Reporting of Reactivity for Heterogeneous Photocatalysis

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The absence of standardization in both the measurement and the reporting of heterogeneous photocatalysis reactivity data has prevented quantitative comparisons between different photocatalysts and advances in fundamental understanding of the photocatalysis reaction, respectively. The call for adoption of a standard photocatalysis measurement procedure, to prevent masking of the photocatalysis reactivity by saturation of light absorption or mass transfer effects, was recently proposed to allow ranking of different photocatalysts for their performance and comparison of reactivity reported from different laboratories.1,2 Adoption of the standardized measurement protocols by photocatalysis researchers is indeed critical for advancing the heterogeneous photocatalysis field. Standardized reactivity measurement, however, still does not address fundamental aspects of the photocatalysis process (e.g., structure–activity relationships), which would require normalizing the reactivity per number of surface photocatalytic active sites as is practiced for heterogeneous catalysis.1

Most heterogeneous photocatalysis publications report the photocatalyst performance as mass normalized Turnover Rate (TORm: moles converted or produced per gram of photocatalyst per unit time), as a consequence of the ease of determining the number of product moles formed, most commonly by chromatography, and simply weighing the mass of the employed photocatalyst. This viewpoint (i) examines the pros and cons of various methods in reporting photocatalysis reactivity (TORm, TOR, (molecules converted or produced per m² of photocatalyst per unit time), and TOF (moles converted or produced per photoactive surface site of photocatalyst per unit time)), (ii) shows how TOF can be determined for heterogeneous photocatalysts from surface characterization methods that provide the number of photoactive surface sites per gram (Nv) of photocatalysts, and (iii) demonstrates how fundamental photocatalytic structure–reactivity relationships can be determined by using the TOR and TOF methodologies to report photocatalysis reactivity.3,4

An examination of the heterogeneous photocatalysis literature reveals that multiple expressions are in use to report photocatalytic reactivity. The term photonic efficiency (PE), formerly referred to as Apparent Quantum Efficiency (AQE), is the initial rate of the photoreaction to the rate of incident photons inside the irradiation window of the reactor under a set of well described conditions.5,6 This term is an apparent efficiency since it depends on the incident photons and not the photons absorbed by the photocatalyst. The intrinsic photocatalytic activity is termed quantum efficiency and is the initial rate of the photoreaction divided by the rate of photons absorbed by the photocatalyst at a set of well described conditions.5,6 Quantum efficiency reflects the overall intrinsic efficiency of a photocatalyst in harnessing the photons absorbed to generate excited electrons and holes that diffuse to the surface to participate in the photocatalytic chemical reaction.5,6 The difficulty associated with the measurement of quantum efficiency for heterogeneous photocatalysts has favored the use of the easier to measure PE of heterogeneous photocatalysts. PE is useful for comparison of photocatalytic reactivity under the same illumination conditions.

Heterogeneous photocatalysis is a complex process since both the photocatalyst bulk lattice and the surface sites contribute to the overall photocatalytic process. The function of the bulk lattice is to absorb the incident photons and generate excited electrons and holes. The function of the surface catalytic active sites is to harness the excited electrons and holes reaching the surface to perform the catalytic reaction (chemical transformation). Although quantum efficiency and even PE of a photocatalyst parameters describe how well a photocatalyst functions for a given reaction at a set of well described conditions, they do not provide any fundamental insights about the individual contributions of the photocatalyst bulk lattice (e.g., particle size, crystallinity, etc.) or photoactive surface sites (e.g., surface area, number of exposed photoactive sites, surface structure, etc.) to the overall photocatalysis process. The current common practice of normalizing photocatalytic productivity per gram of a photocatalyst per unit time informs about the effectiveness of a photocatalyst per unit mass, which may have practical merit, but does not relate photocatalysis performance to possible bulk and surface changes in the characteristics of the photocatalyst bulk lattice and surface catalytic active sites.

For example, altering the heterogeneous photocatalyst surface area affects the number of exposed photoactive surface sites,5,4 or altering the photocatalyst bulk lattice crystallinity (increasing crystal order and decreasing number of bulk defects) can affect photon absorption and decrease the number of undesirable trap sites that recombine excited electrons/holes and prevent them from reaching the surface to participate in the photocatalytic chemical reaction. By analogy to traditional heterogeneous catalysis, there are many advantages that result from the use of a specific reactivity parameter and its nomenclature such as Turnover Frequency (TOF), which is a specific reactivity parameter per exposed active surface site per unit time for a heterogeneous catalyst.7 By normalizing the photocatalytic productivity per number of surface sites, (TORs), or even the specific TOF when the number of photoactive surface sites are known, allows for better understanding of bulk and surface photocatalyst structural variations. In other words, TOR, and TOF photoactivity values would be structure sensitive to both crystallinity of the bulk
lattice (affecting efficiency of absorption of photons and number of e\(^{-}/h^{+}\) traps) and surface features (surface composition and possible preferential exposure of specific surface facets possessing unique photoactivity).\(^5\)

Several examples are given below for determining photocatalytic TOF and TOR, values and how using TOF and TOR\(_{\text{s}}\) to express photocatalyst productivity improves our fundamental understanding of photocatalytic materials and the bulk and surface factors affecting heterogeneous photocatalysis.

**Single Component Mono-Phasic Heterogeneous Photocatalysts.** A single component monophasic photocatalyst consists of a single bulk phase (e.g., TiO\(_2\), GaN, etc.) and is schematically shown in Figure 1 for photocatalytic splitting of water. The high photo-oxidation activity of UV-illuminated (>290 nm) TiO\(_2\) particles for oxidation of undesirable organics in air and water has motivated many photocatalytic studies by TiO\(_2\) as a function of particle size.\(^3\)\(^4\)\(^8\)\(^9\) Typically, both the particle dimension and the bulk lattice crystallinity of a series of TiO\(_2\) catalysts are altered by calcining the starting titania material at higher temperatures.\(^3\)\(^4\)\(^8\)\(^9\) Such thermal treatments can be used to study the effects of particle dimension and/or bulk lattice crystallinity on photoactivity for a family of catalysts. In the case of TiO\(_2\) photo-oxidation of the organic molecule cyclohexanone to cyclohexanone, normalization of the cyclohexane to cyclohexanone photocatalysis as TOR\(_{\text{m}}\) generally leads to an apparent decrease in photoactivity with increasing particle dimension (7–30 nm).\(^3\)\(^4\) Normalization of the cyclohexane to cyclohexanone photocatalytic activity per surface parameter, such as surface area or number of surface hydroxyls (OH), however, gives rise to an increase in photoactivity TOR\(_{\text{s}}\) with increasing particle diameter for the same photocatalyst system data.\(^3\)\(^4\)

![Figure 1. Schematic of single component monophasic heterogeneous photocatalyst for photocatalytic splitting of water.](image.png)

How to reconcile such quite different photoactivity trends obtained for TOR\(_{\text{m}}\) and TOR\(_{\text{s}}\) for the same photocatalysts and photo-reaction? Just from the mass normalized TOR\(_{\text{m}}\) definition, the origin of the decrease in photoactivity is not apparent. Of course, the decrease is dominated by the decrease in number of surface sites as the particles become larger. The increase in the surface normalized TOR\(_{\text{s}}\) with particle diameter, however, reflects a structural change of the TiO\(_2\) photocatalyst since this parameter accounts for the changing number of photoactive surface sites. Complementary characterization studies demonstrated that the increase in the photocatalytic TOR\(_{\text{s}}\) is related to enhanced bulk crystallinity of TiO\(_2\) that increases the number and lifetime of excited e\(^{-}/h^{+}\) pairs in the bulk lattice that will be able to reach the surface.\(^3\)\(^4\) The increase in the photocatalytic TOR\(_{\text{s}}\) specific TOF when normalized per surface OH groups, is only a factor of ∼3 with increasing particle size, which also reveals that the bulk lattice characteristics of TiO\(_2\) NPs employed in this study exert only a small effect on the overall photocatalytic process. This example nicely demonstrates that when a family of photocatalysts undergoes large surface area changes it is important to account for the changing Brunauer–Emmett–Teller (BET) values as TOR\(_{\text{m}}\) or specific TOF when N\(_{\text{s}}\) is known, to be able to extract the fundamental influence of bulk lattice structural changes upon the photoactivity.

**Multicomponent Mono-Phasic Heterogeneous Photocatalysts.** A multicomponent monophasic photocatalyst consists of a single bulk phase (e.g., TiO\(_2\), [(GaN)\(_{1−x}\)(ZnO)\(_x\)], NaTaO\(_3\), etc.) consisting of more than 2 elements. Promoted NaTaO\(_3\) photocatalysts have been found to be the most active materials for photocatalytic splitting of H\(_2\)O to H\(_2\) and O\(_2\) with UV excitation (>270 nm).\(^10\)\(^11\) The addition of La\(_2\)O\(_3\) during the catalyst synthesis was found to increase TOR\(_{\text{m}}\) by a factor of ∼3 and TEM images exhibited the formation of smaller particles containing ordered stepped surfaces. It was proposed that the enhanced TOR\(_{\text{m}}\) photoactivity was related to the accumulation of the La\(_2\)O\(_3\) electronic promoter at the surface steps of NaTaO\(_3\), but other researchers found the steps transfer electrons less efficiently compared to NaTaO\(_3\).\(^12\) A closer examination of the photoactivity rate in terms of TOR\(_{\text{s}}\), however, reveals that the surface normalized TOR\(_{\text{s}}\) actually decreases by a factor of ∼3 upon the addition of the La\(_2\)O\(_3\) promoter to NaTaO\(_3\). The disparity between these two ways of looking at the reactivity, TOR\(_{\text{m}}\) vs TOR\(_{\text{s}}\) of this photocatalyst system is related to the increase in surface area, by a factor of ∼7, resulting from the addition of La\(_2\)O\(_3\) promoter to the synthesis of NaTaO\(_3\) that is not reflected in the TOR\(_{\text{m}}\) rate. It, thus, appears that La\(_2\)O\(_3\) is just a textural promoter that increased the NaTaO\(_3\) surface area and the number of available photoactive surface sites, by stabilizing smaller NaTaO\(_3\) particles. The highly crystalline NaTaO\(_3\) bulk lattice was not significantly perturbed by the introduction of La\(_2\)O\(_3\) (reflected by its same Raman spectrum and UV–vis band gap). Furthermore, the decrease of ∼3 in TOR\(_{\text{m}}\) from the introduction of the La\(_2\)O\(_3\) promoter indicates that the formation of the stepped surfaces for the La-promoted NaTaO\(_3\) photocatalyst does not enhance the specific photoactivity TOR\(_{\text{s}}\). The decrease in TOR\(_{\text{s}}\) is most probably related to the surface La\(_2\)O\(_3\) sites that are actually inactive photocatalytic sites that cover the photoactive surface sites of NaTaO\(_3\) (as surface analysis reveals below, La\(_2\)O\(_3\) is surface segregated on NaTaO\(_3\)). Thus, the role of the La\(_2\)O\(_3\) promoter appears to be that of a textural promoter and not an electronic promoter. This example again shows that when a family of photocatalysts undergoes large surface area changes it is important to account for the changing BET values as TOR\(_{\text{s}}\) to be able to extract the fundamental influence of surface changes upon the photoactivity.

**Biphasic Heterogeneous Photocatalysts.** Biphasic heterogeneous photocatalysts consist of two different phases, and each phase may either be single- or multicomponent (e.g., supported Rh\(_2\)–Cr\(_2\)O\(_3\)/[(GaN)\(_{1−x}\)(ZnO)\(_x\)], supported NiO/NaTaO\(_3\) with NiO NPs at high Ni loadings, etc.) as depicted in Figure 2 for photocatalytic splitting of water. The supported Rh\(_2\)–Cr\(_2\)O\(_3\)/[(GaN)\(_{1−x}\)(ZnO)\(_x\)] system is the most active photocatalyst found to date for splitting of water with visible light excitation (>420 nm).\(^13\)\(^34\) In the absence of the Rh\(_2\)–Cr\(_2\)O\(_3\) nanoparticles (NPs), the [(GaN)\(_{1−x}\)(ZnO)\(_x\)]
oxynitride does not evolve H₂ or O₂. The function of the [(GaN)₁₋ₓ(ZnO)ₓ] oxynitride support is to absorb the photons, generate excited e⁻/h⁺ and supply the e⁻/h⁺ excitons to the photocatalytic active sites at the surface to perform the chemical reactions. It is thought that the function of the supported Rh₀₋ₓCrₓO₃ NPs is to selectively harness the electrons at its surface for H₂ evolution while the holes accumulate at the [(GaN)₁₋ₓ(ZnO)ₓ] oxynitride surface to evolve O₂. The addition of Rh₀₋ₓCrₓO₃ NPs does not perturb the [(GaN)₁₋ₓ(ZnO)ₓ] oxynitride bulk lattice characteristics (reflected by its same Raman spectrum and UV–vis band gap) or surface area indicating that the Rh₀₋ₓCrₓO₃ NPs are truly behaving as electronic promoters and are usually referred to as the cocatalyst. There are two ways to surface normalize the TOR; to the surface area of the Rh₀₋ₓCrₓO₃ NPs or to the overall surface area of the supported Rh₀₋ₓCrₓO₃/[(GaN)₁₋ₓ(ZnO)ₓ] photocatalyst system, and both approaches will be examined below.

With modern cutting edge surface characterization techniques such as high sensitivity-low energy ion scattering (HS-LEIS), it is now also possible to directly quantify the number of surface Rh and Cr atoms on the outermost surface layer (≈0.3 nm) of the photocatalyst. Given that Rh is well-known as an H₂ evolution promoter, the surface site normalized TOF photocatalytic reactivity will be normalized by the number of exposed Rh sites. The TORₚ, TORᵥ, and TOF water splitting rates for several biphasic heterogeneous photocatalyst systems will be compared below.

**Triphasic Heterogeneous Photocatalysts.** Triphasic heterogeneous photocatalysts consist of three different phases and are exemplified by core–shell photocatalyst systems (e.g., supported CrₓO₃/Rh/[(GaN)₁₋ₓ(ZnO)ₓ]₁⁵,₁⁶, LaₓO₃/Rh/[(GaN)₁₋ₓ(ZnO)ₓ]₁⁷, etc.) for photocatalytic splitting of H₂O and is schematically depicted in Figure 3. In this triphasic photocatalyst, the metallic Rh core is initially photodeposited on the [(GaN)₁₋ₓ(ZnO)ₓ] support, and the CrₓO₃ shell is subsequently photodeposited on top of the metallic Rh core.₁⁵,₁⁶ The motivation for this synthesis approach is to coat the metallic Rh sites to suppress the back reaction between H₂ and O₂ by metallic Rh to produce water as indicated in Figure 3. It is thought that the function of the metallic Rh core is to attract electrons that will tunnel through the CrₓO₃ shell and react at the chromia surface with H⁺ ions to evolve H₂ while the O₂ evolution takes place by reaction of the holes with H₂O at the surface of the [(GaN)₁₋ₓ(ZnO)ₓ] oxynitride support. The addition of the CrₓO₃/Rh core–shell NPs does not perturb the [(GaN)₁₋ₓ(ZnO)ₓ] oxynitride bulk lattice characteristics (reflected by its same Raman spectrum and UV–vis band gap) or surface area indicating that the CrₓO₃/Rh NPs truly behave as an electronic promoter, the cocatalyst, since the [(GaN)₁₋ₓ(ZnO)ₓ] oxynitride support is not active for photocatalytic splitting of water. Similar to the biphasic heterogeneous photocatalyst systems discussed above, the TORₚ, TORᵥ, and TOF water splitting rates for several triphasic heterogeneous photocatalyst systems will be compared below.

**Comparison of Heterogeneous Photocatalysts for Splitting of Water.** The performances of the above heterogeneous photocatalysts for water splitting are compared in Table 1 as PE, mass normalized reactivity (TORₚ), surface area normalized reactivity (TORᵥ), and surface site normalized reactivity (TOF). For photocatalytic splitting of water, PE is defined by IUPAC⁶ as

\[
\text{PE} = \frac{\text{(moles of H}_2\text{ evolved)}}{\text{moles of photons reaching the internal surface of the irradiation window}} \times 2 \times 100
\]

The factor of 2 in the above equation reflects that two photons are involved in forming one H₂ molecule. Although several excitations were employed for the various photocatalysts because of their different band gaps, comparing their performance for photocatalytic water splitting is still informative.

The PE values are not available for all of the heterogeneous photocatalysts, but the reported PE values in Table 1 provide some important insights. The addition of only minor amounts of NiO to NaTaO₃-based photocatalysts with UV excitation gives rise to high PE values, as much as 56%, reflecting the electronic promoting characteristics of NiO for this photocatalyst system. In contrast, the best performing visible light activated supported Rh₀₋ₓCrₓO₃/[(GaN)₁₋ₓ(ZnO)ₓ] photocatalyst only exhibits a PE value of 2.5%, a factor of ~20 lower, indicating the significant progress that is still needed to develop efficient water splitting heterogeneous photocatalysts. The impact of excitation source, UV vs visible, upon the photocatalytic splitting of water is also indicated in comparison of the supported Rh₀₋ₓCrₓO₃/[(GaN)₁₋ₓ(ZnO)ₓ] photocatalyst at two different energies in Table 1. The TORᵥ rate for the supported Rh₀₋ₓCrₓO₃/[(GaN)₁₋ₓ(ZnO)ₓ] photocatalyst increases by a factor of ~15 in going from visible light excitation

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Figure 2. Schematic of biphasic heterogeneous photocatalysts for photocatalytic splitting of water. Purple, [(GaN)₁₋ₓ(ZnO)ₓ] oxynitride support; Black, Rh₀₋ₓCrₓO₃ mixed oxide NP.

Figure 3. Schematic of triphasic heterogeneous photocatalysts for photocatalytic splitting of water. Purple, [(GaN)₁₋ₓ(ZnO)ₓ] oxynitride support; Black, Rh metal core NP; Yellow, CrₓO₃ shell.
is a textural promoter that increases surface area and appears to suppress the specific photoactivity of NaTaO₃ while NiO is a potent electronic promoter. The most active surface area normalized photocatalyst under UV excitation is NiO/NaTaO₃:La reflecting the high concentration of photoactive surface sites for this photocatalyst system with a TORᵣ that is \( \sim 4 \) times greater than that for Rh\(_{2-x}\)-CrO\(_y\)/[(GaN)\(_{1-x}\)-(ZnO)\(_x\)] the most active visible light activated photocatalyst. The same surface areas for the mixed oxide Rh\(_{2-x}\)-CrO\(_y\)/[(GaN)\(_{1-x}\)-(ZnO)\(_x\)] and the core/shell CrO\(_y\)/Rh/[(GaN)\(_{1-x}\)-(ZnO)\(_x\)] do not change their relative photoactivity values whether normalized by mass or surface area. Changing the excitation from UV to visible light decreases the TORᵣ value by over an order of magnitude for Rh\(_{2-x}\)-CrO\(_y\)/[(GaN)\(_{1-x}\)-(ZnO)\(_x\)]. Normalizing the activity rates by the surface area of the Rh–Cr mixed oxide and core/shell NPs on the [(GaN)\(_{1-x}\)-(ZnO)\(_x\)] support, quantitatively determined with HS-LEIS surface analysis of the outermost surface layer, increase the TOR, NPs rates by an order of magnitude due to the smaller surface area of the Rh–Cr NPs (0.4 and 0.8 m\(^2\)/g, respectively), and indicate that TOR, NPs rates is \( \sim 3 \) times greater for the Rh–Cr mixed oxide NPs than the Rh–Cr core/ shell NPs. The above analysis demonstrates that a deeper fundamental understanding of the role of promoters (textural vs electronic) and concentration of photoactive surface sites for photocatalysts can be obtained when photocatalytic rates are also examined as TOR, rates.

Analogous to reaction rate normalization practiced in heterogeneous catalysis, the photocatalysis rates were also determined as TOF values and are reported in Table 1. Determination of TOF requires knowing the number of photoactive surface sites that are also given in Table 1. For TiO₂, the number of photoactive surface sites \( (N_s) \) was taken as the number density of surface titania sites. For the other photocatalysts, the \( N_s \) values were determined from HS-LEIS and HR-XPS surface analyses and are also indicated in Table 1. For the NaTaO₃:La photocatalyst, the photoactive surface sites are Ta and for the NiO/NaTaO₃:La, the photoactive sites are Ni because addition of the dispersed NiO increases the TOF by an order of magnitude. The number of photoactive surface sites per gram \( (N_s) \) is strongly related to the surface areas of the photocatalysts, TiO\(_2\) \( \gg \) Rh–Cr/[(GaN)\(_{1-x}\)-(ZnO)\(_x\)] > NaTaO₃:La > NaTaO\(_3\), which suggests higher surface area photocatalysts that are activated by mildly energetic radiation (low band gap values) should be pursued in future studies to design advanced photocatalysts.

It is also important to emphasize the necessity to report surface analysis data for photocatalytic studies to ensure that heterogeneous photocatalysts are clean of surface impurities.
For example, it was recently demonstrated that the high reactivity of nanocrystalline TiO\textsubscript{2} photocatalysts prepared with preferential exposure of the active (001) facet is actually related to contamination of the surface by F from the HF synthesis procedure that enhances the formation of the (001) facet.\textsuperscript{18} Thus, it is critical to assess if synthesis methods or pretreatments produce a clean surface to ensure that the photocatalysis data are indeed representative of a clean photocatalytic system and are not being masked by the presence of extraneous surface impurities.\textsuperscript{19}

Under UV activation, the TOF values vary from a low of 10\textsuperscript{−3} \text{H}_2 \text{molecules/photoactive surface site/s} to a high of ~2 \times 10\textsuperscript{6} \text{H}_2 \text{molecules/photoactive site/s}. TOF values of ~2 \times 10\textsuperscript{6}/s are indeed impressive when compared to TOF values for thermally activated heterogeneous catalysis.\textsuperscript{7} The lowest photoactivity TOF value is exhibited by TiO\textsubscript{2}, the extremely low specific photoactivity rate of TiO\textsubscript{2} further indicates the rather low photoactivity of surface Ti sites relative to surface sites present on more advanced mixed oxide and oxynitride photocatalysts. The TOF photoactivity values for the UV-activated NiO/NaTaO\textsubscript{3} and NiO/NaTaO\textsubscript{3}:La are comparable, sites present on more advanced mixed oxide and oxynitride surface Rh sites on the core/shell photocatalyst possess a factor of 3 lower than the mixed oxide Rh\textsubscript{2}−\text{CrO}_3/[(GaN)\textsubscript{1−x}(ZnO)\textsubscript{x}] photocatalyst when activated with UV radiation. Changing the excitation light from UV (290 nm) to the visible (420 nm) range decreases the specific TOF by a factor of ~10 due to excitation with less energetic photons. Although the core/shell Cr\textsubscript{2}O\textsubscript{3}/Rh/[(GaN)\textsubscript{1−x}(ZnO)\textsubscript{x}] has a greater number of surface Rh atoms than the mixed oxide Rh\textsubscript{2}−\text{CrO}_3/[(GaN)\textsubscript{1−x}(ZnO)\textsubscript{x}], the surface Rh sites on the core/shell photocatalyst possess a specific TOF value that is a factor of ~3 lower than the Rh sites on the mixed oxide photocatalyst, respectively. The lower specific photoactivity is most probably related to the presence of some surface Rh sites that are not covered by the Cr\textsubscript{2}O\textsubscript{3} shell since unpromoted Rh will perform the reverse water oxidation reaction.\textsuperscript{20} Determining the photocatalysis rates as TOF values have provided new fundamental insights about the specific rates for \text{H}_2 evolution per photoactive surface site and indicate that UV activated photocatalysts with rather impressive TOF values have already been discovered (1–2 \text{H}_2 \text{molecules/photoactive surface site/s}).

\section*{CONCLUSIONS}

The above analyses of the series of photocatalysts for water splitting demonstrate that additional fundamental bulk and surface structural-photoactivity insights can be obtained by also determining photocatalysis rates as surface area normalized TOR\textsubscript{m} and photoactive surface site normalized TOF just the commonly accepted reporting of mass normalized TOR\textsubscript{m}. The reporting of surface area normalized TOR\textsubscript{m}, values is critical to fundamentally understand the photocatalysis trends in a series of photocatalysts that are undergoing significant changes in surface area (e.g., series of TiO\textsubscript{2} and NaTaO\textsubscript{3}/NaTaO\textsubscript{3}:La). The reporting of N\textsubscript{H}_2 from application of modern cutting edge surface analyses such as HS-LEIS and HR-XPS, provides new information about the number of photoactive surface sites (e.g., Rh\textsubscript{2}−\text{CrO}_3/[(GaN)\textsubscript{1−x}(ZnO)\textsubscript{x}] and Cr\textsubscript{2}O\textsubscript{3}/Rh/[(GaN)\textsubscript{1−x}(ZnO)\textsubscript{x}]) and specific photoactivity per photoactive surface site (e.g., comparable TOF values for UV activated NiO/NaTaO\textsubscript{3}:La and Rh\textsubscript{2}−\text{CrO}_3/[(GaN)\textsubscript{1−x}(ZnO)\textsubscript{x}]). Reporting of surface analysis of photocatalysts also needs to be adopted by the photocatalysis community since extraneous impurities from the synthesis may have a significant effect on the photocatalysis and will only be known from application of surface analysis. It is proposed that the photocatalytic mass normalized TOR\textsubscript{m}, surface area normalized TOR\textsubscript{s}, and specific photoactivity site normalized TOF rates, as well as PE values, be simultaneously reported in the photocatalysis literature because of the additional fundamental insights about the roles of the bulk lattice and surface features of photocatalysts that can be gained when reporting photocatalytic reactivity as PE, TOR\textsubscript{s}, and TOF rates.

The challenges remaining for heterogeneous photocatalysis are to (i) increase the number density of photoactive surface sites, (ii) increase the specific photoactivity of the photoactive surface sites by at least an order of magnitude under visible light excitation, and (iii) discover materials with lower band gap values that will utilize a wider spectrum of the sun’s light.

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