Nb₂O₅ particles        | MB[^1]                               | 400 W halide lamp (350–700 nm)            | 30                        | 0.19 h⁻¹         | [77]  |
| 41  | Sr–Nb₂O₅                  | MB                                   | 400 W halide lamp (350–700 nm)            | 30                        | 0.60 h⁻¹         | [77]  |
| 42  | Nb₂O₅                     | MB                                   | 100 W Hg lamp                             | 25                        | ≈90% (120 min)   | [109a]|
| 43  | TT-Nb₂O₅ nanoparticles    | MB                                   | UV light                                  | r.t.                      | 0.0733 min⁻¹     | [15a] |
| 44  | TT-Nb₂O₅ nanorods         | MB                                   | 500 W Hg lamp                             | r.t.                      | ≈93% (150 h)     | [14c] |
| 45  | Mesoporous Nb₂O₅          | MB                                   | 250 W Xe lamp                             | 30                        | 0.014 min⁻¹      | [134] |
| 46  | TT-Nb₂O₅ spheres          | MB                                   | 500 W Hg lamp                             | r.t.                      | ≈73% (150 h)     | [14c] |
| 47  | TT-Nb₂O₅ fibers           | MB                                   | 500 W Hg lamp                             | n.m.                      | 96% (50 min)     | [68]  |
| 48  | H-Nb₂O₅ particles         | MB                                   | 15 W UV light                             | 30                        | 0.198 h⁻¹        | [135] |

(Continued)
| No. | Catalysts                  | Pollutants | Light sources | Reaction temperature [°C] | Degradation rate | Refs. |
|-----|---------------------------|------------|---------------|---------------------------|------------------|-------|
| 49  | T-Nb$_2$O$_5$ particles   | MB         | UV lamp       | r.t.                      | 60% (60 min)     | [74]  |
| 50  | Mixed phase Nb$_2$O$_5$ particles | MB         | UV lamp       | n.m.                      | 95% (120 min)    | [136] |
| 51  | Nb$_2$O$_5$ nanofibers    | MB         | 300 W Xe lamp | n.m.                      | 45% (120 min)    | [137] |
| 52  | Nb$_2$O$_5$ fibers        | MB         | 100 W Hg lamp | n.m.                      | 0.025 min$^{-1}$ | [138] |
| 53  | Nb$_2$O$_5$               | MB         | 300 W Hg lamp | r.t.                      | 70% (480 min)    | [139] |
| 54  | Nb$_2$O$_5$ nanoparticles | MB         | 150 W Hg lamp | 25                        | 90% (150 min)    | [140] |
| 55  | Nb$_2$O$_5$               | MB         | 450 W solar simulator | n.m.                      | 90% (20 min)     | [141] |
| 56  | Nb$_2$O$_5$               | MB         | 24 W lamps    | 25                        | 40% (80 min)     | [142] |
| 57  | Nb$_2$O$_5$               | MB         | UV light      | n.m.                      | 40% (300 min)    | [143] |
| 58  | N–Nb$_2$O$_5$             | MB         | 500 W Xe lamp | 25                        | 40% (240 min)    | [87]  |
| 59  | Mo–Nb$_2$O$_5$/W–Nb$_2$O$_5$ | MB         | UV light      | 25                        | n.m.             | [83]  |
| 60  | Pd-xerogel/Nb$_2$O$_5$    | MB         | Visible light | r.t.                      | 30% (300 min)    | [85]  |
| 61  | Nb$_2$O$_5$/TiO$_2$       | MB         | 400 W Xe lamp | n.m.                      | 0.072 min$^{-1}$ | [101] |
| 62  | Nb$_2$O$_5$–TiO$_2$       | MB         | UV light      | r.t.                      | 100% (240 min)   | [99]  |
| 63  | Nb$_2$O$_5$/TiO$_2$       | MB         | 15 W fluorescent lamps (390–720 nm) | n.m.                      | 84% (150 min)    | [111] |
| 64  | Nb$_2$O$_5$/NaX zeolite   | MB         | 80 W Xe lamp  | 25                        | 60% (300 min)    | [144] |
| 65  | Nb$_2$O$_5$/MCM-41        | MB         | 15 W UV lamp  | n.m.                      | 60% (60 min)     | [145] |
| 66  | Nb$_2$O$_5$/(NaX)F         | MB         | Xe lamp (380–780 nm) | r.t.                      | 100% (80 min)    | [106] |
| 67  | α-Fe$_2$O$_3$/Nb$_2$O$_5$ | MB         | 300 W simulated solar irradiation | n.m.                      | 80% (120 min)    | [111] |
| 68  | CdS@Nb$_2$O$_5$           | MB         | 125 W Hg lamp | n.m.                      | 80% (180 min)    | [97]  |
| 69  | Carbon xerogel–Nb$_2$O$_5$ | MB         | Visible light | r.t.                      | 30% (300 min)    | [146] |
| 70  | Carbon xerogel–Nb$_2$O$_5$ | MB         | Visible light | 25                        | 60% (300 min)    | [147] |
| 71  | Nb$_2$O$_5$/tannin-formaldehyde xerogel | MB         | 300 W UV lamp (200–280 nm) | 25                      | 100% (90 min)    | [148] |
| 72  | Carbon xerogel–Nb$_2$O$_5$ | MB         | 300 W simulated solar | r.t.                      | 80% (300 min)    | [149] |
| 73  | CeO$_2$/Nb$_2$O$_5$       | MB         | UV light      | n.m.                      | 98% (150 min)    | [122] |
| 74  | g-C$_3$N$_4$/Nb$_2$O$_5$  | MB         | UV light      | 18                        | 90% (210 min)    | [99]  |
| 75  | TT-Nb$_2$O$_5$ spheres    | MB         | Xe lamp ($\lambda > 380$ nm) | r.t.                      | 90% (90 min)     | [216] |
| 76  | Nb$_2$O$_5$–graphene      | MB         | UV light      | n.m.                      | 99% (5 min)      | [150] |
| 77  | T-Nb$_2$O$_5$ nanowires   | MB         | 100 W mercury lamp | r.t.                      | 95% (150 min)    | [157] |
| 78  | Nb$_2$O$_5$–C$_6$O$_6$    | MB         | UV lamp       | n.m.                      | 97% (5 min)      | [106] |
| 79  | Ag/Nb$_2$O$_5$            | MB         | 500 W mercury lamp | n.m.                      | 0.0108 min$^{-1}$ | [151] |
| 80  | TiO$_2$/Nb$_2$O$_5$/r-GO  | MB         | 300 W Xe lamp | 24–28                     | 97% (240 min)    | [152] |
| 81  | MnO$_2$/Nb$_2$O$_5$/carbon clusters | MB         | Visible light ($\lambda > 460$ nm) | n.m.                      | n.m.             | [153] |
| 82  | N–TiO$_2$–Nb$_2$O$_5$     | MB         | 13 W fluorescent lamp | n.m.                      | 66% (180 min)    | [154] |
| 83  | Nb$_2$O$_5$ nanowires     | MB         | UV light      | r.t.                      | 92% (120 min)    | [155] |
| 84  | Nb$_2$O$_5$ nanophosphates | MB         | 100 W Hg lamp | r.t.                      | $\approx$92% (60 min) | [158] |
| 85  | Ag/TiO$_2$/Nb$_2$O$_5$    | MB         | Visible light | 25                        | 12% (120 min)    | [92]  |
| 86  | r-GO/SnO$_2$/Nb$_2$O$_5$/TiO$_2$ | MO         | 300 W Xe lamp ($\lambda > 400$ nm) | 30–35                   | 95% (120 min)    | [109] |
| 87  | TiO$_2$/Nb$_2$O$_5$/r-GO  | MO         | 300 W Xe lamp | 30–35                     | 93% (240 min)    | [152] |
| 88  | T-Nb$_2$O$_5$ nanowires   | MO         | 100 W Hg lamp | r.t.                      | 70% (150 min)    | [157] |
| 89  | Nb$_2$O$_5$ nanofibers    | MO         | 300 W Hg lamp | r.t.                      | 62% (180 min)    | [157] |
| 90  | Nb$_2$O$_5$               | MO         | 400 W Hg lamp | r.t.                      | 78% (80 min)     | [158] |
| 91  | Nb$_2$O$_5$               | MO         | Sunlight      | 25                        | 95% (60 min)     | [159] |
| 92  | Ag/PdO$_2$/Nb$_2$O$_5$    | MO         | 600 W Xe lamp | n.m.                      | 100% (25 min)    | [160] |
| 93  | Nb$_2$O$_5$@G nanofibers  | MO         | 400 W metal-halide lamp ($\lambda > 380$ nm) | n.m.                      | 0.547 h$^{-1}$  | [161] |
| 94  | Nb$_2$O$_5$/SrNb$_2$O$_6$ | MO         | 300 W Hg lamp | n.m.                      | 95% (40 min)     | [160] |
| 95  | Nb$_2$O$_5$/SrNb$_2$O$_6$ | MO         | 500 W Hg lamp | n.m.                      | $\approx$95% (28 min) | [162] |
| 96  | T-Nb$_2$O$_5$ particles   | MB         | UV light      | 25                        | 61% (120 min)    | [163] |

(Continued)
| No. | Catalysts                  | Pollutants | Light sources            | Reaction temperature [°C] | Degradation rate       | Refs. |
|-----|---------------------------|------------|--------------------------|---------------------------|------------------------|-------|
| 97  | TT-Nb2O5 particles        | RhB        | UV light                 | 18                        | 0.00 757 min⁻¹         | [164] |
| 98  | TT-Nb2O5 particles        | RhB        | UV light                 | n.m.                      | 100% (60 min)          | [165] |
| 99  | Amorphous Nb2O3 particles | RhB        | 5 W white LED light      | n.m.                      | 96% (70 min)           | [166] |
| 100 | Flowerlike T-Nb2O5        | RhB        | 300 W Xe lamp (λ > 420 nm) | n.m.                      | 0.2099 min⁻¹           | [112] |
| 101 | Nb2O5 spheres             | RhB        | UV light                 | 25                        | 78% (120 min)          | [167] |
| 102 | Nb2O5 microflowers        | RhB        | 50 W Hg lamp             | n.m.                      | 0.238 min⁻¹            | [168] |
| 103 | Nb2O5                     | RhB        | 8 W Hg lamp              | r.t.                      | 0.0669 min⁻¹           | [170] |
| 104 | Nb2O5 nanoparticles       | RhB        | 100 W Hg lamp            | r.t.                      | ≥98% (60 min)          | [156] |
| 105 | C-modified Nb2O3          | RhB        | 500 W tungsten halogen lamp | n.m.                      | 100% (180 min)         | [171] |
| 106 | C-Nb2O3                   | RhB        | Xe lamp                  | n.m.                      | 100% (30 min)          | [82a] |
| 107 | N–Nb2O3                   | RhB        | 300 W Xe lamp (λ > 400 nm) | n.m.                      | 100% (15 min)          | [88]  |
| 108 | C, N-modified Nb2O5       | RhB        | 300 W Xe lamp (λ > 420 nm) | 15                        | 100% (40 min)          | [172] |
| 109 | C, N-modified Nb2O5       | RhB        | 300 W Xe lamp (420–720 nm) | n.m.                      | 0.13 572 min⁻¹         | [173] |
| 110 | N, S–Nb2O5                | RhB        | UV light                 | n.m.                      | 92% (180 min)          | [89]  |
| 111 | N–HNb2O4                  | RhB        | 300 W Xe lamp (λ > 420 nm) | n.m.                      | 98% (50 min)           | [174] |
| 112 | C–Nb2O5                   | RhB        | 300 W Xe lamp (λ > 420 nm) | 25                        | ≥90% (30 min)          | [175] |
| 113 | N–HNb2O4                  | RhB        | 300 W Xe lamp (λ > 420 nm) | n.m.                      | 98% (50 min)           | [156] |
| 114 | Au@void@Nb2O3             | RhB        | 300 W Xe lamp (λ > 420 nm) | 15                        | 100% (140 min)         | [92a] |
| 115 | Nb2O3/Pd@SBA-15           | RhB        | UV light                 | r.t.                      | 97% (20 min)           | [177] |
| 116 | Nb2O3/FTO                 | RhB        | 300 W Hg lamp            | n.m.                      | 0.01 212 min⁻¹         | [178] |
| 117 | BiOCl/Nb2O3/BiN2O4Cl      | RhB        | 300 W Hg lamp            | n.m.                      | 99% (40 min)           | [179] |
| 118 | Nb2O3–g-C3N4/graphene aerogel | RhB | 300 W Xe lamp (λ > 420 nm) | n.m.                      | 95% (100 min)          | [180] |
| 119 | BiNb2O4/Nb2O3             | RhB        | 500 W Xe lamp (λ > 420 nm) | n.m.                      | 61% (60 min)           | [181] |
| 120 | Nb2O3–WO3                 | RhB        | 125 W Hg lamp            | n.m.                      | ≥70% (100 min)         | [182] |
| 121 | TT-Nb2O3 particles        | RhB        | UV light                 | 18                        | 0.00 323 min⁻¹         | [183] |
| 122 | g-C3N4/Nb2O5              | RhB        | 15 W fluorescent lamps   | 18                        | 0.0202 min⁻¹           | [13]  |
| 123 | T–Nb2O3 nanowires         | RhB        | 100 W Hg lamp            | r.t.                      | 95% (150 min)          | [184] |
| 124 | C–Nb2O3                   | RhB        | 300 W Xe lamp (λ > 420 nm) | n.m.                      | 100% (30 min)          | [83b] |
| 125 | TT–Nb2O5 nanowires        | RhB        | 500 W Xe lamp (λ > 420 nm) | n.m.                      | 0.047 min⁻¹            | [185] |
| 126 | g-C3N4–mesoporous Nb2O4   | RhB        | 300 W Xe lamp (λ > 420 nm) | n.m.                      | 98% (180 min)          | [99b] |
| 127 | Zn–Nb2O3                  | RhB        | 15 W UV light            | r.t.                      | 90% (180 min)          | [85]  |
| 128 | Zn–C–Nb2O3                | RhB        | Visible light            | n.m.                      | 100% (80 min)          | [186] |
| 129 | C60/ZnS/Nb2O5             | Violet     | 100 W fluorescent lamps  | n.m.                      | 0.054 min⁻¹            | [105b]|
| 130 | r-CO/SnO2/Nb2O3/TiO2       | Violet     | 300 W Xe lamp (λ > 400 nm) | 30–35                     | 98% (120 min)          | [100] |
| 131 | TT–Nb2O3 particles        | Atrazine   | UV light                 | 18                        | 0.0124 min⁻¹           | [187] |
| 132 | TT–Nb2O3 particles        | Atrazine   | UV light                 | 18                        | 0.03 min⁻¹             | [106b]|
| 133 | Nb2O3                     | Basic red-2 | 400 W Hg lamp           | 25                        | 94% (120 min)          | [188] |
| 134 | Fe3O4/Nb2O3               | Methylviologen | 125 W Hg lamp           | 25                        | 0.041 min⁻¹            | [189] |
| 135 | Mesoporous TT–Nb2O3 particles |  | 125 W Hg lamp           | 25                        | 0.069 min⁻¹            | [190] |
| 136 | Nb2O3/bentonite clay      | Blue 19    | 125 W Hg lamp            | 25                        | 98% (120 min)          | [191] |
| 137 | Nb2O3/activated charcoal  | Blue 5G    | 250 W Hg lamp            | 28                        | 94% (300 min)          | [192] |
| 138 | ZnO/Nb2O3                 | Bromophenol blue | 400 W Hg lamp           | 25                        | 0.030 min⁻¹            | [104a]|
| 139 | Nb2O3/ZnAl-LDH            | Congo red   | 300 W Xe lamp (λ > 420 nm) | n.m.                      | ≥85% (390 min)         | [193] |
| 140 | Nb2O3/Br2O3               | Dibenzo-thiophene | 5 W LED lamps         | r.t.                      | 99% (120 min)          | [194] |
| 141 | Nb2O3                     | Reactive blue 59 | 400 W Hg lamp           | n.m.                      | 89% (150 min)          | [195] |
| 142 | TT–Nb2O3 particles        | Rose bengal | Xe lamp (λ > 380 nm)     | r.t.                      | 60% (180 min)          | [71a] |
| 143 | g-C3N4/Nb2O3              | Amilorida   | 15 W fluorescent lamps  | 18                        | 0.0137 min⁻¹           | [13]  |

(Continued)
comparison of activity. These phenomena can be ascribed to the complex reaction mechanism and the difficulty in the product analysis. Further studies in this area are still necessary.

Pure Nb2O5, N–Nb2O5, and composites Nb2O5 photocatalysts were also applied in the removal of toxic Cr(VI) species (Table 1, Nos. 164–166). Unlike the degradation of organic pollutants, the Cr(VI) species are reduced by the photogenerated electrons (Figure 7, path C). Besides, the utilization of Nb2O5-based photocatalysts was also reported in the inactivation of bacteria (Table 1, Nos. 164–166). The *Staphylococcus aureus* and *Escherichia coli* were inactivated by the reacted electrons to the number of incident photons.\(^{[206]}\) This result can be a benchmark for comparison of efficiency in different photocatalytic systems. Recently, the AQY in the photocatalytic water splitting to H2 and O2 was up to \(96\%\) (Table 2, Nos. 2–4). Hence, the challenge and opportunity are still present in further improving the activity of Nb2O5-based photocatalysts in the medical field.

### 4.2. Photocatalytic H2 and O2 Evolution

Photocatalytic hydrogen evolution is the potential process to produce H2 as a clean energy carrier.\(^{[5b, 203]}\) Generally, the excited electrons in semiconductor photocatalysts are utilized for the reduction of H\(^+\) ions or H\(_2\)O to H\(_2\).\(^{[5b]}\) However, the reaction rate over Nb2O5 is limited by several factors, including i) the high recombination efficiency of charge carriers, ii) the low reduction rate of catalytic protons to H\(_2\), iii) the insufficient absorption capacity of visible light, and so on. Thus, some strategies have been developed to enhance the photocatalytic performance.\(^{[5b]}\) For instance, sacrificial agents, like triethanolamine (TEOA), methanol, lactic acid, Na\(_2\)S, and Na\(_2\)SO\(_3\), were introduced into the reaction mixture to consume the holes on Nb2O5-based photocatalysts while the remaining electrons were still utilized for the production of H\(_2\) (Table 2, Nos. 1–5). Similarly, Nb2O5 can be modified with platinum as a cocatalyst was introduced to promote the reduction of protons to H\(_2\) (Table 2, Nos. 1–5). Similarly, Nb2O5 can be modified with Pt and sulfide to enhance the hydrogen evolution rate (Table 2, Nos. 2, 28–29, 31). Meanwhile, the obtained catalyst is active under visible light irradiation (Table 2, No. 4).

Furthermore, the Nb2O5 and Pt/Nb2O5 were applied in the oxidation of water to O2 (Table 2, Nos. 33–34). In this process, AgNO\(_3\) acted as the sacrificial agent, which was reduced by the photogenerated electrons on Nb2O5-based photocatalysts. Especially, the apparent quantum yield (AQY) was mentionedin these processes (Table 2, Nos. 2–4), which is defined by the number of the reacted electrons to the number of incident photons.\(^{[204]}\) The AQY can be a benchmark for comparison of efficiency in different photocatalytic systems. Recently, the AQY in the photocatalytic water splitting to H\(_2\) and O\(_2\) was up to \(96\%\) on Al–SrTiO3 under 360 nm light irradiation.\(^{[207]}\) This result is much higher than that reported on Nb2O5-based catalysts (Table 2, Nos. 2–4). Hence, the challenge and opportunity are still present in further improving the activity of Nb2O5-based photocatalysts.

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**Table 1.**

| No.  | Catalysts                  | Pollutants                  | Light sources          | Reaction temperature [°C] | Degradation rate   | Refs. |
|------|----------------------------|-----------------------------|------------------------|---------------------------|-------------------|-------|
| 145  | HNb3O8 nanosheets           | Bromocresol green           | Hg lamp                | 20–25                     | \(\approx 90\%\) (45 min) | \([56b]\) |
| 146  | Fe\(_2\)O\(_3\)/Nb2O5       | Paper wastewater            | 205 W Hg lamp          | t.t.                      | 0.061 h\(^{-1}\) | \([113a]\) |
| 147  | Ag\(_2\)O/Nb2O5             | Paper wastewater            | 205 W Hg lamp          | t.t.                      | 0.094 h\(^{-1}\) | \([113a]\) |
| 148  | Nb2O5                       | Textile wastewater          | 250 W Hg lamp          | 25                        | \(0.60 \text{ min}\)^\(-1\) | \([113b]\) |
| 149  | Carbon black–Nb2O5          | Textile wastewater          | 250 W Hg lamp          | n.m.                      | \(41\%\) (300 min) | \([113c]\) |
| 150  | Ag/Nb2O5                    | Textile dyes                | UV light bulb           | n.m.                      | \(96\%\) (24 h)  | \([195]\) |
| 151  | Nb2O5/NaX                   | Textile effluents           | 250 W Hg lamp          | 28                        | 0.0033 min\(^{-1}\) | \([194]\) |
| 152  | Nb2O5/ZnO                   | Palm oil mill effluent      | 15 W UV lamp            | n.m.                      | 92\% (240 min)  | \([195]\) |
| 153  | Nb2O5/ZnO                   | Palm oil mill effluent      | 15 W UV lamp            | n.m.                      | 92\% (240 min)  | \([196]\) |
| 154  | Nb2O5                       | Petrol station wastewater   | 250 W Hg lamp          | n.m.                      | \(35\%\) (300 min) | \([197]\) |
| 155  | Nb2O5/TiO\(_5\)             | Vinasse                     | Solar radiation         | n.m.                      | \(55\%\) (24 h) | \([106a]\) |
| 156  | Nb2O5/TeO\(_3\)             | Cr(VI)                      | 20 W UV lamp            | n.m.                      | \(90\%\) (180 min) | \([99a]\) |
| 157  | TT-Nb2O5 nanowires/carbon fiber | Cr(VI)                  | 500 W UV light         | n.m.                      | \(99\%\) (60 min) | \([198]\) |
| 158  | TT-Nb2O5 nanorods/diatomicite | Cr(VI)                    | 500 W Hg lamp          | t.t.                      | 90\% (60 min)  | \([199]\) |
| 159  | Porous TT-Nb2O5            | Cr(VI)                      | 18 W UV light          | n.m.                      | 60\% (120 min) | \([63b]\) |
| 160  | Nb2O5                       | Cr(VI)                      | 250 W Hg lamp          | n.m.                      | \(90\%\) (120 min) | \([200]\) |
| 161  | N-modified Nb2O5           | Cr(VI)                      | Visible light (\(\lambda > 420\) nm) n.m. | \(80\%\) (240 min) | \([111]\) |
| 162  | CuO/Nb2O5                   | Cr(VI)                      | 15 W UV lamps          | 18                        | 23.70 min\(^{-1}\) | \([201]\) |
| 163  | Nb2O5@MIL-125               | Cr(VI)                      | 990 W Xe lamp          | 25                        | \(99\%\) (60 min) | \([202]\) |
| 164  | TT-Nb2O5 particles          | *Escherichia coli*          | Black light lamp        | n.m.                      | 0.034 min\(^{-1}\) | \([203]\) |
| 165  | Sr–Nb2O5                    | *Escherichia coli*          | 400 W halide lamp (350–700 nm) | 30                          | 0.12 min\(^{-1}\) | \([77]\) |
| 166  | Sr–Nb2O5                    | *Staphylococcus aureus*     | 400 W halide lamp (350–700 nm) | 30                          | 0.069 min\(^{-1}\) | \([77]\) |

\(^{a}\) Not mentioned  \(^{b}\) Room temperature  \(^{c}\) Methylene blue  \(^{d}\) Methyl orange  \(^{e}\) Rhodamine B
Table 2. Recent advances in the photocatalytic H$_2$ and O$_2$ evolution over Nb$_2$O$_5$-based photocatalysts.

| No. | Catalysts | Products | Sacrificial agents | Light sources | Reaction temperature [°C] | Reaction rate [µmol g$^{-1}$ h$^{-1}$] | AQY$^a$ [%] | Refs. |
|-----|-----------|----------|-------------------|--------------|---------------------------|---------------------------------|------|------|
| 1   | Pt/H-Nb$_2$O$_5$ nanorods | H$_2$ | Methanol | 500 W Hg lamp | n.m.$^b$ | ≥1820 | n.m. | (205b) |
| 2   | Pt/TT-Nb$_2$O$_5$ nanowires | H$_2$ | Methanol | 300 W Xe lamp ($λ$ > 300 nm) | n.m. | ≥780 | 4.6 | (40a) |
| 3   | Pt/H-Nb$_2$O$_5$ nanosheets | H$_2$ | Methanol | 300 W Xe lamp ($λ$ > 420 nm) | n.m. | ≥1200 | 1.69 | (50f) |
| 4   | Pt/Nb$_2$O$_5$ | H$_2$ | Methanol | 400 W Hg lamp | 20 | 12 350 | n.m. | (19) |
| 5   | CuO/Nb$_2$O$_5$ | H$_2$ | Methanol | 300 W white light | 50 | 1405 | n.m. | (69) |
| 6   | Pt/C-Nb$_2$O$_5$ | H$_2$ | Methanol | 300 W Xe lamp ($λ$ > 420 nm) | n.m. | ≥39 | n.m. | (82c) |
| 7   | Pt/N-Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | 154 | n.m. | (19) |
| 8   | Pt/N–Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | 154 | n.m. | (19) |
| 9   | Pt/N–Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | 154 | n.m. | (19) |
| 10  | Pt/N–Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | 154 | n.m. | (19) |
| 11  | Pt/N–Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | 154 | n.m. | (19) |
| 12  | Carbonaceous Nb$_2$O$_5$ | H$_2$ | Methanol | 500 W Xe lamp | n.m. | 2 | n.m. | (109) |
| 13  | Pt/Nb$_2$O$_5$ | H$_2$ | Methanol | 400 W halide lamp | 43 | 4647 | n.m. | (95a) |
| 14  | Pt/Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W solar simulator | r.t. | ≥25 | 1.06 | (210) |
| 15  | Pt/Nb$_2$O$_5$ | H$_2$ | Methanol | 165 W Hg lamp | 10 | 9790 | n.m. | (211) |
| 16  | Pt/Nb$_2$O$_5$ | H$_2$ | Methanol | 300 W Xe lamp | n.m. | 124 | n.m. | (212) |
| 17  | Pt/Nb$_2$O$_5$/TiO$_2$ | H$_2$ | Methanol | 300 W Xe lamp (320–780 nm) | n.m. | 1800 | n.m. | (213) |
| 18  | Er–Y$_3$Al$_5$O$_12$@Nb$_2$O$_5$/Pt/In$_2$O$_3$ | H$_2$ | Methanol | 300 W Xe lamp (420–800 nm) | 25 | ≥100 | n.m. | (214) |
| 19  | Nb$_2$O$_5$/MoS$_2$/graphene | H$_2$ | Methanol | Visible light | r.t. | 136 800 | n.m. | (215) |
| 20  | N–Nb$_2$O$_5$/r–GO | H$_2$ | Methanol | 500 W Xe lamp | n.m. | 2 | n.m. | (216) |
| 21  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 400 W halide lamp | 43 | 4647 | n.m. | (95a) |
| 22  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 23  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 24  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 25  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 26  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 27  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 28  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 29  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 30  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 31  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 32  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 33  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |
| 34  | Pt/C-modified Nb$_2$O$_5$ | H$_2$ | Methanol | 150 W Xe lamp ($λ$ > 400 nm) | 25 | ≥882 | 13 | (216) |

$^a$ Apparent quantum yield  
$^b$ Not mentioned  
$^c$ Room temperature  
$^d$ Triethanolamine.

### 4.3. Photoreduction of CO$_2$

CO$_2$ as a carbonaceous resource can be applied in the production of chemicals and fuels.\[^{218}\] For instance, CO$_2$ can be reduced to one-carbon (C$_1$) molecules, like CO, HCOOH, HCHO, CH$_3$OH, and CH$_4$, and C$_2$+ products.\[^{218}\] There are two typical reaction modes for photocatalytic reduction of CO$_2$: solid–liquid interface reaction mode (mode I) and solid–vapor interface reaction mode (mode II).\[^{219}\] In the first mode, the photocatalysts were introduced into an aqueous solution. Dissolved CO$_2$ in water can be reduced on the solid–liquid interface. For another one, CO$_2$ molecules were directly reduced on the solid-photocatalysts surface. Especially, two modes were both reported with the utilization of Nb$_2$O$_5$-based photocatalysts.\[^{9b,220}\] The CO, HCOOH, CH$_3$OH, CH$_4$, and CH$_3$COOH were observed in these reduction process (Table 3).\[^{220}\] Because the dissolved CO$_2$ in water is limited in mode I that was widely reported, sacrificial agents, such as triethanolamine, were added to improve the solubility of CO$_2$ in water and consumed the excited holes. Besides, the photoreduction of CO$_2$ can be occurred on amorphous Nb$_2$O$_5$ without any additives (Table 3, No. 3). Some possible reaction pathways were proposed as following Equations (1)–(8)\[^{9a,219}\]

\[ \text{CO}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{HCOOH} \]  
\[ \text{CO}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{CO} + \text{H}_2\text{O} \]
CO₂ + 4H⁺ + 4e⁻ → HCHO + H₂O  
(3)

CO₂ + 6H⁺ + 6e⁻ → CH₃OH + H₂O  
(4)

CO₂ + 8H⁺ + 8e⁻ → CH₄ + 2H₂O  
(5)

CO₂ + H⁺ + e⁻ → •COOH  
(6)

2 • COOH → HCOOCOOH  
(7)

HCOOCOOH + H⁺ + e⁻ → CH₃CHOOH  
(8)

It is very important to underline some critical, analytical, and mechanistic aspects in the photocatalytic conversion of CO₂. Over the past decade, it is known that carbon residues can be involved in photocatalytic water activation and CO₂ reduction.[221] This is particularly relevant for the correct evaluation of the rates of artificial photosynthesis using photocatalysts synthesized with carbon-containing precursors. For this reason, it has become more and more relevant to the use of ¹³CO₂ to prove the mechanism of CO₂ reduction. In fact, the reaction products, often in trace levels, can derive also from light-induced desorption or reaction of carbonaceous impurities or residues from the synthesis in organic media that are not fully removed even by calcination. For instance, the CH₄ can be observed from the catalysts under light irradiation without CO₂.[220] After eliminating the effects of carbon residues, the experimental results are conducive to reveal the process of photocatalytic reduction of CO₂. The photocatalytic efficiency can be evaluated by the AQY, which was not mentioned in these processes (Table 3).[9b,220] Besides, the selectivity of products is also important for catalytic performance. The C₁ products from CO₂ are important chemical intermediates and fuels.[218] High selectivity (>99%) of CO and CH₄ has been obtained, respectively (Table 3, Nos. 1–2). Although other acid products were observed in pure Nb₂O₅,[9d] the selectivity of HCOOH (35%) was competitive with that of CH₃COOH (42%); Table 3, No. 3). The formation of CH₃COOH involved the C–C coupling reaction of •COOH radicals (Equations (6)–(8)).[19a] Unfortunately, the uncontrollable activity of •COOH radicals leads to the simultaneous generation of CH₂COOH and HCOOH.[115] Besides, syngas that is vital in Fischer–Tropsch synthesis can be directly obtained from the reduction of CO₂ and H₂ evolution in photocatalysis.[122] To date, such processes are yet to be recognized over Nb₂O₅-based photocatalysts.

### 4.4. Selective Transformation of Organic Molecules

Amines, aldehydes, and ketones are important organic intermediates for medicines and polymers.[223] The VB maximum of Nb₂O₅ is up to ≈+2.50 V versus NHE (normal hydrogen electrode), implying its potential application in the oxidation and succedent transformation of organic molecules.[29] The amines, alcohols, propene, cyclohexane, toluene, and ethylbenzene were selective oxidation to corresponding imines, aliphatic aldehydes, ketones, benzaldehyde, and acetonaphthene (Table 4). Similar to the photocatalytic reduction of CO₂ (Section 4.3), there were also two typical reaction modes in the selective transformation of organic molecules. In the first mode, O₂, solid photocatalysts, pure organic liquid, or the substrate dissolved in the solvent, like benzene and acetonitrile, were present in the system (Table 4, Nos. 1–16). For another one, the mixture of O₂, substrate, and solid photocatalysts were introduced into the reactor (Table 4, No. 17). The reaction rate of benzyamine observed on Nb₂O₅ was higher than that of TiO₂.[9c] Meanwhile, the selectivity of N-benzyldiene benzyamine on Nb₂O₅ is up to 98%.[9b] Besides, the selectivity of partial oxidation products was up to 97% after the deposition of Nb₂O₅ on the TiO₂ surface under UV light irradiation.[97a] This may be attributed to that the amounts of photogenerated O₃⁻ species over the catalyst drastically decreased, which were estimated by electron spin resonance spectroscopy.[97a] Interestingly, primary alcohols oxidized to aldehydes without the generation of acid on Nb₂O₅ under visible light irradiation.[224] A detailed relationship between product selectivity and structure of Nb₂O₅-based photocatalysts is summarized in the next section.

In addition, Pd/HNb₃O₈ nanosheets were efficient in the reduction of aryl nitro-compounds to aniline (Table 4, No. 18).[50c] Moreover, Nb₂O₅ catalysts were also applied in the photocatalytic coupling reaction. Xie’s group demonstrated that the polyethylene was completely photodegraded on Nb₂O₅ nanosheets while generated CO₂ was further reduced to CH₃COOH (Table 4, No. 19).[9a] Possible reaction mechanism was provided, in which CO₂ was reduced to •COOH radicals, HCOOCOOH, and CH₃COOH (Section 4.3, Equations (6)–(8)).[9a] The transformation of waste plastics to chemicals and fuel can be realized by this process. Although the yield of CH₃COOH is limited, further designs in photocatalysts are possible to enhance its activity. In addition, the acid sites on Nb₂O₅ play an important role in the coupling reaction. For instance, dimethoxymethane molecules were generated in the photooxidation methanol, indicating the coupling formaldehyde and methanol catalyzed by the BAS of Au/Nb₂O₅ (Table 4, No.

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**Table 3.** Recent advances in the photocatalytic reduction of CO₂ over Nb₂O₅-based photocatalysts.

| No. | Catalysts | Substrates | Main product | Light sources | Reaction temperature [°C] | Reaction rate [µmol g⁻¹ h⁻¹] | Refs. |
|-----|-----------|------------|--------------|--------------|----------------------------|----------------------------|------|
| 1   | In₃O₇(OH)₆/Nb₂O₅ nanorods | CO₂ and H₂ | CO | 300 W Xe lamp | 60 | 1400 | [220a] |
| 2   | HNB₃O₈ nanobelts | CO₂ and H₂O | CH₄ | 350 W Xe lamp | 45 | 3.58 | [220b] |
| 3   | Amorphous Nb₂O₅ | CO₂ and H₂O | CH₃COOH | UV light | n.m. | ≈1.35 | [9b] |
| 4   | SiO₂–HNb₃O₈ | CO₂ and H₂O | CH₄ | 350 W Xe lamp | 60 | 2.90 | [220c] |

*Not mentioned.*
Recent advances in the selective photooxidation of organic molecules over Nb$_2$O$_5$-based photocatalysts.

| No. | Catalysts          | Substrates      | Main products       | Light sources                | Reaction temperature [°C] | Reaction rate [µmol g$^{-1}$ h$^{-1}$]$^6$ | AQY [%] | Refs. |
|-----|--------------------|-----------------|---------------------|-----------------------------|----------------------------|--------------------------------------------|---------|-------|
| 1   | HNb$_2$O$_5$ nanosheets | Amines          | Imines              | 300 W Xe lamp ($λ > 420$ nm) | 25                         | ≈1979                                     | 6.57    |       |
| 2   | Nb$_2$O$_5$         | Amines          | Imines              | 500 W Hg lamp               | r.t.$^b$                   | 1298                                       | 14      |       |
| 3   | Nb$_2$O$_5$@NiFe-MMO | Benzyl-amine     | Imine               | 300 W Xe lamp               | 30                         | ≈18281                                    | n.m.$^c$|       |
| 4   | Nb$_2$O$_5$/ZnMgAl-LDH | Anilines        | Azoxy-benzenes      | 50 W violet light LED        | r.t.                       | ≈1979                                     | n.m.    |       |
| 5   | Nb$_2$O$_5$         | 1-pentanol      | Pentanal            | 500 W Hg lamp               | 50                         | ≈1.128                                    | 5.2     |       |
| 6   | HNB$_2$O$_5$ nanosheets | Benzylc alcohol | Benz-aldehyde       | 300 W Xe lamp ($λ > 400$ nm) | 25                         | ≈1969                                    | n.m.    |       |
| 7   | Nb$_2$O$_5$         | Alcohols        | Aldehydes and ketones | 500 W Hg lamp ($λ > 390$ nm) | 50                         | ≈5.2                                      |       |       |
| 8   | Nb$_2$O$_5$         | Alcohols        | Aldehydes and ketones | 500 W Hg lamp ($λ > 390$ nm) | r.t.                       | ≈619                                      | n.m.    |       |
| 9   | Nb$_2$O$_5$         | HMF             | DFF                 | 300 W Xe lamp               | 30                         | ≈333                                      | n.m.    |       |
| 10  | Nb$_2$O$_5$/Ti$_2$O$_5$ | 1-pentanol      | Pentanal            | 500 W Hg lamp               | r.t.                       | ≈8660                                    | n.m.    |       |
| 11  | Nb$_2$O$_5$/Ti$_2$O$_5$ | Alcohols        | Aldehydes and ketones | 500 W Hg lamp               | r.t.                       | ≈48748                                   | n.m.    |       |
| 12  | Nb$_2$O$_5$/Ti$_2$O$_5$ | Aryl alcohol    | Aldehydes and ketones | 200 W Xe lamp               | n.m.                       | 17 600                                    |       |       |
| 13  | Nb$_2$O$_5$/Si$_2$O$_5$ | Ethanol         | Acet-aldehyde       | 500 W Hg lamp ($λ > 320$ nm) | 37                         | ≈107                                     | n.m.    |       |
| 14  | Nb$_2$O$_5$         | CH$_2$ and EB$^h$ | Aldehydes and ketones | 500 W Hg lamp ($λ > 390$ nm) | r.t.                       | ≈120                                     | n.m.    |       |
| 15  | Nb$_2$O$_5$         | Toluene         | Benz-aldehyde       | 200 W Hg-Xe lamp ($λ > 390$ nm) | 20                         | ≈80                                      | 11      |       |
| 16  | N–Nb$_2$O$_5$       | Toluene         | Benz-aldehyde       | 6 W LED                     | 40                         | ≈28                                      | n.m.    |       |
| 17  | Nb$_2$O$_5$/Si$_2$O$_5$ | Propene        | Aldehydes            | 500 W Xe lamp ($λ > 290$ nm) | r.t.                       | ≈13                                       |       |       |
| 18  | Pd/HNB$_2$O$_5$ nanosheets | Aryl nitro-compound | Aniline              | 300 W Xe lamp ($λ > 320$ nm) | 25                         | ≈2168                                    | n.m.    |       |
| 19  | Nb$_2$O$_5$ nanosheet | Plastics        | CH$_3$COOH          | 300 W Xe lamp               | 25                         | ≈0.79                                    | n.m.    |       |
| 20  | Au/Nb$_2$O$_5$      | Methanol        | DMFF$^i$ and H$_2$O | UV light                    | 25                         | ≈2.64                                    |       |       |
| 21  | Nb$_2$O$_5$/ZnIn$_2$S$_4$ | HMFF$^j$ and H$_2$O | DFF$^k$ and H$_2$ | Simulated solar light       | 30                         | ≈429                                     | n.m.    |       |

$^a$ Productivity of the main product  
$^b$ Room temperature  
$^c$ Not mentioned  
$^d$ Cyclohexane  
$^e$ Ethylbenzene  
$^f$ Dimethoxymethane  
$^g$ 5-Hydroxymethylfurural  
$^h$ 2,5-Diformylfuran.

The other example reported by Lei's group demonstrated that 2,5-diformylfuran (DFF) and H$_2$ are produced from 5-hydroxymethylfurural (HMFF) and H$_2$O on Nb$_2$O$_5$/ZnIn$_2$S$_4$, in which HMFF acted as a sacrificial agent to consume the holes to improve the evolution of H$_2$ with the formation of DFF (Table 4, No. 21). This strategy is available to improve the efficiency of photogenerated holes and electrons simultaneously.

5. The Structure—Activity Relationship

5.1. The Role of Size and Crystalline Phases

Previously, Nb$_2$O$_5$-based catalysts with high SSA can be efficient photocatalysts (Figure 8a–c). In the degradation process of trichloroethylene, T-Nb$_2$O$_5$ nanotubes showed higher activity than that of layered K$_x$Nb$_5$O$_{12}$, which were ascribed to their higher crystallinity and specific surface area. After that, Zhang's group reported that H-Nb$_2$O$_5$ nanorods exhibited higher photocurrent density than that of commercial counterpart, due to the positive effect of high SSA on the separation of photocarriers.

Besides, the thickness of Nb$_2$O$_5$-based catalysts may play an important role in photocatalysis. Tsang's group reported that a higher photocatalytic H$_2$ evolution rate was observed with smaller numbers of the layer on Nb$_2$O$_5$-based nanosheets. In Yu's results, the photocatalytic H$_2$ evolution rate was enhanced with a decrease in the wall thickness of porous Nb$_2$O$_5$. These results imply a positive role of the thin-walled structure of Nb$_2$O$_5$ in the separation of charge carriers.

Although the crystal faces of Nb$_2$O$_5$, like (100), were revealed by the high-resolution transmission electron microscopy (HRTEM), the role of these structures is rarely reported in photocatalysis. Previously, Kudo's group afforded a possible explanation. In the photocatalytic H$_2$ evolution, higher activity of TT-Nb$_2$O$_5$ nanowires was observed than that of bulk counterpart in their results. Meanwhile, the Pt particles were selectively distributed on the short-axis plane of the TT-Nb$_2$O$_5$ nanowires in the photodeposition process. These results suggested that the photogenerated electrons moved along the nanowire growth direction while holes migrated to the nanowire sidewall. Although some Pt particles were also observed on other facets, Kudo's group described the mobility difference of charge carriers in the crystal growth direction. After that, the driving force can be ascribed to the formation of a built-in electric field between different facets, which is instructive to the separation of e$^-$ and h$^+$. In addition, Tsang's group reported that (001) facet on Nb$_2$O$_5$ nanorods was active for photodegradation of methylene blue. This can be attributed to the strong Lewis acidity of Nb$_2$O$_5$ nanorods, which is summarized in Section 5.3.

Previously, TT-Nb$_2$O$_5$ exhibited a higher SSA and reactivity than those of T-Nb$_2$O$_5$ and H-Nb$_2$O$_5$. Whereas, some research groups found that T-Nb$_2$O$_5$ and H-Nb$_2$O$_5$ showed higher activity than that of TT-Nb$_2$O$_5$ in photodegradation of methylene blue.
blue and selective oxidation of 5-hydroxymethylfurfural (Table 4, No. 9).\cite{9e,135} For instance, the T-Nb$_2$O$_5$ obtained by calcination at 800 °C showed the highest photocurrent density than those of counterparts treated at 300 and 500 °C.\cite{9e} Except for the SSA, these results indicated other factors might play an important role in photocatalysis. Previously, the formation energy of oxygen vacancy is changed on different crystalline phases of metal oxide.\cite{236} As revealed by the results of X-ray photoelectron spectroscopy (XPS), a high concentration of oxygen vacancies was observed on H-Nb$_2$O$_5$.\cite{135} These results suggest the positive effect of oxygen vacancy induced by phase transformation in photocatalysis. The detailed discussion of the role of oxygen vacancy is shown in Section 5.2.

As mentioned above, the photochemical characterizations of catalysts are necessary to reveal the distribution and migration of charge carriers. The photocurrent response, electrochemical impedance spectroscopy (EIS), and photoluminescence spectroscopy (PL) are developed to verify the separation of electrons and holes (Figure 8d–f). Besides, the theoretic calculation was utilized to study the transfer process of excited holes and electrons on metal oxide (Figure 8g).\cite{237,240} Recently, the charge carriers can be directly detected by surface photovoltage microscopy (SPVM).\cite{238} As shown in Figure 8h–j, a circular ring was observed on the differential spectrum of surface photovoltage over Au/TiO$_2$, which is corresponding to the accumulation of excited holes in the interface (Au–O–Ti) under light irradiation.\cite{239} In principle, these characterization techniques are universal and conducive to the profound understanding of the spatial distribution of charge carriers on Nb$_2$O$_5$.

**5.2. The Role of Unsatuated Nb Sites and Oxygen Vacancies**

The oxygen vacancies of Nb$_2$O$_5$ play important roles in the absorption and activation of the substrate.\cite{229,241} Previously, the unsaturated Nb sites were observed with the formation of oxygen vacancies, which were revealed by the results of electron paramagnetic resonance (EPR) and XPS.\cite{229,241} The EPR signal at 2.003 is assigned to the oxygen vacancy.\cite{229} After the adsorption of BA on HNb$_3$O$_8$ nanosheets, the intensity of the signal at 2.003 was weakened. Meanwhile, the characteristic O–H and C–O bands of BA were shifted to the lower wavenumber in Fourier transform infrared spectra (FT-IR), indicating that the BA molecules were adsorbed on unsaturated Nb sites by the formation of C–O–Nb complex.\cite{229} As a result, the optical absorption edge of BA/HNb$_3$O$_8$ nanosheets was extended to visible light, indicating that this structure was beneficial for the migration of charge carriers.\cite{229}
Besides, the unsaturated Nb sites and oxygen vacancies are conducive to the separation of charge carriers.\[50c\] The HNbO\(_8\) nanosheets with abundant oxygen vacancies exhibited a faster reaction rate and higher separation efficiency of charge carriers than those of urchin-like Nb\(_2\)O\(_5\) and NbO\(_2\) nanorods, as shown by the results of EIS, photocurrent response.\[132c\] Meanwhile, PL analysis and time-resolved fluorescence (TRF) results suggested that the oxygen vacancies were conducive to the separation of photogenerated holes and electrons.\[177\] In addition, the optical absorption ability of catalysts can be affected by the unsaturated Nb sites and oxygen vacancies.\[17c,242\] The HNbO\(_8\) nanosheets exhibited a wide bandgap (~3.4 eV), corresponding to the absorption spectrum within 370 nm.\[150\] With the formation of oxygen vacancies, the bandgap of HNbO\(_8\) nanosheets was narrowed.\[50c\] Moreover, new energy states with a small bandgap (<0.5 eV) were observed with the increasing concentration of surface unsaturated Nb sites and oxygen vacancies.\[175\] This electronic structure can be utilized for the absorption of the full solar spectrum (250–2500 nm).\[175\] Thus, heat sourced from the absorption of infrared light over HNbO\(_8\) nanosheets contributed to enhancing reaction rate in kinetics.\[175\] The inert C–H bonds of hydrocarbons can be activated by the holes generated at the valence band under UV light irradiation in the thermodynamics.\[9c\] These results shed light on the balance of electronic structure and concentration of oxygen vacancies for photocatalyst design and preparation.

Especially, the unsaturated Nb sites and oxygen vacancies can be formed without any sacrificial agents under UV light irradiation, indicating that light irradiation can be utilized for the modification of catalyst.\[130\] Meanwhile, the concentration of oxygen vacancies was not constant and changed under irradiation.\[50c\] To reveal the structure of NbO\(_2\) in situ under light irradiation, theoretical calculations in oxygen-vacancy formation energy on different facets and crystalline phases are necessary for the profound understanding of these phenomena.\[9c\]

### 5.3. The Role of LAS, BAS, and Acidity

There are consecutive tandem steps involved in photocatalytic processes: 1) light-harvesting on photocatalysts, 2) separation and migration of photogenerated holes and electrons, and 3) successive surface redox reactions.\[245\] Particularly, the surface redox reactions and selectivity of products are related to the acid–base properties of photocatalysts.\[245\] Previously, propene was oxidized to propanal, propanol, and acetaldehyde on NbO\(_2\)/SiO\(_2\) photocatalysts under light irradiation.\[213\] The selectivity of propanal was much different on the NbO\(_2\)/SiO\(_2\) catalysts.\[105a\] As revealed by results of x-ray absorption near edge structure (XANES) and extended x-ray absorption fine structure (EXAFS), tetrahedral NbO\(_4\) and octahedral NbO\(_6\) units were present on 0.66 and 4.6 wt% NbO\(_2\)/SiO\(_2\), respectively.\[233\] Notably, the NbO\(_6\) octahedra acted as the BAS.\[142a\] The LAS can be observed with the formation of NbO\(_4\) and NbO\(_3\) polyhedron.\[15\] The roles of acid sites are possibly revealed by these results. However, other products, like acetone and acrolein, were also observed, leading to the difficulty in the understanding of the relationship between BAS, LAS, and photooxidation processes.\[105a\]

After that, the unique acidity of NbO\(_2\) was found to be instructive to the adsorption–activation process in the photooxidation reaction.\[14a,244\] The deep oxidation products of alcohols were observed with increasing Lewis acidity of NbO\(_2\), which may be ascribed to the strong adsorption of aldehydes intermediates on LAS.\[228\] Besides, the NbO\(_2\)–amide surface complex was generated by the adsorption of amines on NbO\(_2\).\[245\] This complex can be excited by light (λ > 390 nm) with lower energy than that of NbO\(_2\).\[245\] Meanwhile, the yield and selectivity of benzylamine to N-benzylidene benzylamine over commercial NbO\(_2\) were higher than those over TiO\(_2\) under visible light irradiation.\[9c\] This is mainly due to the activation of amines adsorbed on NbO\(_2\) via the ligand-to-metal charge transfer (LMCT) transition (Figure 9).\[245\] The electrons transferred from the N 2p orbitals of amides to Nb 4d orbitals of NbO\(_2\).\[245\] Then, the ππ̅–H bonds were activated to form the imines.\[245\] This direct excitation of amines is beneficial to improve the selectivity of the product by inhibiting the generation of other oxygen-containing species, such as ozonide anion radicals (O3–) and hydroxyl radicals (HO•).\[245\] Thus, the undesired deep oxidation was restricted under visible light irradiation.\[246\] Similarly, alcohols were selectively oxidized to corresponding aldehydes without further oxidation to carboxylic acids.\[224\] When the surface isolated –OH groups on NbO\(_2\) were partly removed by a vacuum heat treatment, inert aromatic hydrocarbons with relatively large ionization energy also can be transformed to aldehydes under visible light irradiation (Figure 9).\[130\] However, the active sites on NbO\(_2\) are still unclear for the activation of the inert sp\(^3\) C–H bond on toluene.\[12b,18\] Besides, Tsang’s group proposed the adsorption–activation process of dyes on NbO\(_2\).\[131a\] In their results, NbO\(_2\) nanorods exhibited higher activity than that of ZnO in the photocatalytic degradation of methylene blue.\[131a\] After the introduction of a radical scavenger, the comparable activity of NbO\(_2\) nanorods was observed, indicating that hydroxyl radicals (HO•) played a marginal role in the reaction.\[131a\] As revealed by FT-IR results, the number of methyl blue molecules adsorbed on NbO\(_2\) nanorods was higher than that on ZnO, implying that the strong Lewis acidity of NbO\(_2\) nanorods was beneficial for the adsorption–activation process of methylene blue.\[131a\]

In addition, the acidity of NbO\(_2\) is also associated with the selectivity of products in the photoreduction reaction. The photoreduction of CO\(_2\) to CH\(_4\) was dominated on HNbO\(_8\) nanosheets and SiO\(_2\)-pillared HNbO\(_8\) that mainly exposed the BAS.\[15,221b,c\] The yield of CH\(_4\) reached 2.9 µmol g\(^{-1}\) h\(^{-1}\) over SiO\(_2\)-pillared HNbO\(_8\), which is much higher than that over HNbO\(_8\) (0.47 µmol g\(^{-1}\) h\(^{-1}\)), implying the promoting effects of BAS derived from the dispersed HNbO\(_8\) on SiO\(_2\).\[200\] Meanwhile, Ribeiro’s group found a quite different tendency that improving the number of acid sites on NbO\(_2\) can promote the photoreduction of CO\(_2\) to CO, HCOOH, and CH\(_3\)COOH.\[9b\] As shown in Equations (1)–(8) (Section 4.3), protons are vital in the reduction of CO\(_2\) to CH\(_4\). However, the number of acid sites on different NbO\(_2\) samples was measured by the ionic-exchange and titration approach, leading to unclear amounts of BASs on the surface of catalysts.\[9b\] Meanwhile, the activation of CO\(_2\) is related to the local structure of Nb–O–Nb.\[247\] These results lead to an ambiguous understanding of the photoreduction of CO\(_2\). Hence, further studies are still necessary to get insight into the relationship between the surface –OH groups, NbO\(_x\) units, BAS, LAS, and product selectivity in the photoreduction of CO\(_2\).
5.4. The Role of Dopant and Surface Metal Species

The photodegradation of pollutants was observed on doped Nb$_2$O$_5$ and M/Nb$_2$O$_5$ catalysts under visible light irradiation (Table 1). The optical absorption ability on doped Nb$_2$O$_5$ catalysts was revealed by the experimental and theoretical analysis. For instance, an energy level sourced from N 2p orbitals was higher than that of the conduction band of O 2p states in pristine Nb$_2$O$_5$, leading to low bandgap energy of N–Nb$_2$O$_5$ (≈2.61 eV).[19] In addition, the doping level formed by metal dopants was lower than that of the conduction band on pristine Nb$_2$O$_5$.[85,249] Meanwhile, the corresponding energy levels are still competent in the generation of O$_2$•− species for photodegradation. Furthermore, Nb$_2$O$_5$ catalysts modified by surface species can be active under visible light irradiation.[171] Zhang’s group reported the carbonate modified Nb$_2$O$_5$ for photodegradation of RhB under visible light irradiation.[171] The $E_g$ of C–Nb$_2$O$_5$ was increased to 3.06 eV after 500 °C calcination, suggesting the carbonaceous species for the enhanced visible-light harvesting.[171] Similar phenomena were also observed in N modified and C, N co-modified Nb$_2$O$_5$.[157,171,175] This can be ascribed to the transfer of electrons from surface NO$_x$ and CO$_x$ species to Nb$_2$O$_5$ under irradiation, which is analogous of dye-sensitized photocatalysis.[173] For M/Nb$_2$O$_5$ catalysts, the surface plasmon resonance (SPR) effect of metal species (e.g., Ag, Au, and Cu) is conducive to enhance the response to the visible light irradiation, ascribed to the match between the frequency of the incident light photons and the frequency of surface electrons on metal species.[171,206,225]

The catalysts structure and properties are also changed by the introduction of dopants on Nb$_2$O$_5$-based photocatalysts, including the SSA, concentration of oxygen vacancies, and acidity. For instance, the SSA of doped Nb$_2$O$_5$ catalysts was higher than that of pristine counterpart.[82,85] These phenomena may be ascribed to the lattice distortion and inhibition of crystal growth by heteroatoms.[82,85] Besides, the concentration of oxygen vacancies can be increased when Nb$_2$O$_5$ catalysts were doped with N, Zr, Y, Zn, or Mo species.[77,90,184] These phenomena were also observed on other metal oxides, like Cu–CeO$_2$.[250] As a result, the photocurrent density of N–Nb$_2$O$_5$ was higher than that of the pristine one.[12b,19] The recombination efficiency of charge carriers is also changed with the concentration of oxygen vacancies, implying an optimal concentration of oxygen vacancies on the Nb$_2$O$_5$-based photocatalysts in photocatalysis. In the future, machine learning is a promising tool to predict the structure and performance of catalysts.[251]

In addition, the acidity of Nb$_2$O$_5$-based photocatalysts is also influenced by the dopant and surface metal species. Wolski’s group reported ≈40% selectivity of dimethoxymethane (DMM) from methanol on Au/Nb$_2$O$_5$ while <5% selectivity of DMM on Nb$_2$O$_5$ was observed under UV light irradiation.[225] The DMM is produced by the condensation reaction between the formaldehyde from the oxidation of methanol and adsorbed methanol molecules, implying the significantly decreased acidity of Nb$_2$O$_5$ after the introduction of the Au species.[225] As revealed by FT-IR results, the number of LASs decreased faster than that of BASs.[225] Meanwhile, the numbers of BASs and LASs were distinct by different preparation approaches.[225] These may be ascribed to the formation of Nb$^{5+}$ species from the reduction of Nb$^{5+}$ in NbO$_4$ units by hydrogen spillover in the reducing atmosphere.[14b,252] Besides, the BAS is possibly neutralized by basic additives in the deposition–precipitation approach.[8c] Occasionally the adsorption of the substrate is enhanced by the dopant on Nb$_2$O$_5$-based photocatalysts. The adsorption of methylene blue molecules on Zr–Nb$_2$O$_5$ is considerably stronger than that over the pristine counterpart.[77] Similarly, the intact interaction between methyl violet molecules and Mo–Nb$_2$O$_5$ cluster was speculated, as revealed by the results of surface-enhanced Raman scattering (SERS) and first-principles calculation.[90] Furthermore, CO was obtained with a selectivity of 99.5% from the hydrogenation of gaseous CO$_2$ using the small Pd nanocrystals.
supported on Nb$_2$O$_5$.[253] Density functional theory (DFT) calculations suggested that the Pd(111) facets dominated on the larger nanoparticles were the most favorable sites for methanation of CO$_2$.[253]

5.5. The Role of Formed Heterojunctions

Previously, Zheng’s group synthesized an amorphous layer on TT-Nb$_2$O$_5$ microfibers (HN-500).[234] As revealed by the results of VB XPS spectra, the edges of the maximum energy for and TT-Nb$_2$O$_5$ were identical with that of the amorphous counterpart.[234] Meanwhile, the bandgap of amorphous-phase is ≈0.2 eV higher than that of TT-Nb$_2$O$_5$, indicating the formation of heterojunction on HN-500.[254] The electronic structure of heterojunction has an advantage in the separation of charge carriers. Besides, short-range ordered Nb$_2$O$_5$ can be dispersed on the surface of amorphous structure, leading to the formation of the interface between amorphous and ordered Nb$_2$O$_5$.[166] This may be conducive to the desorption of desired products, due to the distinction in acid strength on different phases.[144]

In addition, the spatial distribution of charge carriers can be observed in other Nb$_2$O$_5$-based photocatalysts.[253] The type II heterojunctions were obtained by modification of Nb$_2$O$_5$ with other composites, such as TiO$_2$, WO$_3$, ZnO, CdS, C$_3$N$_4$, Ag$_3$PO$_4$, SnNb$_2$O$_6$, BiWO$_4$, BiNb$_5$O$_14$, and so on.[196, 100, 101, 116, 161, 162, 181, 191, 205a] For instance, electrons transfer from the CB of Nb$_2$O$_5$ to the CB of BiWO$_4$ while the holes migrated from the VB of BiWO$_4$ to the VB of Nb$_2$O$_5$ under UV light irradiation, leading to limited redox potentials of Nb$_2$O$_5$/BiWO$_4$.[191] When Nb$_2$O$_5$ was deposited on the ZnIn$_2$S$_4$, a Z-scheme heterojunction was observed.[217] Partial photogenerated holes and electrons were still present on the VB of Nb$_2$O$_5$ and CB of ZnIn$_2$S$_4$, respectively. This electronic structure can maintain the oxidizing potential of Nb$_2$O$_5$ and reducing the capacity of ZnIn$_2$S$_4$, respectively.[217] In Z-scheme heterojunction, partial electrons are transferred from the CB of Nb$_2$O$_5$ to the VB of ZnIn$_2$S$_4$, which is attributed to photocatalytic performance.[217] Similar heterojunction structures were also observed on Er–Y$_3$Al$_5$O$_12$@Nb$_2$O$_5$/Pt/In$_2$O$_3$ composite catalyst.[254]

Especially, the interface is present in composited Nb$_2$O$_5$ catalysts.[227] Previously, Cu$_2$O/Nb$_2$O$_5$ exhibited higher activity than that of the pristine counterpart in the photooxidation of alcohol.[248, 256] As revealed by FT-IR results, the adsorption of cyclohexanone over Cu (l) was weaker than that over Nb$^{5+}$ species in the photooxidation of cyclohexanol.[256a] Meanwhile, the oxidative dehydrogenation of alcohols was realized on Nb$^{5+}$ species, indicating the accelerated catalytic recycle on Nb–O–Cu (l) interface.[248] To this end, a series of Nb$_2$O$_5$-based catalysts have been widely reported in the photocatalytic process. However, few studies focus on the role of the catalyst interface in photocatalysis.

6. Summary and Outlook

This review summarized recent advances in the synthesis and application of Nb$_2$O$_5$-based photocatalysts. Especially, the reaction pathways in the reduction of CO$_2$, oxidation of amines, alcohols, and hydrocarbons are related to the acidity, generated oxygen species, and functional groups on Nb$_2$O$_5$-based photocatalysts under light irradiation. The understanding greatly relies on the studies in the local structure of Nb$_2$O$_5$, which is still attractive for researchers, especially in the field of photocatalysis. The universal characterization techniques and photoelectronic properties are the cornerstones to reveal the active sites of Nb$_2$O$_5$-based photocatalysts.

In the future, Nb$_2$O$_5$-based photocatalysts are still the potential candidates for the conversion of waste plastics and biomass that are abundant carbon resources. The activations of sp$^3$ C–H bonds and C–C bonds are feasible over Nb$_2$O$_5$ that exhibits suitable photo-redox potentials under light irradiation. Although the yield and selectivity of desired products are limited in the conversion of hydrocarbon and biomass, the reactivity of Nb$_2$O$_5$ can be further improved by the design of catalyst structure and components. Besides, the local structure and corresponding acidity strength can be situ controlled on Nb$_2$O$_5$ under light irradiation. As a result, it is possible to realize the hydrolysis reaction, dehydration reaction, and hydrodeoxygenation reaction under mild conditions. Using the blueprint of photocatalysis, we can improve the conversion of waste plastics and renewable biomass.

Despite the great potential of Nb$_2$O$_5$-based photocatalysts, the exposed challenges and issues should be considered. The roles of NbO$_3$ and NbO$_6$ units are unclear in photocatalysis, due to the lack of spatiotemporal characterization technique. Apart from that, the studies are insufficient in the interface of Nb–O–metal, which can afford the profound understanding of the adsorption–desorption process and active sites in photocatalysis. Meanwhile, the development of the reactor is conducive to the practical application of the photocatalytic process.[257] Studies in these aspects are necessary for the rational design of Nb$_2$O$_5$-based photocatalysts. Moreover, novel processes and concepts are urgently required for the large-scale production of Nb$_2$O$_5$-based photocatalysts.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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