Research article

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Recommendations for Improving Rigor and Reproducibility in Site Specific Characterization

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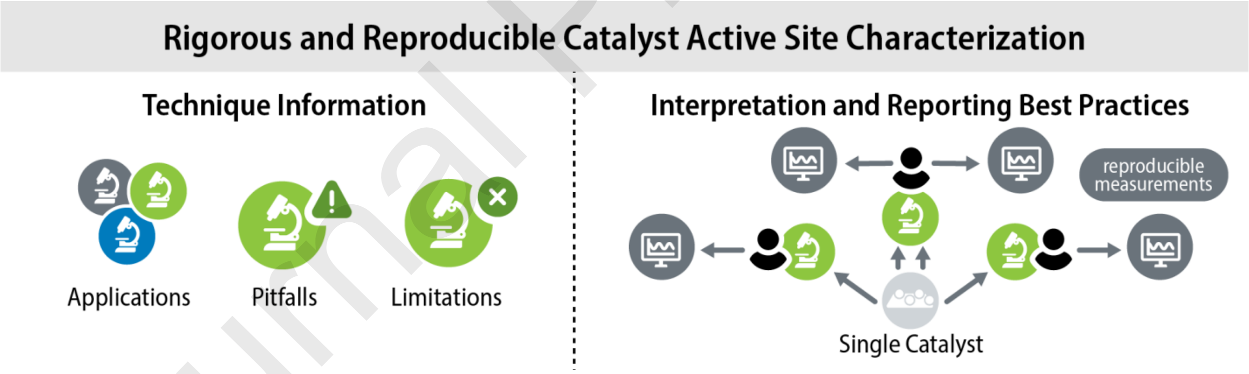

Research Highlights:

- Heterogeneous catalysis is driven by the interaction of reactant molecules and the active site.
- Numerous techniques exist to characterize the active site, each with its own applications and limitations.
- Improving rigor in characterization requires an understanding of these limitations.
- We provide an overview of these techniques and recommend reporting best practices.

Abstract

Heterogeneous catalysis is driven by the interaction of reactant molecules and the catalyst surface. The locus of this interaction as well as the surrounding ensemble of atoms is referred to as the catalyst active site. Active site characterization attempts to distinguish active catalytic sites from inactive surface sites, to elucidate the structural and chemical nature of active sites, and to quantify active site concentration. Numerous techniques have been demonstrated to provide compositional and structural information about the active sites within a catalyst. However, each technique has its own limitations and experimental pitfalls that can lead to data misinterpretation or irreproducible results. This work aims to provide an overview of the types of data that can be collected, to outline common experimental challenges and how to avoid them, and to assemble relevant references for the most used active site characterization techniques. More broadly, we aim to outline best practices for researchers to collect, interpret, and report active site characterization data in a way that provides the most benefit to the broader catalysis community. Increasing the rigor and reproducibility of active site characterization offers a strategy to better link properties with catalytic performance and to enable the community to develop consensus concerning these relationships.

1. Introduction

Heterogeneous catalysis is a dynamic process in which reactions occur between reactant molecules and adsorption sites on the catalyst surface. The adsorption site, together with the surrounding ensemble of atoms, which can include metal-support interfaces, meso- and micropores surrounding the site, support modifiers, and solvents constitute the active site for the reaction, as illustrated in Figure 1. Often, active sites make up a small portion of the catalyst surface. Catalysts may contain a collection of different active sites, each with their own characteristic activity and selectivity, which may evolve during reaction. This concept, originally formulated by Taylor, is foundational in the field of catalysis.[1]

The catalytic activity of a specific binding site may vary with the local coordination geometry or arrangement of surface atoms.[2,3] In some cases, the observed catalytic activity is dominated by a small fraction of the accessible portion of the identified catalytically active element or combination of elements. For instance, it has been shown that methanol synthesis over Cu step edges in the presence of Zn atoms is much faster than all other Cu sites.[4] Catalytic mechanisms may also rely on distinct types of active site acting in cooperation or in sequence.[5] It is therefore of great importance for catalyst researchers to not only quantify the concentration of surface sites within a catalyst, but to also understand their geometric and chemical makeup, and clearly describe how active sites are distinguished from other surface sites.

Site quantification, preferably under conditions relevant to the catalyzed reaction, allows for the calculation of reaction rates normalized by the number of active sites that catalyze a complete reaction cycle. This ratio is defined as the turnover frequency (TOF) or turnover rate.[6] Transforming catalytic performance into TOFs facilitates comparisons between catalysts and with computational reactivity predictions. Knowledge of the local structure of the active sites and normalized catalytic rates of reaction can help to provide insight into how different site types confer catalytic activity.

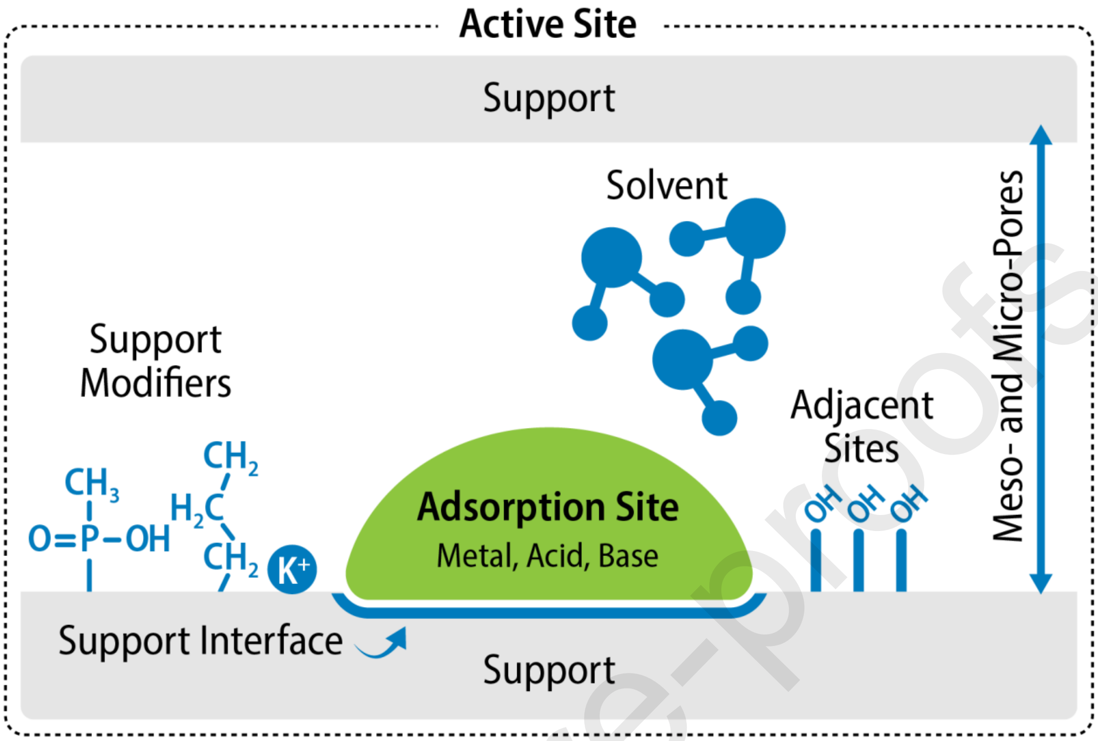

Figure 1 – Schematic demonstrating a holistic view of the catalyst components that comprise the active site.

Surface characterization techniques can be used to probe and quantify the surface sites on various catalytic materials, as opposed to bulk techniques, which average the properties of both the catalyst surface and bulk volume. In some cases, bulk techniques can become surface sensitive when the fractional exposure of the characterized sites approaches 100%. Effective characterization allows distinction between catalytic active sites from inactive surface sites when correlated with catalytic activity. Common surface site characterization techniques leverage the specific binding between a probe molecule and accessible active sites. The number of probe molecules adsorbed by a unit of the catalyst can be quantified to determine the concentration of surface sites using an assumed or determined adsorption stoichiometry. For example, CO chemisorption is a common surface characterization technique used to determine the concentration of surface metal sites present in supported metal catalysts.

In addition to quantifying the uptake of probe molecules, spectroscopic techniques can be applied to determine the state of the adsorbed probe molecule and provide more detailed information about the surface site. For example, adsorbed pyridine molecules probed by infrared spectroscopy can be used to distinguish between Lewis and Brønsted acid sites.[7] Finally, several other characterization techniques can be used in conjunction with active site models and structural assumptions to specifically probe the catalyst surface. For example, imaging of metal nanoparticles using electron microscopy provides a measure of the number of surface metal sites based on the particle size distribution and the observed projection of its physical shape.

Elucidating the structure-function relationship of a catalyst's active sites constitutes the primary objective of most fundamental catalyst research; however, it is extremely difficult to identify the operating ("true") active site. In many cases, the site can be inferred using a collection of characterization tools, but a single tool is rarely capable of characterizing the "true" active site with a high degree of certainty. Furthermore, catalyst surfaces are often dynamic under activation, reaction, and regeneration conditions, which may fundamentally alter the nature of the active site over the course of their lifecycle. [8,9]

This perspective focuses on surface site characterization. Section 2 provides an overview of common characterization techniques. The description of each technique is accompanied by a brief explanation of instances where the technique is best applied to catalyst active site characterization, references to in-depth descriptions and best practices of the technique, and precautions to take when collecting and interpreting data using a given technique. Section 3 provides a set of recommendations for reporting surface site characterization data. Finally, Section 4 discusses best practices for conducting and reporting surface site characterization to yield reproducible results. The approach of this work is described in Figure 2. This work focuses on active site characterization using common laboratory techniques and does not address synchrotron techniques such as x-ray absorption spectroscopy which are described elsewhere,[10,11] and are the topic of a similar rigor and reproducibility perspective.[12]

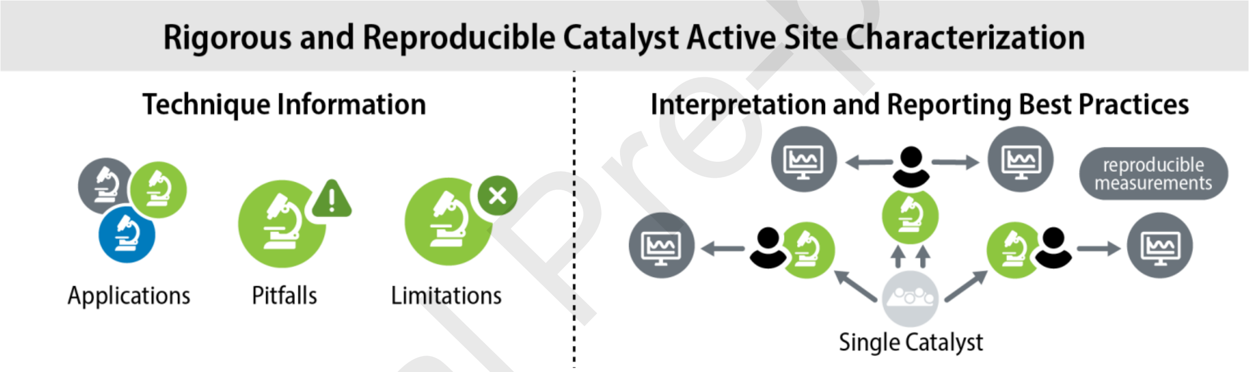

Figure 2 – Schematic depicting how this work will combine information about specific surface site characterization techniques and best practices for interpreting and reporting data to enable rigorous and reproducible catalyst active site characterization.

2. Common Surface Site Characterization Techniques

2.1 Infrared Spectroscopy (IR) of adsorbates

IR spectroscopy can be used to characterize chemical bonds. This technique is typically applied to catalysts by probing the bonds of molecules adsorbed to their surfaces. In some cases, changes in the active site structure will lead to changes in the interaction between the probe molecule and the incoming infrared radiation as demonstrated in Figure 3.

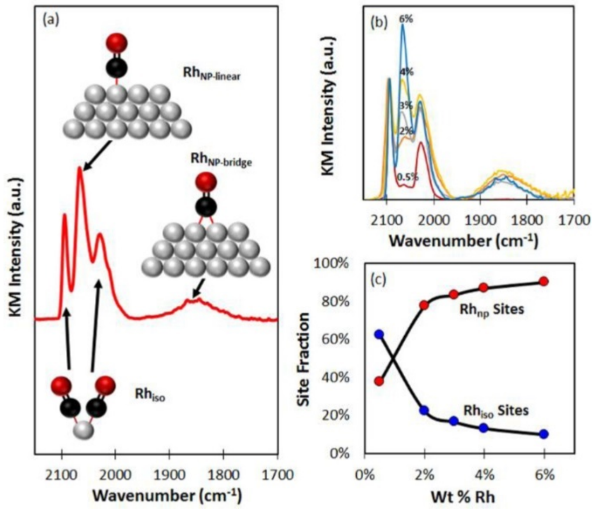

Figure 3 – IR spectroscopy of CO adsorbed onto Rh single atoms and nanoparticles supported on TiO_2. (a) IR absorbance peaks are assigned for CO adsorbed in a geminal conformation on isolated Rh atoms, CO adsorbed linearly on Rh nanoparticles, and CO adsorbed on bridged sites in Rh nanoparticles and (b,c) the relative intensity of each absorbance is tracked as a function of Rh loading. Reprinted with permission from Ref. [13] Copyright (2015) American Chemical Society.

Common Applications:

- Quantifying acid sites using the adsorption of amines or other basic probe molecules.
- Distinguishing between Brønsted and Lewis acid sites.
- Determining the distribution of probe molecule binding energies via thermal stability.
- Using adsorbed probe molecules such as CO and NO to characterize surface metal site ensemble size such as distinguishing between metal nanoparticles and single atoms.
- Quantifying relevant surface binding sites using the sorption of reactants.

Precautions to take when collecting and interpreting data:

- Adsorbate molecules may not be able to access all sites either due to steric constraints from the surface coverage, pore confinement, or steric hinderance from other adsorbed molecules.[14]
- Similar site types with different catalytic activity may not be distinguished by the probe molecule used.[15]
- Some titrants may require conditions for adsorption that are difficult to reach or maintain. For example, CO can be used to probe Lewis acid sites, but adsorption requires cryogenic temperatures (~ 100 K).
- Site quantification with IR requires accurate knowledge of extinction coefficients. Determination of extinction coefficients requires a careful calibration of the uptake concentration using volumetric or gravimetric measurements.[16] Extinction coefficients may depend on catalyst composition, catalyst particle size, and surface coverage. In bimetallic samples, intensity borrowing may result in dramatic changes to extinction coefficients relative to corresponding monometallic samples. As a result, using reported values from literature should be done with caution.

- Corrections for spectral contributions from the gas phase must be appropriately applied to interpret *operando* measurements to achieve quantitative results.[17] This can be done by measuring the gas phase spectrum of the reactor effluent.
- Operation at high pressures or temperatures requires specially designed cells.
- Diluting agents such as KBr can adsorb molecules from the environment. They should be stored in desiccators or gloveboxes. The use of such diluents may induce ion exchange processes in oxides and molecular sieves.
- Strong adsorbate-catalyst interactions, such as those observed between CO and the surface of metals can cause rearrangements, as observed in bimetallic alloys.[18]
- IR band positions depend on temperature, adsorbate surface coverage, and co-adsorption.[19,20]
- In most IR cells, the temperatures of the catalyst and the heated environment show deviations.[21]
- Cells or catalysts that are prone to react with CO to form carbonyl complexes, may result in contamination of the sample and lead to complex IR spectra.[22]
- Deconvolution protocols must be described explicitly for convoluted peaks.

References for best practices:

- General reference for diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) experiments.[23]
- Identification of metal nanoparticles and single atoms.[24]
- Selection of adsorbate molecules[25] and reactors.[26,27]
- Calculation of extinction coefficients.[16,28]

2.2 *Uptake and Temperature Programmed Reaction/Desorption (TPR/TPD) of Adsorbates*

In uptake and temperature programmed reaction/desorption, reactants or probe molecules are adsorbed onto the catalyst surface, often at temperatures below the reaction temperature of interest. The temperature of the catalyst is then steadily increased while observing the desorption or reaction products that leave the reactor as a function of temperature. With an estimated stoichiometry between the probe molecule and active site (determined, for example, gravimetrically), this technique gives the researcher an idea of the concentration of the sites within a catalyst as well as of how strongly those sites interact with the selected probe molecule.

Common Applications:

- Determining the concentration and binding energy of acid sites using amines and base sites using CO_2 adsorption.
- Quantifying metal sites using CO, H_2, and N_2O adsorption.
- Measuring adsorbate specific binding energies, potentially at varying coverages.
- Quantifying redox sites using oxygen uptake and reactivity towards H_2.
- Measuring the density of acid, base, or redox sites in oxide catalysts using alcohols and carboxylic acids.

Precautions to take when collecting and interpreting data:

- Large probe molecules may not be able to access sites within narrow pores or at constrained sites, leading to an undercounting of active sites. When feasible, parallel titration with titrants carrying the same binding function but differing kinetic diameters should be carried out to ensure the lack of steric constraints. Alternatively, probe molecules with a similar size to reactant molecules can be selected such that the same sites are accessible to both reactants and titrants.
- Care must be taken that only probe molecules are measured during desorption when using thermal conductivity detector (TCD). This can be done using traps for moisture or other desorbing molecules but may be challenging when probe molecules react to form unknown products. Mass spectrometry can also be used to identify the desorbed molecules.
- Adsorption time must be sufficient to saturate the catalyst surface.
- Pretreatment at or above the highest temperature examined is needed to ensure that the catalyst does not change over the course of the experiment.
- Probe molecules may bind at sites that are not active for catalysis. Careful consideration of measured data is needed to demonstrate that the active site of interest is the only adsorption site characterized.
- Invariance of site quantities with purge time after the adsorption step is necessary to assure that only strongly chemisorbed probe molecules are considered.[15]
- Probe molecule desorption temperatures depend on transport processes such as heat transfer or re-adsorption effects.[29] Care must be taken to avoid over-interpreting desorption peak temperatures. Multiple ramp rates can be used to ensure that data are not convoluted by heat transfer effects.[30,31]
- The concentration of adsorbed probe molecules may change based on the probe molecule partial pressure and the temperature of the adsorption step. The probe molecule of interest may not saturate the surface if its pressure is too low, or the adsorption temperature is too high. This becomes a more significant concern as the surface-adsorbate interactions become weaker. Both these variables should be carefully considered and reported accurately to allow for comparison between protocols.
- Care should be taken when choosing a desorption temperature as catalysts may react with probe molecules to form new structures. For example, Cu nanoparticles react with N_2O at high temperatures to form bulk oxides, eliminating surface sensitivity.
- Adsorbate-probe molecule stoichiometry may be unknown or may change with catalyst structure or reaction conditions. For example, CO binds with different stoichiometry to different metal surface indices and ensemble sizes.[32]
- Care should be taken if the probe molecules may form more than one monolayer on the catalyst surface. For example, O_2 adsorption on Cu nanoparticles at room temperature leads to the uptake equivalent of two to three O_2 monolayers.[33]
- TPD measurements are not able to distinguish between Bronsted and Lewis acid sites.

References for best practices:

- General protocols.[34]
- Measuring zeolite acid site density.[35,36]
- TPD in porous materials.[37,38]
- Oxygen uptake for measuring redox sites.[39]

2.3 *In-Situ Titration of Active Sites*

In this technique, a probe molecule known to adsorb strongly to the proposed active site is slowly dosed into the reactor under reaction conditions while observing the rate of the reaction of interest. As the probe molecule adsorbs and blocks active sites, the rate of the reaction decreases, allowing the researcher to determine the number of active sites as well as the distribution of catalytic activity for the active site population as shown in Figure 4.

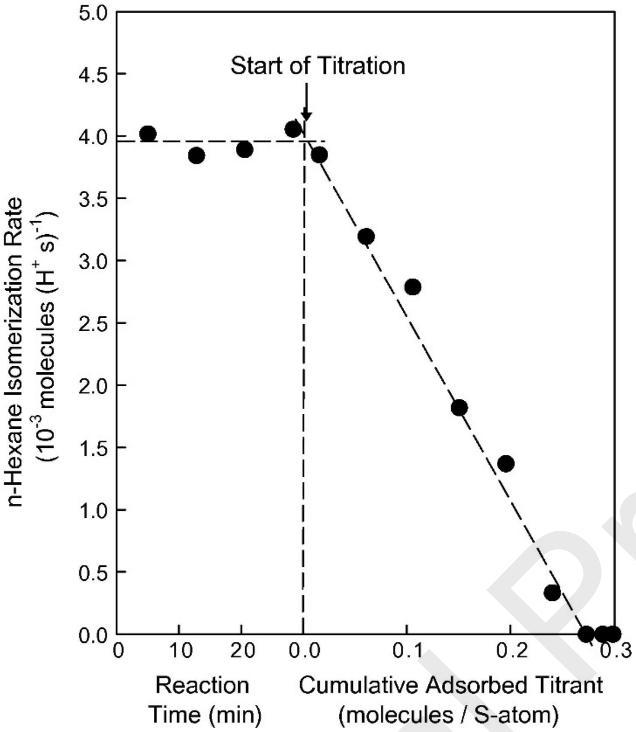

Figure 4 – Plot of the rate of n-hexane isomerization over a SO_4-ZrO_2 catalyst as a function of 2,6-di-tert-butylpyridine titrated over the catalyst. The initial four points show the steady rate of the catalyst prior to titrating the active sites. Reprinted from Ref.[40] Copyright (2009) with permission from Elsevier.

Common Applications:

- Determining the concentration of surface sites present under operating conditions.

Precautions to take when collecting and interpreting data:

- Probe molecules must be chosen based on detailed knowledge of their interactions. A good probe molecule binds quasi-irreversibly to the surface site of interest for the length of the experiment and will not interact with the reactant or product molecules. Control experiments are needed to demonstrate that the probe molecule does not also bind to inactive sites.
- If multiple types of sites (with different intrinsic activity) are present, the kinetic titration curve may not be linear. For instance, the slope of the titration curve can be higher at low titrant coverage if the more active sites are preferentially titrated.[41]
- Relationships between titrant coverage and the measured reaction rate can provide insight into the uniformity of active site catalytic activity. During transient titration measurements (when the

titrant is added to a catalyst bed of finite depth) concentration gradients may result in adsorption first to sites upstream of concentration fronts rather than those that bind the titrant strongest. Therefore, conducting titration experiments under various partial pressures could provide more information regarding site uniformity if different active sites bind the titrant under distinct pressure regimes. However, it is necessary to understand whether titrant binding is reversible or irreversible.
- Interpretation of kinetic titrations in terms of several active sites requires assumptions regarding the stoichiometry between the titrant and the active site, as well as the relative poisoning strength of the titrant. These assumptions should be clearly articulated.

References for best practices:

- Using propionic acid to quantify the number of Lewis acid-base pairs in oxides during aldol condensation.[42]
- Using 2,6-di-tert-butylpyridine (2,6-DTBP) to quantify the number of acid sites in polyoxometallates during alkane isomerization[43] and zeolites[44] during acetone condensation. 2,6-DTBP is selective for Brønsted acid sites in catalysts with both Brønsted and Lewis acid sites such as supported WO_x.[45]
- Using pyridine and acetonitrile to quantify the concentration of Lewis acid sites.[15,46]
- Using NO to quantify the number of redox Fe active sites.[47]

2.4 H_2/D_2 Scrambling

In H_2/D_2 scrambling experiments, researchers co-feed H_2 and D_2 over the catalyst and observe the production of HD. Increased production of HD indicates an increased concentration of metal active sites capable of dissociating H_2 and D_2.

Common Applications:

- Determining supported metal dispersion, especially in catalysts with low metal loadings.
- Quantification of Brønsted acid site density.

Precautions to take when collecting and interpreting data:

- The reaction between H_2 and D_2 is best regarded as an approach to equilibrium whose equilibrium constant is particularly sensitive to temperature. Control experiments must be performed to determine the equilibrium conversion under the specific conditions of the experiment prior to conducting site quantification experiments. Subsequently, measurements of HD rates should be conducted at D_2 conversions below the equilibrium conversion to avoid HD consumption in the reverse reaction. Alternatively, kinetic treatments describing the approach to equilibrium are also appropriate.
- To estimate apparent dispersion values, H_2/D_2 exchange rates must be measured at the same D_2 conversion for a control material with known dispersion to avoid overestimation of active sites.

References for best practices:

- An example protocol for H_2/D_2 scrambling over metal catalysts.[48]
- Protocol for determining Brønsted acid site density using H_2/D_2 exchange.[49]

2.5 Solid-State Nuclear Magnetic Resonance (NMR) Spectroscopy

NMR spectroscopy measures how atoms with non-zero nuclear spins interact with an external magnetic field. This can be leveraged to characterize solid catalysts by either probing specific elements within the catalyst itself or by probing elements within molecules adsorbed to sites on the catalyst surface.

Common Applications:

- Determining the concentrations of Brønsted and Lewis acid sites using trimethylphosphine.
- Quantifying the strengths of Brønsted and Lewis acid sites using trimethylphosphine oxide and trimethylphosphine, respectively.
- Understanding the location of acid sites within catalysts using probe molecules of different sizes such as trimethylphosphine and trioctylphosphine.
- Determining the oxidation and bonding state of metal atoms within zeolites.

Precautions to take when collecting and interpreting data:

- NMR measurements are very sensitive to the degree of sample hydration and oxidation. Exposure of samples to ambient conditions will alter NMR results and may also degrade probe molecules such as trimethylphosphine. Catalysts should be dried, handled in a glovebox, processed using dry solvents, and transferred in NMR tubes with air-tight seals.
- NMR measurement programs and data interpretation techniques vary between different elements and environments. Techniques that work for collecting spectra for one element or in solution will not necessarily translate to other elements or solid-state materials.
- When using probe molecules to quantify sites, care should be taken to ensure that sufficient probe molecules are provided to titrate all sites of interest. However, it is also important not to provide too much probe molecule to avoid obscuring the signal of interest with signal from unbound probe molecule. This requires first calculating an estimate for the concentration of sites of interest in a catalyst sample and then supplying a small excess (2 to 5 times excess) of probe molecule, or using treatments to remove excess probe molecules while leaving bound probe molecules attached to active sites. Several different probe molecule levels should be tested to demonstrate that all sites of interest are titrated.
- Binding stoichiometry and location in zeolites can influence the chemical shifts of trimethylphosphine oxide.[50]
- When using NMR measurements to quantitatively measure surface sites, standard materials should be tested to demonstrate that all experimental parameters are set properly to allow for accurate quantification.
- Some probe molecules commonly used such as trimethylphosphine are pyrophoric and toxic and must be handled with care. Note that trimethylphosphine can readily undergo oxidation into trimethylphosphine oxide, potentially causing erroneous results.

References for best practice:

- General NMR information.[51]
- Acid site characterization with NMR.[52,53]
- NMR characterization of metals.[54]

2.6 Catalytic probe reactions

Catalytic sites can be quantified, and materials can be compared under relevant conditions using reactions known to be catalyzed by the active site of interest. Claims of the identity of the active site can be strengthened by demonstrating that the rate of the probe reaction scales linearly with the concentration of the site of interest in the catalyst as demonstrated in Figure 5.

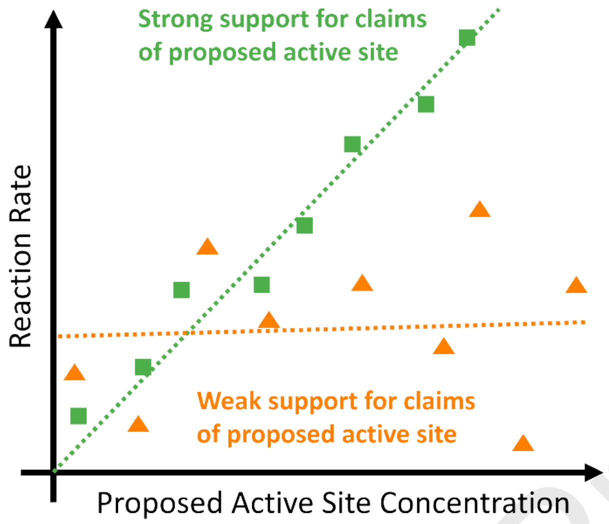

Figure 5 – Hypothetical plot of probe reaction rate versus the concentration of the proposed active site. A linear relationship between the reaction rate and the active site concentration (green) is strong evidence that the proposed active site catalyzes the probe reaction while weak correlation between the reaction rate and the proposed active site concentration (orange) undermines active site identification claims.

Common Applications:

- Determining the acid, base, or redox character of oxide materials.
- Probing the oxidation state of sites using CO oxidation.

Precautions to take when collecting and interpreting data:

- Ensure that reactions are run in the differential regime to minimize secondary reactions and to ensure that there are no transport limitations within the catalyst pellet and the reactor.[55] Differential kinetics require cofeeding of product molecules when they are strongly inhibiting.[56]
- Large probe reactants may be unable to reach sites within porous materials. Ensure that diffusional limitations do not limit the overall rates.[57]
- Ensure that catalysts do not lose sites due to deactivation through processes such as sintering or coking while collecting information from the probe reaction.
- Use probe reactions that involve only the same sites as the reaction of interest.
- Understand the proximity Brønsted acid sites within the material being probed. The rate of alkane cracking can be influenced by the proximity of Brønsted acid sites,[58] but in cases where

their distributions are similar or are in the dilute limit, rates have been directly correlated with active site density.[59]

References for best practices:

- Oxide probing with methanol,[60] and amines.[61]
- CO oxidation.[62]
- Alkane cracking.[58]
- Alcohol dehydration and alkane isomerization.[40]

2.7 Raman Spectroscopy

Raman Spectroscopy probes the vibrational modes of a material. This information can be used to determine the structure of a catalyst as well as the presence of adsorbates on the surface of a catalyst.

Common Applications:

- Determining the coverage, oxidation state, and coordination of supported oxides.

Precautions to take when collecting and interpreting data:

- The absorption frequency associated with surface groups can be coverage, moisture, and support dependent. It is therefore important to dehydrate catalysts before experiments.
- Raman lasers may cause local sample heating, which can alter the catalyst or adsorbate. Care should be taken to avoid local heating by using large spot sizes, low laser intensities, moving the sample, or using a fluidized catalyst bed. Control experiments should be conducted to demonstrate that heating effects are not an issue.
- Material impurities or defects can fluoresce at energies similar to the energies of interest in a specific sample. Care should be taken to choose laser wavelengths that produce Raman shifts away from fluorescent signals. Time gating detection methods can be used to increase detector selectivity for faster Raman lifetimes over longer fluorescence lifetimes.
- Signal for surface layers and species can be as much as 10^5 times weaker than bulk signal. Techniques aimed to enhance Raman responses from specific groups such as Resonance Raman are helpful to increase the signal from surface groups of interest.

References for best practices:

- General information.[63]
- Supported metal oxides.[64]
- Resonance Raman, Surface Enhanced Raman, and Tip Enhanced Raman.[65,66]
- Local heating effects in Raman spectroscopy.[67]
- Raman spectrokinetics.[68]

2.8 Transmission Electron Microscopy (TEM)

TEM allows for the imaging of small areas of a catalyst's surface using its interactions with a beam of electrons. The contrast of the collected images is dependent on the atomic number of the materials being imaged. TEM can be paired with other spectroscopic techniques such as energy-dispersive X-ray spectroscopy (EDS) to allow for visualization of the distribution of elements within an image as demonstrated by Figure 6.

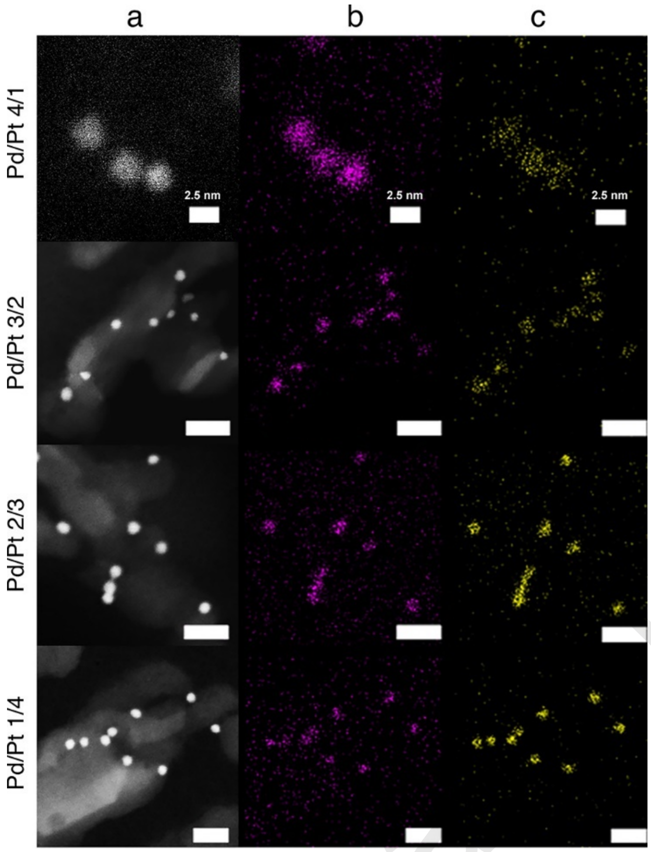

Figure 6 – (a) High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images of Pd/Pt nanoparticles supported on Al_2O_3. EDS mapping of (b) Pd and (c) Pt demonstrate the co-location of both elements within the nanoparticles. Reprinted with permission from Ref.[69] Copyright (2017) American Chemical Society

Common Applications:

- Imaging supported metal nanoparticles, clusters, and single atoms.
- Elemental analysis and elemental mapping of selected catalyst areas when paired with EDS or electron energy loss spectroscopy (EELS).
- Analysis of the catalyst nanostructure using diffraction techniques and catalyst electronic structure using electron spectroscopy.
- Estimation of metal dispersion based on nanoparticle size distribution with an estimated average geometric shape.[70]

Precautions to take when collecting and interpreting data:

- TEM produces projections of a small fraction of the total catalyst surface and may not be able to consistently image small nanoparticles or single atoms over the entire sample. Therefore, images may be biased towards the most easily imaged nanoparticles and may not be representative of the entire catalyst. Stronger claims can be made by imaging several different areas and discussing differences between the images. Even stronger claims can be made by correlating image statistics with appropriate bulk and surface characterization techniques.
- The high energy electron beam may alter the catalyst during the measurement. Time-dependent control experiments must be performed for assessing beam damage effects. Measurements in environmental TEMs are also possible to probe differences between changes caused by process conditions and beam effects.
- Images project 3D materials onto 2D planes and may not be able to distinguish between surface and encapsulated nanoparticles. TEM should be used in combination with size dependent probe reactions or surface spectroscopy to demonstrate encapsulation.[71,72]

References for best practices:

- Reporting nanoparticle sizes and distributions.[73,74]
- Applications in catalysis.[11,75]
- *In Situ* electron microscopy.[76]

Table 1 – Description of which sites can be characterized with each of the techniques listed above. Example probe molecules for each relevant technique/site pair are listed in parentheses.

Technique	Metal Sites	Acid Sites	Base Sites	Redox Sites
IR Spectroscopy	Yes (CO)	Yes (Pyridine)	Yes (CO_2)	Yes
TPD	Yes (CO)	Yes (Ammonia)	Yes (CO_2)	Yes (O_2/H_2)
H_2/D_2 Scrambling	Yes	Yes		
In situ Titration		Yes (2,6-di-tert-butylpyridine)	Yes (Propanoic acid)	Yes (NO)
Solid-State NMR Spectroscopy	Yes (Zn, Ga, Mo only)	Yes (trimethylphosphine)		Yes (trimethylphosphine)
Probe Reactions	Yes (CO oxidation)	Yes (Alkane cracking)	Yes (Methanol oxidation)	Yes (Methanol oxidation)

Raman Spectroscopy				Yes
TEM	Yes			

3 Recommendations for Reporting Active Site Characterization

Surface site characterization techniques involve many parameters and assumptions that can dramatically impact their results. To ensure reproducibility, we encourage reporting experimental procedures and assumptions in as much detail as possible and to provide access to raw characterization data.[77,78] The availability of this information will allow for the identification of measurement steps or assumptions that could skew surface site characterization data. Detailed protocols will also be useful for the consistent characterization of catalysts reproduced in other laboratories as well as newly developed catalysts with similar surface sites.

Detailed experimental protocols are critical for reproducing active site characterization measurements and include aspects such as:

1. Instrument specifications, such as the detector or spectrometer used.
2. Instrument settings such as electron beam energy or laser wavelength.
3. Experimental details such as gas flow rate, temperature ramp rate, and quantities of materials used.
4. Catalyst history information such as pretreatment and storage history.
5. The purity and source of reagents used such as gas impurity levels.
6. Instrument calibration protocols such as alignment and baselining.
7. Blank or control experiments performed and their results such as signal produced by bare support.
8. The reproducibility of measurements and their uncertainty.
9. Details of data processing protocol such as baseline corrections, normalization, and curve smoothing as well as the software and equations used.

Table 2 provides two sample descriptions of the same experiment to highlight the depth of information necessary to accurately reproduce an active site characterization experiment. While lengthy, the details described in the effective description will enable future researchers to reproduce current work, extend the techniques to new systems, and identify measurement details that could influence final conclusions. These details need not be included in the main text of future publications but should be included in methods or supplemental information sections in their entirety to highlight where the applied methods may deviate from methods in the literature and to spare readers the task of following citation chains to find a desired protocol.

Table 2 – Samples of poor and effective descriptions of a hypothetical ammonia temperature programmed desorption (TPD) experiment.

Poor Description	Effective Description
Following oxidation of the catalyst, acid sites were probed with ammonia	After synthesis, all catalysts were stored in a solvent-free nitrogen glovebox until needed. Acid sites were characterized using an Altamira AMI-390 microflow reactor system equipped with a thermal conductivity detector (TCD). 100 mg of catalyst were loaded into a quartz U-tube (d = 0.5 in.) reactor and held between plugs of quartz

temperature programmed desorption.	wool with a thermocouple inserted into the catalyst bed. Samples were heated under 50 mL/min 10% O_2/He (certified mixture, Airgas) to 723 K at 5 K/min and held at that temperature for 2 hours. The samples were then cooled to 393 K under 50 mL/min He (99.999%, Airgas) before saturating with 10% NH_3/He (certified mixture, Airgas) for 30 minutes. Excess NH_3 was removed by flowing 50 mL/min He at 393K for one hour. Temperature programmed desorption of NH_3 was performed by heating the sample from 393 to 723 K at 30 K/min and holding it at 723 K for 30 minutes in 50 mL/min He. All gases were passed through a water trap (molecular sieve 5A, Thermo Scientific) prior to entering the system. The TCD was calibrated before each experiment by measuring 10 pulses of 10% NH_3/He from a 5 mL sample loop. A blank experiment was conducted for comparison with 50 mL/min He passed over the catalyst instead of 10% NH_3/He to demonstrate that all TCD signal was produced by NH_3. All results were benchmarked to the NH_3 uptake by a silica-alumina with a known acid site density. Measurements were conducted in triplicate. All reported values are the average of the three measurements with their associated standard deviation.

We also recommend that researchers report all assumptions made when interpreting surface site characterization data, such as the adsorbate to surface site stoichiometry or the shape of nanoparticles used to model electron microscopy data. For example, increasing the assumed stoichiometry of CO on metal sites from one CO molecule per surface metal atom to two CO molecules per surface metal atom would decrease the number of measured metal sites by half for a given measured CO uptake, comparably changing calculated reaction rates by a factor of two. Common assumptions made when interpreting surface site characterization data include:

- Stoichiometry of adsorbates on active sites.
- Metal nanoparticle shape when extracting the number of sites from TEM images.
- The number of different active site populations expected and which of them are probed by the titrant of interest. For example, is it assumed that all active sites have the same activity or are there more and less active site populations being probed?

These assumptions, while often reasonable and standard, play a key role in determining the calculated surface site concentration and speciation, and therefore should be articulated to allow for reproduction and reinterpretation of the reported findings. Similarly, we recommend that authors clearly demonstrate how TOF values were calculated from experimental results and how experimental error was propagated through the calculations. This will allow for more robust comparison of TOF values throughout the literature, placing new work into proper context of previous studies.

Beyond experimental details, including raw, unprocessed characterization data in the supplementary files of a published work is encouraged. This will allow other researchers to re-process data using different assumptions should the state of the technology change, or new interpretations of the nature of an active site arise. For example, supplementary files could include raw output signals from temperature programmed desorption profiles as a table of signal versus temperature readings, along with the relevant calibration information. This information could help future researchers identify similarities in desorption behavior of reproduced or newly synthesized materials. The collection of surface characterization data in a single repository may also enable future insights through the application of data science techniques across many data sets.[79,80]

4 Best Practices in Active Site Characterization

The overall objective of active site characterization is to correlate active site concentration with reactivity data, preferably under differential reaction conditions with the aim of establishing a physically meaningful metric of site activity. In some cases, multiple surface sites, such as metal corner sites and metal-support interface sites, may similarly correlate with reactivity data, making unambiguous determination of “the” active site difficult. Active site interpretations are always subject to reevaluation in the context of future data; understanding and acknowledging this reality will increase the long-term importance of any given study.[81]

While the techniques to measure heterogeneous catalyst surface sites may vary, there are several universal steps researchers can take to increase the strength of claims made based on surface site characterization measurements.

4.1 Clearly demonstrate trends in methodology

First, we encourage researchers to synthesize and characterize catalysts in which the surface concentration of potential active sites is intentionally varied, allowing changes in activity with the change in surface site concentration to be correlated. This procedure provides the strongest evidence for inferring that a particular surface site is the catalytic active site. For example, when characterizing metal active sites using CO chemisorption, synthesizing and characterizing catalysts with a series of metal loadings enables the assessment of the relationship between the concentration of surface sites and the metal loading. Showing a linear correlation between the concentration of metal surface sites and the catalytic activity would then suggest that those metal sites, or a subset of the total metal sites, are the catalytic active site.

Several groups have demonstrated how coupling reaction kinetics with intentional variation of metal nanoparticle size and loading can enable the identification of specific active sites on the metals themselves.[82–84] For example, researchers have varied the size of Pt, Pd, and Ni nanoparticles on CeO_2 to control the number of metal sites and shown that CO combustion rates scale closely with number of metal-interface sites. This result suggests that the interfacial sites are responsible for the catalytic activity as shown in Figure 7.[82] Characterizing a series of catalysts with changing surface site concentrations, particularly when other factors such as particle size remain constant, will support claims that the intentionally varied surface site is responsible for the observed catalysis.

If the catalyst of interest is a new formulation that has not been extensively characterized and reported previously in the literature, researchers are encouraged to benchmark their characterization techniques with a similar known material. This benchmarking demonstrates that the new characterization protocol reproduces previous results. For example, when characterizing a new acidic catalyst using NH_3 TPD, researchers are encouraged to also characterize a standard material with known properties to demonstrate that the characterization technique is appropriate for the desired materials.

In addition to comparing characterization results to benchmark materials, combining several characterization techniques improves understanding of the surface sites present and benefits discussions of specific catalyst active sites. Besides corroborating catalyst surface site quantification, using multiple techniques may enable a more nuanced discussion of the different types of surface sites within the catalyst and aid in correlating reactivity data to subsets of surface sites.[85] Time resolved techniques such as modulation excitation, common in infrared spectroscopy, can be used to provide additional information about which surface sites participate in the catalysis.[86] Researchers may also consider combining their experimental characterization results with theoretical models to bolster claims of the active site identity. For example, *in situ* DRIFTS spectroscopy and density functional theory (DFT) modeling have been combined to suggest that the active site for CO oxidation on model Au/TiO$_2$ catalysts is the interface between the metal nanoparticle and the oxide support. This was achieved by observing the sites where CO is consumed and modeling a potential site and mechanism for O$_2$ dissociation.[87]

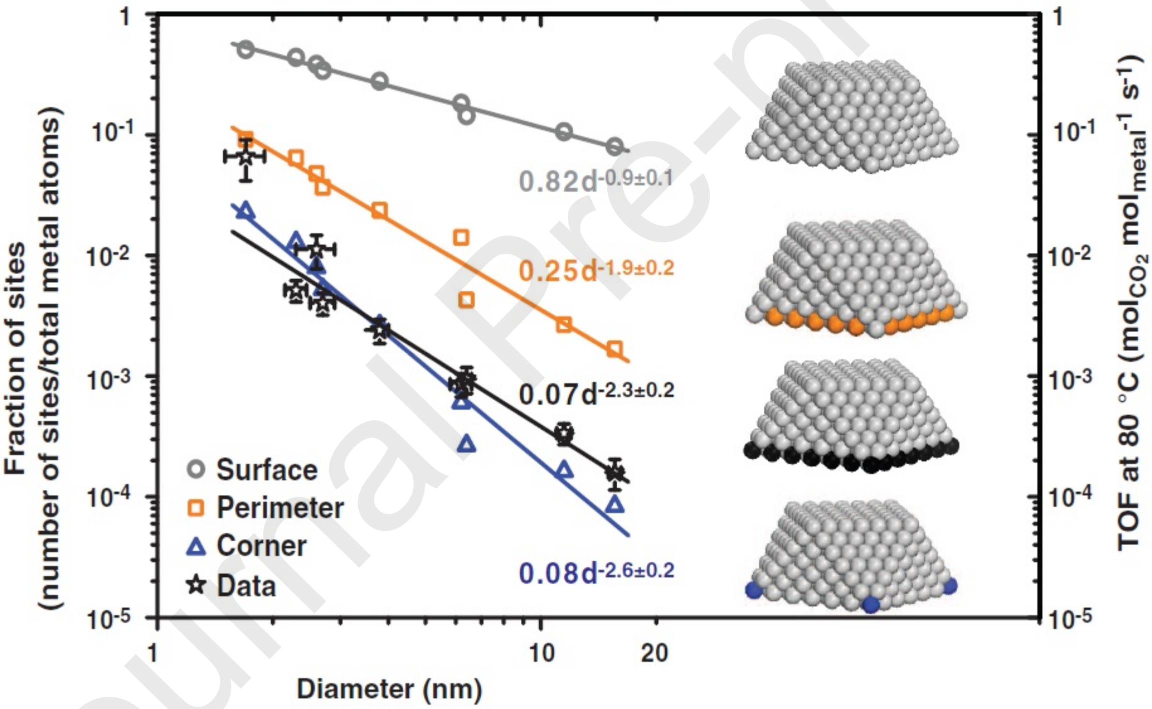

Figure 7 – Comparison of the fraction of corner (blue), metal-support perimeter (orange), and metal surface (gray) sites amongst all metal atoms in a nanoparticle as a function of nanoparticle size to CO oxidation TOF (black) of Pd, Pt, and Ni nanoparticles on CeO$_2$. From Ref.[82] Reprinted with permission from AAAS.

4.2 Compare characterization results to synthetic expectations and other results

Once a surface site concentration has been determined from catalyst characterization data, we encourage researchers to discuss how it corresponds to the expected concentration of surface sites based on the catalyst synthesis protocol. For example, how does the uptake of CO onto a supported metal catalyst compare with the amount of metal in the catalyst system? These discussions are important for understanding the state of the catalyst, which may be quite different from the proposed form based on the catalyst synthesis. This provides a simple check to determine the reliability of characterization results. For instance, site quantities that significantly exceed bulk metal contents are an indicator of unselective titrant adsorption. Furthermore, differences between complementary techniques or between experiment and theoretical calculations should be explained. We recommend that any discrepancies from synthetic expectations or other experiments be discussed to make the strongest claims about a catalyst's activity.

4.3 Consider catalyst operating conditions

We also encourage researchers to consider the catalyst operating conditions while characterizing its surface sites, as the number and nature of surface sites can change based on reaction parameters such as temperature, pressure, or gas/liquid composition. Several techniques such as electron microscopy can be operated under conditions similar to reaction conditions and can strengthen claims about the working form of a catalyst.[88] For example, past work has demonstrated the ability to observe metal sites using X-ray photoelectron spectroscopy under model reaction conditions (*in situ*) and to track the occlusion of those metal sites due to strong metal support interactions.[89] Others have reported the titration of catalyst acid sites under reaction conditions while tracking product formation (*operando*).[90] In cases where *in situ* or *operando* characterization is not possible, we recommend that catalysts be characterized with the same technique before and after reaction to identify any irreversible changes that may have occurred during reaction. While this approach will not capture all changes that may have occurred during operation, it will strengthen claims about the identity of the active site and normalized reaction rates.

4.4 Align the level of active site claims to rigor of characterization performed

Above all, we encourage researchers to align the level of their catalytic claims with the rigor of the surface site characterization and reactivity data on which those claims are based. For example, some surface site characterization techniques may not distinguish between unique site geometries. In those cases, we recommend that researchers report an average site activity, acknowledging that different site types may have different individual activities. Authors are also encouraged to discuss the detection limits of the techniques they apply. This will allow for comparisons between various experimental results, enable discussions of measurement uncertainty, and contextualize the catalytic activity of materials thought to be devoid of the active site of interest. Overall, it is important that the researcher, editors, and reviewers ensure that claims are in line with the information supplied by the characterization technique to avoid misinterpretation by future readers.

5 Conclusion

The concept of the active site lies at the foundation of heterogeneous catalysis. Our community has developed many techniques enabling both the characterization and quantification of active sites in many, but not all, circumstances. Each technique yields unique information and entails critical considerations for accurate data collection and interpretation. When combined with kinetic data, characterization results allow for linking active site properties to the catalytic action.

In this perspective, we have collected common pitfalls encountered in the use of some of the most common active site characterization techniques, and have provided best practice recommendations for researchers, reviewers, and editors to encourage more careful and reproducible active site characterization and reporting. The recommendations of this perspective aim to serve as a resource for new researchers in the field and as a guide to producing high quality data that will accelerate future catalyst research and discovery.

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References

[1] H.S. Taylor, E.F. Armstrong, A theory of the catalytic surface, Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character 108 (1925) 105–111. https://doi.org/10.1098/rspa.1925.0061.

[2] K. Honkala, A. Hellman, I.N. Remediakis, A. Logadottir, A. Carlsson, S. Dahl, C.H. Christensen, J.K. Nørskov, Ammonia Synthesis from First-Principles Calculations, Science 307 (2005) 555–558. https://doi.org/10.1126/science.1106435.

[3] C. Vogt, B.M. Weckhuysen, The concept of active site in heterogeneous catalysis, Nat Rev Chem 6 (2022) 89–111. https://doi.org/10.1038/s41570-021-00340-y.

[4] M. Behrens, F. Studt, I. Kasatkin, S. Kühl, M. Hävecker, F. Abild-Pedersen, S. Zander, F. Girgsdies, P. Kurr, B.-L. Kniep, M. Tovar, R.W. Fischer, J.K. Nørskov, R. Schlögl, The Active Site of Methanol Synthesis over Cu/ZnO/Al_2O_3 Industrial Catalysts, Science 336 (2012) 893–897. https://doi.org/10.1126/science.1219831.

[5] C.J. Wrasman, A.R. Riscoe, H. Lee, M. Cargnello, Dilute Pd/Au Alloys Replace Au/TiO_2 Interface for Selective Oxidation Reactions, ACS Catal. 10 (2020) 1716–1720. https://doi.org/10.1021/acscatal.9b05227.

[6] M. Boudart, Turnover Rates in Heterogeneous Catalysis, Chem. Rev. 95 (1995) 661–666. https://doi.org/10.1021/cr00035a009.

[7] E.P. Parry, An infrared study of pyridine adsorbed on acidic solids. Characterization of surface acidity, Journal of Catalysis 2 (1963) 371–379. https://doi.org/10.1016/0021-9517(63)90102-7.

[8] A.J. Martín, S. Mitchell, C. Mondelli, S. Jaydev, J. Pérez-Ramírez, Unifying views on catalyst deactivation, Nat Catal 5 (2022) 854–866. https://doi.org/10.1038/s41929-022-00842-y.

[9] J. Dou, Z. Sun, A. A. Opalade, N. Wang, W. Fu, Franklin (Feng) Tao, Operando chemistry of catalyst surfaces during catalysis, Chemical Society Reviews 46 (2017) 2001–2027. https://doi.org/10.1039/C6CS00931J.

[10] Y. Iwasawa, K. Asakura, M. Tada, eds., XAFS Techniques for Catalysts, Nanomaterials, and Surfaces, Springer International Publishing, Cham, 2017. https://doi.org/10.1007/978-3-319-43866-5.

[11] ed. Neil M Schweitzer, ed. Rajamani Gounder, ed. Robert M Rioux, Addressing Rigor and Reproducibility in Thermal, Heterogeneous Catalysis, Zenodo, 2023. https://doi.org/10.5281/zenodo.8029159.

[12] R.J. Meyer, S.R. Bare, G.A. Canning, J.G. Chen, P.M. Chu, A.S. Hock, A.S. Hoffman, A.M. Karim, S.D. Kelly, Y. Lei, E. Stavitski, C.J. Wrasman, Recommendations to standardize reporting, execution, and interpretation of X-ray Absorption Spectroscopy measurements, Journal of Catalysis (2024) 115369. https://doi.org/10.1016/j.jcat.2024.115369.

[13] J.C. Matsubu, V.N. Yang, P. Christopher, Isolated Metal Active Site Concentration and Stability Control Catalytic CO2 Reduction Selectivity, J. Am. Chem. Soc. 137 (2015) 3076–3084. https://doi.org/10.1021/ja5128133.

[14] J.W. Harris, W.-C. Liao, J.R. Di Iorio, A.M. Henry, T.-C. Ong, A. Comas-Vives, C. Copéret, R. Gounder, Molecular Structure and Confining Environment of Sn Sites in Single-Site Chabazite Zeolites, Chem. Mater. 29 (2017) 8824–8837. https://doi.org/10.1021/acs.chemmater.7b03209.

[15] J.W. Harris, M.J. Cordon, J.R. Di Iorio, J.C. Vega-Vila, F.H. Ribeiro, R. Gounder, Titration and quantification of open and closed Lewis acid sites in Sn-Beta zeolites that catalyze glucose isomerization, Journal of Catalysis 335 (2016) 141–154. https://doi.org/10.1016/j.jcat.2015.12.024.

[16] V. Zholobenko, C. Freitas, M. Jendrlin, P. Bazin, A. Travert, F. Thibault-Starzyk, Probing the acid sites of zeolites with pyridine: Quantitative AGIR measurements of the molar absorption coefficients, Journal of Catalysis 385 (2020) 52–60. https://doi.org/10.1016/j.jcat.2020.03.003.

[17] F.C. Meunier, In situ FT-IR spectroscopy investigations of dimethyl carbonate synthesis: on the contribution of gas-phase species, RSC Adv. 6 (2016) 17288–17289. https://doi.org/10.1039/C4RA15157G.

[18] Y. Yao, D.W. Goodman, In situ IR spectroscopic studies of Ni surface segregation induced by CO adsorption on Cu–Ni/SiO2 bimetallic catalysts, Phys. Chem. Chem. Phys. 16 (2014) 3823. https://doi.org/10.1039/c3cp54997f.

[19] R. Carrasquillo-Flores, I. Ro, M.D. Kumbhalkar, S. Burt, C.A. Carrero, A.C. Alba-Rubio, J.T. Miller, I. Hermans, G.W. Huber, J.A. Dumesic, Reverse Water–Gas Shift on Interfacial Sites Formed by Deposition of Oxidized Molybdenum Moieties onto Gold Nanoparticles, J. Am. Chem. Soc. 137 (2015) 10317–10325. https://doi.org/10.1021/jacs.5b05945.

[20] J.S. Bates, B.C. Bukowski, J.W. Harris, J. Greeley, R. Gounder, Distinct Catalytic Reactivity of Sn Substituted in Framework Locations and at Defect Grain Boundaries in Sn-Zeolites, ACS Catal. 9 (2019) 6146–6168. https://doi.org/10.1021/acscatal.9b01123.

[21] H. Li, M. Rivallan, F. Thibault-Starzyk, A. Travert, F.C. Meunier, Effective bulk and surface temperatures of the catalyst bed of FT-IR cells used for in situ and operando studies, Phys. Chem. Chem. Phys. 15 (2013) 7321. https://doi.org/10.1039/c3cp50442e.

[22] F.C. Meunier, On the contamination with nickel and nickel tetracarbonyl during FT-IR investigation of catalysts under CO-containing gases, Journal of Catalysis 372 (2019) 388. https://doi.org/10.1016/j.jcat.2019.03.006.

[23] F.C. Meunier, Pitfalls and benefits of in situ and operando diffuse reflectance FT-IR spectroscopy (DRIFTS) applied to catalytic reactions, React. Chem. Eng. 1 (2016) 134–141. https://doi.org/10.1039/C5RE00018A.

[24] F.C. Meunier, Relevance of IR Spectroscopy of Adsorbed CO for the Characterization of Heterogeneous Catalysts Containing Isolated Atoms, J. Phys. Chem. C 125 (2021) 21810–21823. https://doi.org/10.1021/acs.jpcc.1c06784.

[25] J.A. Lercher, C. Gründling, G. Eder-Mirth, Infrared studies of the surface acidity of oxides and zeolites using adsorbed probe molecules, Catalysis Today 27 (1996) 353–376. https://doi.org/10.1016/0920-5861(95)00248-0.

[26] J. Ryczkowski, IR spectroscopy in catalysis, Catalysis Today 68 (2001) 263–381. https://doi.org/10.1016/S0920-5861(01)00334-0.

[27] F.C. Meunier, A. Goguet, S. Shekhtman, D. Rooney, H. Daly, A modified commercial DRIFTS cell for kinetically relevant operando studies of heterogeneous catalytic reactions, Applied Catalysis A: General 340 (2008) 196–202. https://doi.org/10.1016/j.apcata.2008.02.034.

[28] J. Sirita, S. Phanichphant, F.C. Meunier, Quantitative Analysis of Adsorbate Concentrations by Diffuse Reflectance FT-IR, Anal. Chem. 79 (2007) 3912–3918. https://doi.org/10.1021/ac0702802.

[29] R.J. Gorte, Temperature-programmed desorption for the characterization of oxide catalysts, Catalysis Today 28 (1996) 405–414. https://doi.org/10.1016/S0920-5861(96)00249-0.

[30] T. Ioannides, Effects of degree of mixing on quantitative interpretation of TPD spectra, Journal of Catalysis 120 (1989) 157–169. https://doi.org/10.1016/0021-9517(89)90257-1.

[31] J.M. Kanervo, S. Kouva, K.J. Kanervo, R. Kolvenbach, A. Jentys, J.A. Lercher, Prerequisites for kinetic modeling of TPD data of porous catalysts—Exemplified by toluene/H-ZSM-5 system, Chemical Engineering Science 137 (2015) 807–815. https://doi.org/10.1016/j.ces.2015.07.032.

[32] S. Ladas, The effect of metal particle size on the stoichiometry of adsorption, Surface Science 175 (1986) L681–L686. https://doi.org/10.1016/0039-6028(86)90074-9.

[33] E. Iglesia, M. Boudart, Decomposition of formic acid on copper, nickel, and copper-nickel alloys: I. Preparation and characterization of catalysts, Journal of Catalysis 81 (1983) 204–213. https://doi.org/10.1016/0021-9517(83)90158-6.

[34] J.L. Falconer, J.A. Schwarz, Temperature-Programmed Desorption and Reaction: Applications to Supported Catalysts, Catalysis Reviews 25 (1983) 141–227. https://doi.org/10.1080/01614948308079666.

[35] W.E. Farneth, R.J. Gorte, Methods for Characterizing Zeolite Acidity, Chem. Rev. 95 (1995) 615–635. https://doi.org/10.1021/cr00035a007.

[36] L. Damjanović, A. Auroux, Determination of Acid/Base Properties by Temperature Programmed Desorption (TPD) and Adsorption Calorimetry, in: A.W. Chester, E.G. Derouane (Eds.), Zeolite Characterization and Catalysis: A Tutorial, Springer Netherlands, Dordrecht, 2009: pp. 107–167. https://doi.org/10.1007/978-1-4020-9678-5_3.

[37] R.J. Gorte, Design parameters for temperature programmed desorption from porous catalysts, Journal of Catalysis 75 (1982) 164–174. https://doi.org/10.1016/0021-9517(82)90131-2.

[38] J.S. Rieck, A.T. Bell, Influence of adsorption and mass transfer effects on temperature-programmed desorption from porous catalysts, Journal of Catalysis 85 (1984) 143–153. https://doi.org/10.1016/0021-9517(84)90118-0.

[39] S. Tanabe, H.E. Davis, D. Wei, R.S. Weber, Normalization by oxygen uptake of the rates of oxidative dehydrogenation of methanol and ethanol, in: J.W. Hightower, W. Nicholas Delgass, E. Iglesia, A.T. Bell (Eds.), Studies in Surface Science and Catalysis, Elsevier, 1996: pp. 337–344. https://doi.org/10.1016/S0167-2991(96)80244-8.

[40] J. Macht, R.T. Carr, E. Iglesia, Functional assessment of the strength of solid acid catalysts, Journal of Catalysis 264 (2009) 54–66. https://doi.org/10.1016/j.jcat.2009.03.005.

[41] G. Kumar, L. Ren, Y. Pang, X. Li, H. Chen, J. Gulbinski, P.J. Dauenhauer, M. Tsapatsis, O.A. Abdelrahman, Acid Sites of Phosphorus-Modified Zeosils, ACS Catal. 11 (2021) 9933–9948. https://doi.org/10.1021/acscatal.1c01588.

[42] S. Wang, K. Goulas, E. Iglesia, Condensation and esterification reactions of alkanals, alkanones, and alkanols on TiO2: Elementary steps, site requirements, and synergistic effects of bifunctional strategies, Journal of Catalysis 340 (2016) 302–320. https://doi.org/10.1016/j.jcat.2016.05.026.

[43] W. Knaeble, R.T. Carr, E. Iglesia, Mechanistic interpretation of the effects of acid strength on alkane isomerization turnover rates and selectivity, Journal of Catalysis 319 (2014) 283–296. https://doi.org/10.1016/j.jcat.2014.09.005.

[44] S. Herrmann, E. Iglesia, Elementary steps in acetone condensation reactions catalyzed by aluminosilicates with diverse void structures, Journal of Catalysis 346 (2017) 134–153. https://doi.org/10.1016/j.jcat.2016.12.011.

[45] C.D. Baertsch, K.T. Komala, Y.-H. Chua, E. Iglesia, Genesis of Brønsted Acid Sites during Dehydration of 2-Butanol on Tungsten Oxide Catalysts, Journal of Catalysis 205 (2002) 44–57. https://doi.org/10.1006/jcat.2001.3426.

[46] B.A. Johnson, J.R. Di Iorio, Y. Román-Leshkov, Identification and quantification of distinct active sites in Hf-Beta zeolites for transfer hydrogenation catalysis, Journal of Catalysis 404 (2021) 607–619. https://doi.org/10.1016/j.jcat.2021.10.026.

[47] M.C. Simons, J.G. Vitillo, M. Babucci, A.S. Hoffman, A. Boubnov, M.L. Beauvais, Z. Chen, C.J. Cramer, K.W. Chapman, S.R. Bare, B.C. Gates, C.C. Lu, L. Gagliardi, A. Bhan, Structure, Dynamics, and Reactivity for Light Alkane Oxidation of Fe(II) Sites Situated in the Nodes of a Metal–Organic Framework, J. Am. Chem. Soc. 141 (2019) 18142–18151. https://doi.org/10.1021/jacs.9b08686.

[48] L. Paz Herrera, L. Freitas De Lima E Freitas, J. Hong, A.S. Hoffman, S.R. Bare, E. Nikolla, J.W. Medlin, Reactivity of Pd–MO $_2$ encapsulated catalytic systems for CO oxidation, Catal. Sci. Technol. 12 (2022) 1476–1486. https://doi.org/10.1039/D1CY01916C.

[49] C.D. Baertsch, S.L. Soled, E. Iglesia, Isotopic and Chemical Titration of Acid Sites in Tungsten Oxide Domains Supported on Zirconia, J. Phys. Chem. B 105 (2001) 1320–1330. https://doi.org/10.1021/jp003073d.

[50] C. Bornes, M. Fischer, J.A. Amelse, C.F.G.C. Geraldes, J. Rocha, L. Mafra, What Is Being Measured with P-Bearing NMR Probe Molecules Adsorbed on Zeolites?, J. Am. Chem. Soc. 143 (2021) 13616–13623. https://doi.org/10.1021/jacs.1c05014.

[51] A.T. Bell, NMR Techniques in Catalysis, CRC Press, 2019.

[52] A. Zheng, S.-J. Huang, S.-B. Liu, F. Deng, Acid properties of solid acid catalysts characterized by solid-state 31P NMR of adsorbed phosphorous probe molecules, Phys. Chem. Chem. Phys. 13 (2011) 14889. https://doi.org/10.1039/c1cp20417c.

[53] A. Zheng, S.-B. Liu, F. Deng, Acidity characterization of heterogeneous catalysts by solid-state NMR spectroscopy using probe molecules, Solid State Nuclear Magnetic Resonance 55–56 (2013) 12–27. https://doi.org/10.1016/j.ssnmr.2013.09.001.

[54] J. Xu, Q. Wang, F. Deng, Metal Active Sites and Their Catalytic Functions in Zeolites: Insights from Solid-State NMR Spectroscopy, Acc. Chem. Res. 52 (2019) 2179–2189. https://doi.org/10.1021/acs.accounts.9b00125.

[55] G. Noh, Z. Shi, S.I. Zones, E. Iglesia, Isomerization and β-scission reactions of alkanes on bifunctional metal-acid catalysts: Consequences of confinement and diffusional constraints on reactivity and selectivity, Journal of Catalysis 368 (2018) 389–410. https://doi.org/10.1016/j.jcat.2018.03.033.

[56] J.W. Harris, A.A. Verma, J.W. Arvay, A.J. Shih, W.N. Delgass, F.H. Ribeiro, Consequences of product inhibition in the quantification of kinetic parameters, Journal of Catalysis 389 (2020) 468–475. https://doi.org/10.1016/j.jcat.2020.06.014.

[57] V.J. Frillette, W.O. Haag, R.M. Lago, Catalysis by crystalline aluminosilicates: Characterization of intermediate pore-size zeolites by the "Constraint Index," Journal of Catalysis 67 (1981) 218–222. https://doi.org/10.1016/0021-9517(81)90273-6.

[58] E.E. Bickel, C.T. Nimlos, R. Gounder, Developing quantitative synthesis-structure-function relations for framework aluminum arrangement effects in zeolite acid catalysis, Journal of Catalysis 399 (2021) 75–85. https://doi.org/10.1016/j.jcat.2021.04.027.

[59] W.O. Haag, R.M. Lago, P.B. Weisz, The active site of acidic aluminosilicate catalysts, Nature 309 (1984) 589–591. https://doi.org/10.1038/309589a0.

[60] J.M. Tatibouët, Methanol oxidation as a catalytic surface probe, Applied Catalysis A: General 148 (1997) 213–252. https://doi.org/10.1016/S0926-860X(96)00236-0.

[61] A.I. Biaglow, D.J. Parrillo, R.J. Gorte, Characterization of H,Na-Y Using Amine Desorption, Journal of Catalysis 144 (1993) 193–201. https://doi.org/10.1006/jcat.1993.1323.

[62] H.-J. Freund, G. Meijer, M. Scheffler, R. Schlögl, M. Wolf, CO Oxidation as a Prototypical Reaction for Heterogeneous Processes, Angew. Chem. Int. Ed. 50 (2011) 10064–10094. https://doi.org/10.1002/anie.201101378.

[63] C. Hess, New advances in using Raman spectroscopy for the characterization of catalysts and catalytic reactions, Chem. Soc. Rev. 50 (2021) 3519–3564. https://doi.org/10.1039/D0CS01059F.

[64] I.E. Wachs, Raman and IR studies of surface metal oxide species on oxide supports: Supported metal oxide catalysts, Catalysis Today 27 (1996) 437–455. https://doi.org/10.1016/0920-5861(95)00203-0.

[65] H. Kim, K.M. Kosuda, R.P. Van Duyne, P.C. Stair, Resonance Raman and surface- and tip-enhanced Raman spectroscopy methods to study solid catalysts and heterogeneous catalytic reactions, Chem. Soc. Rev. 39 (2010) 4820. https://doi.org/10.1039/c0cs00044b.

[66] Y.-H. Wang, J. Wei, P. Radjenovic, Z.-Q. Tian, J.-F. Li, In Situ Analysis of Surface Catalytic Reactions Using Shell-Isolated Nanoparticle-Enhanced Raman Spectroscopy, Anal. Chem. 91 (2019) 1675–1685. https://doi.org/10.1021/acs.analchem.8b05499.

[67] S.J. Tinnemans, M.H.F. Kox, M.W. Sletering, T.A. (Xander) Nijhuis, T. Visser, B.M. Weckhuysen, Dealing with a local heating effect when measuring catalytic solids in a reactor with Raman spectroscopy, Phys. Chem. Chem. Phys. 8 (2006) 2413–2420. https://doi.org/10.1039/B602311H.

[68] J. Moncada, W.R. Adams, R. Thakur, M. Julin, C.A. Carrero, Developing a Raman Spectrokinetic Approach To Gain Insights into the Structure–Reactivity Relationship of Supported Metal Oxide Catalysts, ACS Catal. 8 (2018) 8976–8986. https://doi.org/10.1021/acscatal.8b02041.

[69] E.D. Goodman, S. Dai, A.-C. Yang, C.J. Wrasman, A. Gallo, S.R. Bare, A.S. Hoffman, T.F. Jaramillo, G.W. Graham, X. Pan, M. Cargnello, Uniform Pt/Pd Bimetallic Nanocrystals Demonstrate Platinum Effect on Palladium Methane Combustion Activity and Stability, ACS Catal. 7 (2017) 4372–4380. https://doi.org/10.1021/acscatal.7b00393.

[70] G. Bergeret, P. Gallezot, Particle Size and Dispersion Measurements, in: Handbook of Heterogeneous Catalysis, John Wiley & Sons, Ltd, 2008: pp. 738–765. https://doi.org/10.1002/9783527610044.hetcat0038.

[71] A.B. Laursen, K.T. Højholt, L.F. Lundegaard, S.B. Simonsen, S. Helveg, F. Schüth, M. Paul, J.-D. Grunwaldt, S. Kegnæs, C.H. Christensen, K. Egeblad, Substrate Size-Selective Catalysis with Zeolite-Encapsulated Gold Nanoparticles, Angewandte Chemie 122 (2010) 3582–3585. https://doi.org/10.1002/ange.200906977.

[72] A.R. Riscoe, C.J. Wrasman, A.A. Herzing, A.S. Hoffman, A. Menon, A. Boubnov, M. Vargas, S.R. Bare, M. Cargnello, Transition state and product diffusion control by polymer–nanocrystal hybrid catalysts, Nat Catal 2 (2019) 852–863. https://doi.org/10.1038/s41929-019-0322-7.

[73] C.J. Murphy, J.M. Buriak, Best Practices for the Reporting of Colloidal Inorganic Nanomaterials, Chem. Mater. 27 (2015) 4911–4913. https://doi.org/10.1021/acs.chemmater.5b02323.

[74] R.S. Weber, Lies, damned lies, and turnover rates, Journal of Catalysis 404 (2021) 925–928. https://doi.org/10.1016/j.jcat.2021.06.024.

[75] A.K. Datye, Electron microscopy of catalysts: recent achievements and future prospects, Journal of Catalysis 216 (2003) 144–154. https://doi.org/10.1016/S0021-9517(02)00113-6.

[76] L.I. van der Wal, S.J. Turner, J. Zečević, Developments and advances in *in situ* transmission electron microscopy for catalysis research, Catal. Sci. Technol. 11 (2021) 3634–3658. https://doi.org/10.1039/D1CY00258A.

[77] J.E. Millstone, W.C.W. Chan, C.R. Kagan, L.M. Liz-Marzán, N.A. Kotov, P.A. Mulvaney, W.J. Parak, A.L. Rogach, P.S. Weiss, R.E. Schaak, Redefining the Experimental and Methods Sections, ACS Nano 13 (2019) 4862–4864. https://doi.org/10.1021/acsnano.9b03753.

[78] J.M. Buriak, B. Korgel, The Experimental Section: The Key to Longevity of Your Research, Chem. Mater. 26 (2014) 1765–1766. https://doi.org/10.1021/cm500632c.

[79] P.S.F. Mendes, S. Siradze, L. Pirro, J.W. Thybaut, Open Data in Catalysis: From Today’s Big Picture to the Future of Small Data, ChemCatChem 13 (2021) 836–850. https://doi.org/10.1002/cctc.202001132.

[80] A.J. Medford, M.R. Kunz, S.M. Ewing, T. Borders, R. Fushimi, Extracting Knowledge from Data through Catalysis Informatics, ACS Catal. 8 (2018) 7403–7429. https://doi.org/10.1021/acscatal.8b01708.

[81] S.L. Scott, The Burden of Disproof, ACS Catal. 9 (2019) 4706–4708. https://doi.org/10.1021/acscatal.9b01623.

[82] M. Cargnello, V.V.T. Doan-Nguyen, T.R. Gordon, R.E. Diaz, E.A. Stach, R.J. Gorte, P. Fornasiero, C.B. Murray, Control of Metal Nanocrystal Size Reveals Metal-Support Interface Role for Ceria Catalysts, Science 341 (2013) 771–773. https://doi.org/10.1126/science.1240148.

[83] M. Shekhar, J. Wang, W.-S. Lee, W.D. Williams, S.M. Kim, E.A. Stach, J.T. Miller, W.N. Delgass, F.H. Ribeiro, Size and Support Effects for the Water–Gas Shift Catalysis over Gold Nanoparticles Supported on Model Al_2O_3 and TiO_2, J. Am. Chem. Soc. 134 (2012) 4700–4708. https://doi.org/10.1021/ja210083d.

[84] A. Mahdavi-Shakib, L.C. Rich, T.N. Whittaker, B.D. Chandler, Hydrogen Adsorption at the Au/TiO_2 Interface: Quantitative Determination and Spectroscopic Signature of the Reactive Interface Hydroxyl Groups at the Active Site, ACS Catal. 11 (2021) 15194–15202. https://doi.org/10.1021/acscatal.1c04419.

[85] J. Resasco, S. Dai, G. Graham, X. Pan, P. Christopher, Combining *In-Situ* Transmission Electron Microscopy and Infrared Spectroscopy for Understanding Dynamic and Atomic-Scale Features of Supported Metal Catalysts, J. Phys. Chem. C 122 (2018) 25143–25157. https://doi.org/10.1021/acs.jpcc.8b03959.

[86] P. Müller, I. Hermans, Applications of Modulation Excitation Spectroscopy in Heterogeneous Catalysis, Ind. Eng. Chem. Res. 56 (2017) 1123–1136. https://doi.org/10.1021/acs.iecr.6b04855.

[87] I.X. Green, W. Tang, M. Neurock, J.T. Yates, Spectroscopic Observation of Dual Catalytic Sites During Oxidation of CO on a Au/TiO_2 Catalyst, Science 333 (2011) 736–739. https://doi.org/10.1126/science.1207272.

[88] B.M. Weckhuysen, Determining the active site in a catalytic process: Operando spectroscopy is more than a buzzword, Phys. Chem. Chem. Phys. 5 (2003) 4351. https://doi.org/10.1039/b309650p.

[89] A. Caballero, J.P. Holgado, V.M. Gonzalez-delaCruz, S.E. Habas, T. Herranz, M. Salmeron, In situ spectroscopic detection of SMSI effect in a Ni/CeO_2 system: hydrogen-induced burial and dig out of metallic nickel, Chem. Commun. 46 (2010) 1097–1099. https://doi.org/10.1039/B920803H.

[90] M.M. Sullivan, J.T. Held, A. Bhan, Structure and site evolution of molybdenum carbide catalysts upon exposure to oxygen, Journal of Catalysis 326 (2015) 82–91. https://doi.org/10.1016/j.jcat.2015.03.011.

Declaration of interests

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

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: