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Correlating the Surface Basicity of Metal Oxides with Photocatalytic Hydroxylation of Boronic Acids to Alcohols

Wan Ru Leow,^[a] Jiancan Yu,^[a] Bin Li,^[a] Benhui Hu,^[a] Wei Li,^[b] and Xiaodong Chen*^[a]

Abstract: Photoredox catalysis provides opportunities in harnessing clean and green resources such as sunlight and O₂, while the acid and base surface sites of metal oxides are critical for industrial catalysis such as oil cracking. Here, we elucidated the contribution of metal oxide surfaces towards photocatalytic aerobic reactions, as demonstrated through the hydroxylation of boronic acids to alcohols. The strength and proximity of the surface base sites appeared to be two key factors in driving the reaction; basic and amphoteric oxides such as MgO, TiO₂, ZnO and Al₂O₃ enabled high alcohol yields, while acidic oxides such as SiO₂ and B₂O₃ gave only low yields. The reaction is tunable to different irradiation sources by merely selecting photosensitizers of compatible excitation wavelengths. We believe that such surface complexation mechanisms between reactants and earth abundant materials can be effectively utilized to achieve a wider range of photoredox reactions.

Photoredox catalysis is a promising strategy for the sustainable production of industrially-valuable products under mild conditions and with minimal toxic reagents, which renders them benign to health and the environment.^[1] A prominent subset of photoredox catalysis is selective aerobic photocatalytic oxidations, which utilize clean and abundant resources such as O₂ and sunlight^[2] to drive difficult organic transformations such as the production of sulfoxides from thioanisoles^[2b, 3] and imines from benzylamines,^[4] which are important synthesis intermediates in the fine chemicals and pharmaceutical industries. Recently, much interest has been dedicated towards dual photocatalysis, in which photocatalysis is merged with other types of catalysis such as organocatalysis^[5] or transition metal complex^{[6][7]} catalysis, in order to extend the range of organic transformations achievable. For example, Ru or Ir photocatalysts are paired with Ni^[6] or Pd catalysts^[8] to achieve C-C bond formations from substrates of various functional groups.^[1a, 9] Photocatalysts can also be paired with Brønsted acids^[10] or bases^[11] for proton-coupled electron transfer,^[12] Lewis acids for the activation of reactants to attack by nucleophiles,^[13] and Lewis bases such as secondary amines for the reductive quenching of the photoexcited photocatalyst.^[5, 14]

The utilization of surface properties in heterogeneous catalysts to enable organic transformations constitutes a well-established class of catalysis with wide applications. The acid and base surface sites of aluminum oxide, silicon dioxide, silica-

aluminas and zeolites are widely used to catalyze or promote the catalysis of several important industrial reactions, such as oil cracking and naphtha reforming. The interface between such surface sites and supported catalysts play a significant role in promoting catalytic activity; for example, proton abstraction by the surface base sites of Ag/Al₂O₃ can enhance alcohol dehydrogenation,^[15] while the activation of O₂ by Lewis acid sites on Au/Al₂O₃ can enable CO oxidation.^[16] We believe that the base sites on metal oxide surfaces can support photosensitizers in achieving a wider range of reactions. It has been suggested that the surface acidity of photocatalytic semiconductors, such as that of TiO₂^[17] and HNb₃O₈,^[18] can increase the rate of visible-light-induced benzylalcohol oxidation. However, there remains a need for greater understanding and utilization of the surface properties of heterogeneous catalysts. Previously, we have demonstrated that the surface complexation of organic reactants with Al₂O₃ can support photocatalysts in enabling the selective photocatalytic transformation of benzyl alcohols to aldehydes with molecular O₂ and visible light.^[19] The abstraction of proton from benzyl alcohol by the surface base sites on Al₂O₃ resulted in an upshift in its HOMO for electron abstraction by the photosensitizer. It is believed that such surface complexation mechanisms between the reactants and earth abundant materials can be effectively utilized to achieve a wider range of photoredox reactions.

In this article, we elucidated the contribution of metal oxide surfaces towards photocatalytic aerobic reactions, as demonstrated through the selective hydroxylation of boronic acids to alcohols. The hydroxylation of boronic acids to alcohols, traditionally conducted with alkaline H₂O₂, plays a useful synthetic role towards reactions such as the preparation of chiral aliphatic alcohols from alkenes^[20] or from the homologation of boronic esters,^[21] as well as the one-pot synthesis of meta-substituted phenols from benzene derivatives, which may be difficult to achieve through other methods.^[22] Here, we showed that with the photocatalytic route can enable the reaction to proceed under mild conditions, i.e., the use of molecular O₂ as the oxidant and visible light irradiation from a 7 W household white light LED. The 9 metal oxides used are commercially available, and their characterization data, such as SEM images, XRD spectra and BET surface areas can be found in Figures S1-3 and Table S1. The CO₂-TPD of the metal oxides, which is a standard technique for elucidating the surface basicity of heterogeneous materials,^[23] can be found in Figure S4 and Table S2. The elucidated base sites are categorized based on their strength; strong base sites are defined here as those corresponding to CO₂-TPD peak maxima ranging within 150-600 °C, while weak base sites are defined as those corresponding to peak maxima within 50-100 °C. The density of base sites are further characterized with respect to the metal oxides' surface area, in order to understand the contribution of the base sites' proximity, and with respect to the metal oxides' mass (Figure S5). It was discovered that when amphoteric and basic metal oxides (MO_x) such as ZnO, Al₂O₃, TiO₂ and MgO were coupled with Ru(bpy)₃²⁺, high yields of 4-chlorophenol (4-CIPhOH, **2a**)

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could be obtained from the hydroxylation of 4-chlorophenylboronic acid (4-ClPhB(OH)₂, **1a**) in 3 h (Figure 1). The yields of **2a** were much lower when acidic oxides such as B₂O₃ and SiO₂ were coupled with Ru(bpy)₃²⁺. In the middle region comprising Al₂O₃ of varying basic strength (Aldrich 11501-3), positive correlation appears to exist between the **2a** yields and the density of strong base sites w.r.t. surface area. The mere addition of basic or amphoteric oxide to Ru(bpy)₃²⁺ increased the turnover number (TON) and quantum yield (QY) by >6.8 times, which at least 2.4 times that of the MO_x alone (Table S3-5). There appears to be no positive correlation between the yields of the MO_x-Ru(bpy)₃²⁺ surface complexation-photocatalytic systems and the density of weak or all base sites with respect to the MO_x surface area (Figure S6). This suggests that the strength of the base sites is a crucial factor towards driving the hydroxylation of **1a**. There also appears to be no positive relationship between the yields of the MO_x-Ru(bpy)₃²⁺ dual catalytic systems and the density of base sites with respect to the MO_x mass (Figure S7). This indicates that the proximity between neighbouring base sites on the surface is important, which suggests that two or more **1a** molecules may possibly interact during the reaction.

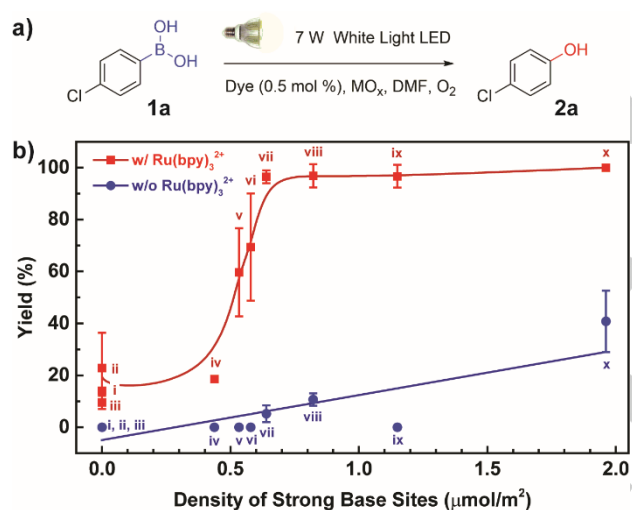


Figure 1. a) The selective photocatalytic hydroxylation of **1a** to **2a** under O₂ and visible light. b) Yields of **2a** generated by different metal oxide (MO_x) and Ru(bpy)₃²⁺ surface complexation-photocatalytic systems as a function of the density of strong base sites w.r.t. surface area. Data point labels: i – no metal oxide, ii – B₂O₃, iii – SiO₂, iv – Al₂O₃ (Aesar 11502), v – Al₂O₃ (Aesar 11503), vi – Al₂O₃ (Aesar 11501), vii – Al₂O₃ (Aldrich 517747), viii – ZnO, ix – MgO, and x – TiO₂. The lines serve as a guide to the eye.

The nature of the selective photocatalytic hydroxylation was then investigated through a series of control experiments with Al₂O₃ (Aldrich 517747) as the metal oxide of interest, as it provided a good yield of **2a** from **1a**, and is an abundant and non-toxic material. The generality of the Al₂O₃-Ru(bpy)₃²⁺ surface complexation-photocatalytic system is demonstrated through the high yields (56.3-96.0 %) of alcohols (**2a-h**) achieved with 8 boronic acid derivatives (**1a-h**) in 3 h, as shown in Figure 2a. This includes electron-rich phenols (**2d-f**), which are difficult to obtain from the traditional nucleophilic substitution

of aryl halides.^[14b] The use of Ru(bpy)₃²⁺ only provided low yields of alcohols (5.02-23.3%). The yield of **2f** is lower than that of **2d** and **2e** as the methoxy group provides more steric hindrance to the B(OH)₂ group in the ortho and meta positions. It can be seen from Figure S8a that the rate of **2a** production from **1a** is almost linear with time. Hence, the initial yield (defined arbitrarily as the product yield in the 1st hour of reaction) may be reflective of the initial reaction rate. The turnover frequency (TOF) of the reaction is 4.0-37 times greater for the Al₂O₃-Ru(bpy)₃²⁺ surface complexation-photocatalytic system compared to that of Ru(bpy)₃²⁺ only (Figure S8b).

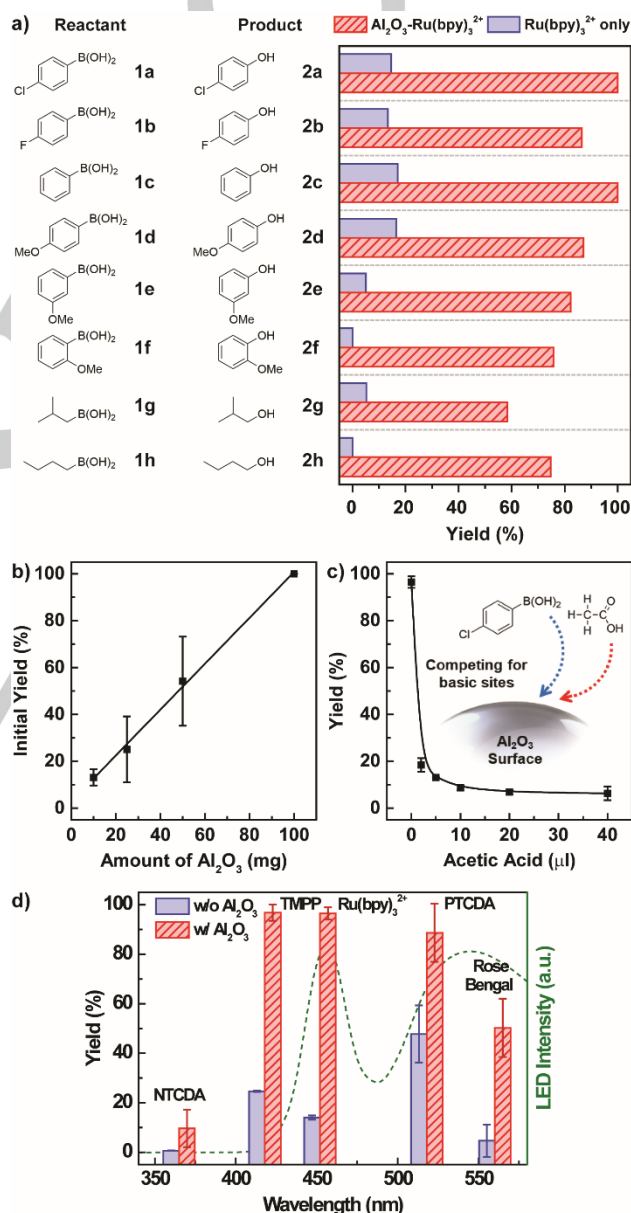


Figure 2. a) The selective photocatalytic hydroxylation of boronic acids (**1a-h**) to alcohols (**2a-h**) catalyzed by the Al₂O₃-Ru(bpy)₃²⁺ surface complexation-photocatalytic system and Ru(bpy)₃²⁺ only. b) Initial yield of **2a** vs Al₂O₃ mass. c) Quenching of the Al₂O₃ surface base sites with acetic acid. The lines serve as a guide to the eye. d) Yield of **2a** catalyzed by Al₂O₃ in conjunction with different photosensitizers.

Meanwhile, the initial yield of **2a** increases linearly with the mass of Al_2O_3 used, which indicates that the initial rate of the reaction may be dependent on the adsorption of **1a** on the Al_2O_3 surface sites (Figure 2b). This is further evidenced through introduction of acetic acid, which would compete with **1a** for chemisorption on the base sites and result in the quenching of the reaction (Figure 2c). The absence of either component of the Al_2O_3 - $\text{Ru}(\text{bpy})_3^{2+}$ surface complexation-photocatalytic system, or the absence of any catalyst, would result in low yields of **2a** (Figure S9). The negligible yield of **2a** obtained under N_2 indicates that O_2 acts the oxidant that accepts protons and electrons from **1a** to enable its hydroxylation to **2a**. The low **2a** yield in the dark suggests that $\text{Ru}(\text{bpy})_3^{2+}$ acts as the photosensitizer that absorbs visible light and facilitates electron transfer between **1a** and O_2 , while the strong base sites on the Al_2O_3 surface facilitates proton transfer. This suggests that Al_2O_3 -photosensitizer surface complexation-photocatalytic system can be extended to other photosensitizers, provided the excitation wavelength of the photosensitizer corresponds to the LED emission (Figures 2d and S10). 5,10,15,20-Tetrakis(4-methoxyphenyl)porphyrin (TMPP), $\text{Ru}(\text{bpy})_3^{2+}$ and perylene-3,4,9,10-tetracarboxylic dianhydride (PTCDA) possess excitation wavelengths within 400–550 nm, and thus showed high yields of (96.7±3.30) %, (96.5±2.47) % and (88.6±11.7) %, respectively. 1,4,5,8-Naphthalenetetracarboxylic dianhydride (NTCDA), which absorbs light below 365 nm, provided only a low yield of (9.59±7.59) %. Rose Bengal was able to effect significant yield of (50.2±11.8) %, but its lack of stability detracts from a higher yield even though its excitation wavelength is within the range of the LED. Without Al_2O_3 , the photosensitizers produced only low yields of 0.65–47.7 %. This suggests that the Al_2O_3 -photosensitizer surface complexation-photocatalytic system can be programmed for compatibility with light sources of different wavelength ranges simply by using a suitable photosensitizer. Al_2O_3 can also be paired with dyes such as Rose Bengal to realize a transition metal-free catalytic system that is benign to the environment.

Next, we investigated the potential source of proton that constitutes the OH group of the alcohol product. In the traditional route of boronic acid hydroxylation, water is thought to be the source of the proton. The ipso-carbon of $\text{B}(\text{OH})_2$ is proposed to migrate from the B atom to an O atom in hydrogen peroxide, and the resultant intermediate undergoes hydrolysis to form alcohol.^[22a, 24] However, our photocatalytic reaction is able to proceed to high yield in anhydrous solvent, which suggests that H_2O does not take part in the reaction as an O or H donor (Figure 3a). Figure 3b shows that the initial yield of **2a** is reduced with a larger percentage of H_2O in the solvent. This suggests that the reaction may not involve hydrolysis of the intermediate as in Figure 3c, and that H_2O may even compete with **1a** for adsorption on the Al_2O_3 surface. When we scrutinize the components of the reaction system (Al_2O_3 , $\text{Ru}(\text{bpy})_3^{2+}$, boronic acid, DMF), the only possible source of H appears to be the $\text{B}(\text{OH})_2$ group. This is confirmed by the observation that negligible **2a** yield was obtained with 4-chlorophenylboronic acid pinacol ester **1i** (Figure 3a). The atom balanced equation (Figure 3d) appears to be consistent with our aforementioned suggestion that two or more boronic acid molecules are required to be in proximity during the reaction.

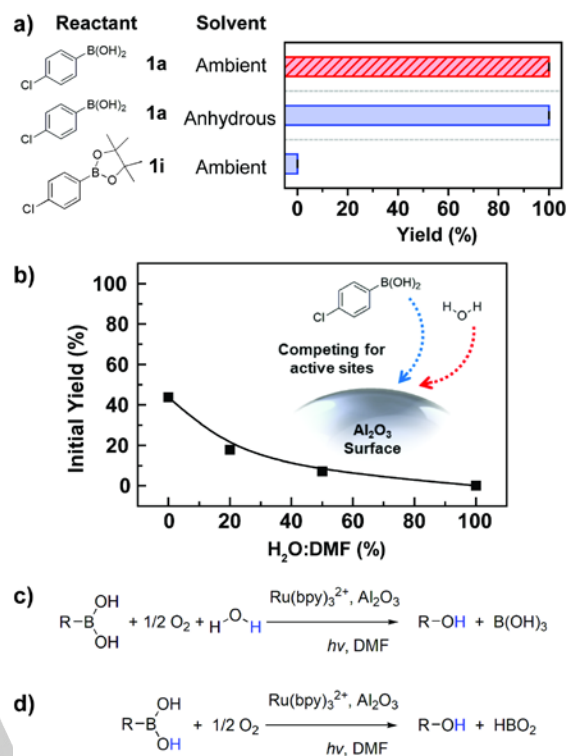
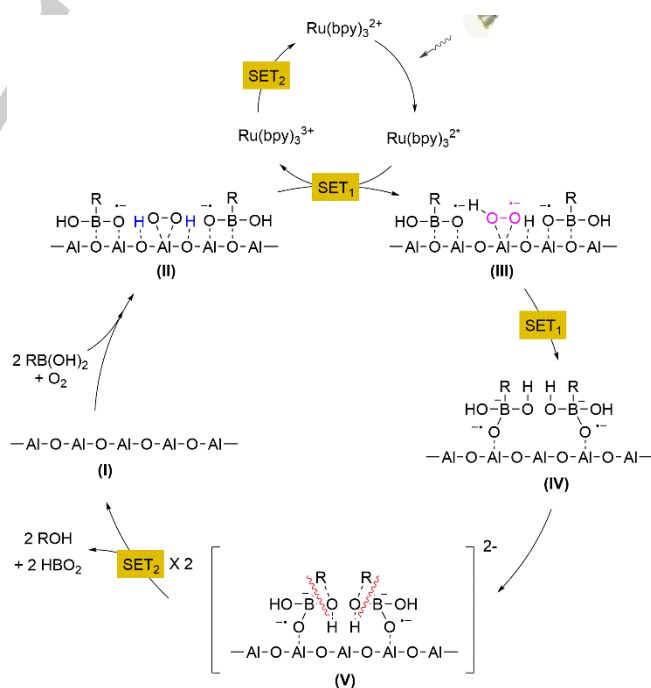


Figure 3. a) Importance of the proton of the boronic acid group towards the reaction; the yield of **2a** with non-anhydrous DMF versus that with anhydrous DMF, as well as the yield of **2a** produced from **1i**, as catalysed by Al_2O_3 - $\text{Ru}(\text{dcbpy})_2(\text{bpy})^{2+}$. b) Initial yield of **2a** with different percentages of H_2O in the solvent. The line serves as a guide to the eye. Proposed reaction equations c) without and d) with the involvement of H_2O .



Scheme 1. Proposed mechanism for the selective photocatalytic hydroxylation of boronic acids catalysed by Al_2O_3 - $\text{Ru}(\text{bpy})_3^{2+}$ surface complexation-photocatalytic system under O_2 and visible light.

From the aforementioned clues elucidating the nature of the selective photocatalytic hydroxylation of boronic acids, the following mechanism is proposed. The B atom of the boronic acid, being a Lewis acid, binds to the Lewis base site of Al_2O_3 , while a proton is abstracted from the $\text{B}(\text{OH})_2$ group by the surface base site of Al_2O_3 (Scheme 1, step I-II). Meanwhile, $\text{Ru}(\text{bpy})_3^{2+}$ is photoexcited to $\text{Ru}(\text{bpy})_3^{2+*}$, which donates a single electron to the adsorbed O_2 to form $\text{Ru}(\text{bpy})_3^{3+}$ and superoxide (step II-III). The superoxide would accept protons abstracted by the Al_2O_3 surface base sites and the neighbouring boronic acid groups, resulting in the cleavage of the O-O bond (step III-IV). The alkyl group would then migrate from the B atom to the O atom that previously constituted molecular O_2 (step IV-V). Single electron transfer from the boronic acid surface complex to $\text{Ru}(\text{bpy})_3^{3+}$ would then release phenol (step V-I). In this way, the Al_2O_3 - $\text{Ru}(\text{bpy})_3^{2+}$ surface complexation-photocatalytic system would have enabled the overall transfer of two hydrocarbon groups, four electrons and two protons from two boronic acid molecules to an adsorbed O_2 molecule.

In conclusion, we have successfully demonstrated that the surface base properties of metal oxides can be utilized for selective photocatalytic organic transformations. The MO_x - $\text{Ru}(\text{bpy})_3^{2+}$ surface complexation-photocatalytic system enabled high yields of alcohols from boronic acids, even though MO_x nor $\text{Ru}(\text{bpy})_3^{2+}$ individually could only induce low yields of alcohols. The proximity of the base sites appear to be crucial towards the reaction, which suggests that the reaction mechanism involves the interaction of two or more boronic acids with O_2 . The strength of the base sites appear to be another factor influencing the reaction; there seems to be a positive relationship between the yields of alcohol and the quantity of strong base sites of Al_2O_3 , rather than with the quantity of weak or all base sites. The reaction proceeds via a photocatalytic aerobic pathway, and can work with a plethora of photosensitizers of different moieties. This discovery highlights a significant role that heterogeneous surfaces may play in contributing to photocatalytic organic transformations, thus opening up the possibility of utilizing surface complexation mechanisms between the reactants and earth-abundant materials to bring forth a wider range of photoredox transformations. Such benign and environmentally green organic transformations that utilizes sustainable and abundant resources such as sunlight and metal oxides are potentially beneficial to industrial conversion of raw materials into valuable products, such as in the pharmaceutical, flavor and fragrance industries.

Acknowledgements

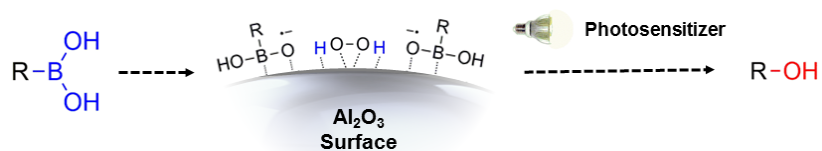
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Keywords: photocatalysis • surface base sites • boronic acids • alcohols • hydroxylation

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Entry for the Table of Contents

COMMUNICATION



W. R. Leow, J. Yu, B. Li, B. Hu, W. Li, X. Chen*

Page No. – Page No.

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Elucidating the contribution of metal oxide surfaces towards photocatalytic aerobic reactions. The strength and proximity of the base sites on metal oxide surfaces, when coupled with photosensitizer, are crucial factors driving the selective photocatalytic aerobic hydroxylation of boronic acids to alcohols.