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Data availability statements

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All data supporting the findings of this study are presented in the main article and in the Supplementary Information.

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Environmental Significance Statement

Nanomaterials hazard is associated with their surface reactivity. We report an *in chemico* approach to probe the number, nature and reactivity of surface sites. This approach tells how many sites we have at the surface of nanomaterials; relevant for a dose metric based on actual sites rather than on surface or mass. This would allow better insight on dose-response investigations. This NAM provides insights into whether sites are oxidative, acidic, basic, or a combination thereof, and additionally aids in ranking NMs by reactivity, which is crucial for understanding their mechanisms of toxicity. In a broader view, it can characterize nanomaterials and how their reactivity evolves as they change making multicomponent nanomaterials and as they age during operation and in the environment.

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***In chemico* methodology for engineered nanomaterials categorization according to number, nature and oxidative potential of reactive surface sites**

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Keywords

Surface descriptor, chemisorption, oxidative potential, active sites, dose metrics, probe molecule, probe reaction, new approach methodologies

Abstract

Methanol probe chemisorption quantifies the number of reactive sites at the surface of engineered nanomaterials, enabling normalization per reactive site in reactivity and toxicity tests, rather than per mass or physical surface area. Subsequent *temperature-programmed surface reaction* (TPSR) of chemisorbed methanol identifies the reactive nature of surface sites (acidic, basic, redox or combination thereof) and their reactivity. Complementary to methanol assay, dithiothreitol (DTT) probe oxidation reaction is used to evaluate oxidation capacity. These acellular approaches to quantify the number, nature, and reactivity of surface sites constitute a New Approach Methodology (NAM) for site-specific classification of nanomaterials. As a proof of concept, CuO, CeO₂, ZnO, Fe₃O₄, CuFe₂O₄, Co₃O₄ and two TiO₂ nanomaterials were probed, and a harmonized reactive descriptor was obtained: DTT oxidation rate per reactive site, or *Oxidative Turnover Frequency* (OxTOF). CuO and CuFe₂O₄ nanoparticles exhibit the largest reactive sites surface density and are the most oxidative in the series, as estimated by DTT probe reaction, followed by CeO₂ NM-211 and, then, by titania nanomaterials (DT-51 and NM-101) and Fe₃O₄. DTT depletion in ZnO NM-110 was associated with dissolved zinc ions rather than the ZnO particles themselves, but the basic character of the ZnO NM-110 particles surface was evidenced by methanol TPSR. These acellular assays allow ranking the 8 nanomaterials into three categories with statistically different oxidative potential: CuO, CuFe₂O₄ and Co₃O₄ are the most reactive, ceria exhibits a moderate reactivity, and iron oxide and the titanias possess a low oxidative potential.

1 INTRODUCTION

The surface of engineered nanomaterials (ENMs). Metal oxides possess a lattice which unit cell repeats *ad infinitum*. However, materials are finite, and interact with the surrounding environment through their surface, the end of the lattice periodic structure, which is characterized by descriptors such as specific surface area (BET area), pore size, or zeta-potential (ζ).¹ Surface chemistry defines materials' reactivity (type and strength), in metal oxides often associated with surface oxygen species, such as bridging oxygen, oxide, superoxide, peroxide, or hydroxyl sites (**Error! Reference source not found.**), which properties are determined by underlying cations, defects, and the bulk structure. Charge unbalances such as surface vacancies, defects and others, are stabilized to keep the material neutrality, typically by surface interactions with, e.g., environmental water, generating surface hydroxyl groups. The compensation mechanisms for defects may vary depending on the nature of the material; like the formation of *farb* centers, covalent bonding or transitions between valence and conduction bands in ionic, covalent on transition element oxides, respectively². Surface relevance is maximized in non-soluble nanomaterials (NMs, with one dimension in the 1-100 nm range)³, in which a high surface-to-volume ratio confers them with distinctive properties. For example, in the field of ecotoxicology, 40 mg/L of nano-sized CuO particles completely inhibit the growth of *S. cerevisiae*, while 4000 mg/L of CuO bulk material are needed⁴; the number of exposed sites is probably not dramatically different between these two very different amounts of CuO materials.

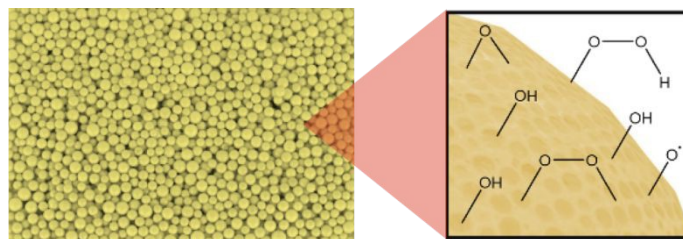


Figure 1. Reactive sites on ENMs surface

Rise of engineered nanomaterials and concern about their toxicity. Engineered nanomaterials applications have grown significantly, influencing societal challenges and the economy, especially in Asia-Pacific, America, and Europe.^{5,6,7} Transition metal oxide ENMs, including TiO₂, CuO, ZnO, and others, have versatile uses like pigments and catalysts.^{8,9} This has prompted numerous characterization, exposure and hazard studies¹⁰⁻¹² to understand and prevent possible adverse effects or pathologies, e.g. derived from reactive

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oxygen species (ROS) release,^{13,14} and to adopt a knowledge-based safe-by-design (SbD) approach^{15,16}, essential to ensure safe ENM applications as well as faster, economic and more effective production routes.^{17,18} Integrated information related to toxicity (*in vitro* and *in vivo* testing) and physicochemical properties underpins hazard prediction^{16, 19, 20, 21 22 23}, with machine learning serving as the primary tool.²⁴ Grouping ENMs based on similarities can optimize resource management, aligning with OCDE guidelines for risk assessment and promoting non-animal testing methodologies.^{25,26} New approach methodologies (NAMs) may provide the basis for this objective.^{27,28,29} The overarching aim is to contribute to the understanding of Adverse Outcome Pathways (AOPs) and, particularly, what reactive properties are associated with the triggering of adverse effects by nanomaterials.³⁰

New approach methodology based on surface sites reactivity. Nanomaterial surface reactivity plays a vital role in oxidative-stress-induced adverse effects.^{31,32,33,34} As reactivity is an extrinsic property considered a key parameter to describe the interaction of ENMs with their surroundings,^{16, 19} the development of abiotic *in chemico* assays to evaluate surface reactivity and link it with key events in reactive-based nanotoxicity would help to fundamentally understand the modes of action^{35,36,37} and better group ENMs while minimizing *in vivo* testing.³⁸ Surface reactivity characterization complements other physicochemical information relevant to the nanotoxicity field¹⁹ to investigate toxic ion release, lung fibrosis, inflammasome activation, interference with embryonic hatching or membrane lysis, among others. In the context of reactive-based toxicity assessment of engineered nanomaterials, it is widely acknowledged that materials with identical chemical compositions can lead to significantly varied biological oxidative damage.³⁴ Thus, characterizing the amount, nature and reactivity of surface sites is essential for identifying an additional parameter impacting nanomaterial's effects. The interaction with biological systems depends on the surface properties of the nanomaterials, the presence of any kind of active site may have effects on their interaction with molecules. We hypothesize that mapping all reactive sites (redox, acidic and basic) may provide a better reactive description of nanomaterials than just oxidative sites, and enable a more reliable grouping of nanomaterials based on their surface reactivity. Formally equivalent problems have formally equivalent solutions: as key events in reactive-based toxicity and catalytic reactions occur at the surface, more specifically, at the reactive sites, we propose the use of catalytic methods based on adsorption and reaction of probe molecules to quantify the surface

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3 reactive sites of ENMs and to characterize their reactive nature, thus delivering descriptors
4 relevant for ENMs classification.^{39,40}
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8 The reactive characterization may also provide new dose metrics. In *in vitro* tests with
9 different cell lines, quantitative dose-dependent cellular/biological effects are typically
10 normalized by mass or physical BET area. These dose metrics may sometimes not be useful
11 to compare exposure because mass or exposed physical area do not necessarily correlate
12 with the number of reactive sites, which trigger chemical processes, *e.g.*, ROS formation
13 (generation of ROS by particles is one of the possible molecular initiating events that lead
14 to adverse outcomes, as confirmed *e.g.* for PM, CuO, or photo-activated TiO₂). We do not
15 tackle photocatalytic phenomena that are unlikely to happen inside the body. Research in
16 heterogeneous catalysis has traditionally faced the same challenge when comparing the
17 activity of catalytic materials and has reached a consensus that the most relevant metric is
18 the turnover frequency (TOF). TOF is the number of times that the overall catalytic reaction
19 takes place (*i.e.*, molecules that react) per reactive site and unit time.^{41,39,42,43,44} Our research
20 posits that probe molecules will allow quantification of reactive surface sites, their nature
21 and reactivity; TOF calculation can thus be made based on relevant probe reactions (*e.g.*,
22 DTT), offering new metrics for reactivity and toxicological studies.
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26 The most typical probe molecules used to quantify reactive sites in heterogeneous catalysis
27 are carbon monoxide, for metal NPs,⁴⁵ and methanol, for metal oxides, both in the gas/vapor
28 phase. The latter is considered a “smart” probe molecule that can not only quantify the
29 number of surface sites by chemisorption, but also report on their reactive profile by
30 temperature-programmed surface reaction (TPSR),^{46,47} a powerful technique to identify and
31 quantify acidic, basic, redox, and bifunctional sites^{48,49} on materials that are not thermally
32 sensitive. In addition, several probe molecules in the liquid phase may specifically assess
33 the oxidative potential (OP),^{50,51,52,53,54,55} which is particularly relevant to human health due
34 to its involvement in cellular damage by oxidative stress.^{10,56,57,58,59,60} Among those,
35 dithiothreitol (DTT) is suggested here as an acellular, liquid-phase, low-temperature probe
36 reaction to assess the nanomaterials OP, as this molecule has been previously used to
37 quantify the oxidative capacity of particulate matter.^{61,62,63,64,65,66} We introduce therefore a
38 NAM based on using gas-phase methanol chemisorption and subsequent TPSR as well as
39 liquid-phase DTT consumption in PBS-water solutions with nanomaterials. By normalizing
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DTT oxidation rate via methanol chemisorption, we derive the Oxidative Turnover Frequency (OxTOF) to measure surface site reactivity. We suggest dose normalization to the reactive sites' amount and reactivity. As a proof of concept seven metal oxide nanomaterials (CeO₂, ZnO, CuO, Fe₃O₄, Co₃O₄, and two TiO₂ variants), one bimetallic nanooxide (CuFe₂O₄) and an oxide with larger particles (Co₃O₄) are analyzed to investigate the usefulness of this NAM to 1), categorize the reactivity of eight benchmark engineered nanomaterials; 2), assess the differences in reactivity between ENMs with the same composition (TiO₂ NM-101 vs TiO₂ DT-51); 3), assess the effect of bimetallic compositions on the surface reactivity of metal nano-oxides (monometallic vs. bimetallic); 4), calculate reactive rankings according to three dose metrics based on mass, surface area and surface sites; and 5), assess the size-dependent reactivity of a material, by comparing Co₃O₄ nanoparticles to its larger counterpart.

2 EXPERIMENTAL

2.1 Nanomaterials

All nanomaterials were used as supplied. Two anatase TiO₂ powders were compared: DT51 (CristalACTiV™) and NM-101 (labeled as JRCNM01001a by the supplier, the Joint Research Centre, JRC). In addition, two more JRC samples: CeO₂ NM-211 (JRCNM02101a) and ZnO NM-110 (JRCNM62101a), as well as four commercial samples from Sigma-Aldrich: CuO (ref. number: 544868, CuO-SA), CuFe₂O₄ (ref. number: 641723, CuFe₂O₄-SA), Fe₃O₄ (ref. number: 637106, Fe₃O₄-SA), and Co₃O₄ (ref. number: 637025, Co₃O₄-SA), were evaluated. **Error! Reference source not found.** summarizes data and information on these proof-of-concept samples. The size dependence of reactivity was evaluated using Co₃O₄ microparticles (ref. number: 221643, Sigma-Aldrich <10 μm).

2.2 Specific surface area

Specific surface area was calculated by the BET method with data obtained in a Micromeritics ASAP 2020 adsorption isotherm equipment. All ENMs were pretreated by degassing under vacuum for 16 h at 120 °C before nitrogen adsorption at liquid nitrogen temperature.

2.3 Methanol chemisorption and subsequent temperature-programmed surface reaction (TPSR)

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Methanol chemisorption/TPSR procedure (see a detailed description in the SI, **Error! Reference source not found.**A and Figure S 2) is made on a clean dehydrated sample. 100-250 mg of nanomaterial (aggregated samples with aggregates ranging from 25 to 100 μm) were diluted with 500 mg of inert SiC (black 180, Navarro SiC S.A.), to ensure isothermal conditions, are and placed in a fixed-bed reactor (0.4 cm internal diameter). The sample is first pretreated by heating from room temperature to 450 $^{\circ}\text{C}$ at 10 $^{\circ}\text{C}/\text{min}$ in a 150 mL/min synthetic air flow and kept at this temperature for 35 min to ensure the removal of moisture and burn away impurities from its surface. After pretreatment, the sample is cooled down to 100 $^{\circ}\text{C}$ (or 50 $^{\circ}\text{C}$ for highly reactive ENMs) in synthetic air. After such treatment the surface remains hydroxylated, but not hydrated; next, the flow feed is switched to argon (100 mL/min) purge. The chemisorption temperature was optimized to prevent the formation of multilayers in the case of highly reactive materials, looking for a balance between methanol condensation at lower temperatures and methanol reaction at higher temperatures, either of which would lead to an overestimation of the surface sites.^{67,68} After purging, still at 100 $^{\circ}\text{C}$ (or 50 $^{\circ}\text{C}$ for highly reactive ENMs), 100 mL/min of 2000 ppm methanol in argon with 5% helium is fed until saturation, as determined by online mass spectrometry residual gas analysis (cf. supplementary information). The 5%helium in the argon stream is used as an internal reference for online mass spectrometry. The methanol vapor chemisorbs titrating surface hydroxyl groups; this process converts CH_3OH molecule into a chemisorbed CH_3O -moiety, the missing hydrogen atom reacts with the surface hydroxyl thus releasing an H_2O molecule per CH_3OH molecule that chemisorbs. We monitor the effluent gases by a quadrupole residual gas analyzer Pfeiffer OmniStar mass spectrometer. The m/z values followed were: CH_3OH (methanol) = 31, HCHO (formaldehyde) = 30, CH_3OCH_3 (dimethyl ether, DME) = 45, CH_3OOCH (methylformate) = 60, $(\text{CH}_3\text{O})_2\text{CH}_2$ (dimethoxy methane) = 75, H_2O (water) = 18, and CO_2 (carbon dioxide) = 44. Blank tests were performed with 500 mg of inert SiC (Figure S3). Details on the procedure, the calculation of the reactive surface sites and the surface reactions in methanol-TPSR (equations S1-5) are available in the supplementary material. This methodology is limited to thermally stable samples like metal oxides.

2.4 DTT consumption assay

DDT catalytic oxidation was performed in a batch reactor for 1h. First, a 200 $\mu\text{g}/\text{mL}$ suspension of ENM in 1 mM phosphate buffer is obtained by sonication, following

NanoGenoTox SOP (16 min at 400 W and 10% amplitude).⁶⁹ 3 mL of the ENM suspension is incubated for 1 h at 37 °C and 500 rpm with 3 mL of 100 μM DTT, obtaining a 6 mL reaction mixture with 100 μg/mL of ENM and 50 μM DTT. Then, the nanoparticles are removed by filtration, and the filtrate, with the unreacted DTT and the reaction products, is mixed with an equal volume of 1 mM Ellman's reagent (5,5'-dithiobis-(2-nitrobenzoic acid), DTNB) to quantify the non-oxidized DTT (**Error! Reference source not found.**B). Ellman's reagent reacts with the thiol groups (-SH) of the free DTT molecules, forming 5-mercapto-2-nitrobenzoic acid, a colorful complex that is measured at 412 nm by UV-Vis spectrophotometry (Shimadzu, UV-2100). In parallel, as a negative control, DTT in phosphate buffer without ENM is incubated under the same conditions and mixed with the Ellman's reagent to evaluate the DTT consumed by direct reaction without catalyst. Hydrogen peroxide 30 % (w/w) in H₂O is used as a positive control, as it provides similar DTT conversion as 1,4-naphthoquinone,⁶² being safer and not requiring filtration. All reactions were performed in triplicate. Linearity in measurements at 412 nm of DTT-DTNB nm complex was calibrated (Figure S4). DTT oxidative potential is expressed as DTT conversion (Eq. 1), as a normalized index of oxidant generation using hydrogen peroxide as a positive control (Eq. 2), or as DTT reaction rate, normalized vs. mass (Eq. 3), vs. ENM surface area (Eq. 4), or vs. number of reactive sites (Eq. 5), i.e., OxTOF.

$$\text{DTT depleted (mol \%)} = 100 - \frac{\text{Reaction absorbance}}{\text{Blank absorbance}} \cdot 100 \quad (\text{Eq. 1})$$

$$\text{NIOG (0-1)} = \frac{\text{DTT depleted by nanomaterial}}{\text{DTT depleted by positive control}} \quad (\text{Eq. 2})$$

$$\text{OP}_{\text{mass}} (\text{mol} \cdot \text{s}^{-1} \cdot \text{g}^{-1}) = \frac{\text{depleted DTT moles}}{\text{time} \cdot \text{mass of NM}} \quad (\text{Eq. 3})$$

$$\text{OP}_{\text{area}} (\mu\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2}) = \frac{\text{depleted DTT moles}}{\text{time} \cdot \text{surface area of NM}} \quad (\text{Eq. 4})$$

$$\text{OxTOF (s}^{-1}\text{)} = \frac{\text{depleted DTT molecules}}{\text{time} \cdot \text{active sites of NM}} \quad (\text{Eq. 5})$$

2.5 Statistical analysis

DTT OP_{mas}, OP_{area} and OxTOF are expressed as average ± sd (standard deviation). The statistical analysis was performed with SPSS 20 (IBM, Armonk, USA) using logarithmic values to obtain a better normal distribution. One-way ANOVA (Analysis of Variance) was performed to determine statistically significant differences. Subsequently, a Tukey test was

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performed to assess pairwise differences with a significance level of $p < 0.05$ and classify ENMs according to the oxidative potential.

3 RESULTS

3.1 Surface area and reactive sites

In the series, TiO₂ NM-101 exhibits the largest BET area, 225 m²/g; the rest of ENMs have significantly lower BET values: TiO₂-DT51, 84 m²/g; CeO₂ NM-211, 76 m²/g; CuO-SA, 12 m²/g; ZnO NM-110, 9 m²/g; CuFe₂O₄-SA, 33 m²/g; Fe₃O₄-SA, 11 m²/g, and Co₃O₄-SA, 26 m²/g (**Error! Reference source not found.A**). These data are consistent with the values reported in the literature and in the supplier's technical sheets.^{70, 71, 72, 73, 74} **Error! Reference source not found.B** illustrates the specific number of sites (mmol per g). While the order of materials remains similar, the relative values change significantly between Figure 2A and B. Thus, the reactive sites surface density (site per nm²) may follow a different trend. Figure 2C shows this surface descriptor, calculated from **Error! Reference source not found.A** and B data. Interestingly, the ENMs with smaller surface area have higher reactive sites surface density: 16.6 and 21.8 sites/nm² for ZnO NM-110 and CuO-SA, respectively (values obtained at 50 °C). These data show that due to differences in site types and/or distribution, surface area and reactive sites number do not linearly correlate for these samples, as it might be erroneously assumed. It is remarkable that TiO₂-DT51, with 2.7 times lower specific surface area than TiO₂ NM-101, doubles its reactive sites surface density (14 vs. 7 sites/nm²). Therefore, BET (physical) may not be the most relevant descriptor of ENMs surface chemistry. **Error! Reference source not found. D** summarizes the trends shown in **Error! Reference source not found. A-C**, after data normalization to the most described nanomaterial in the literature: TiO₂ NM-101.

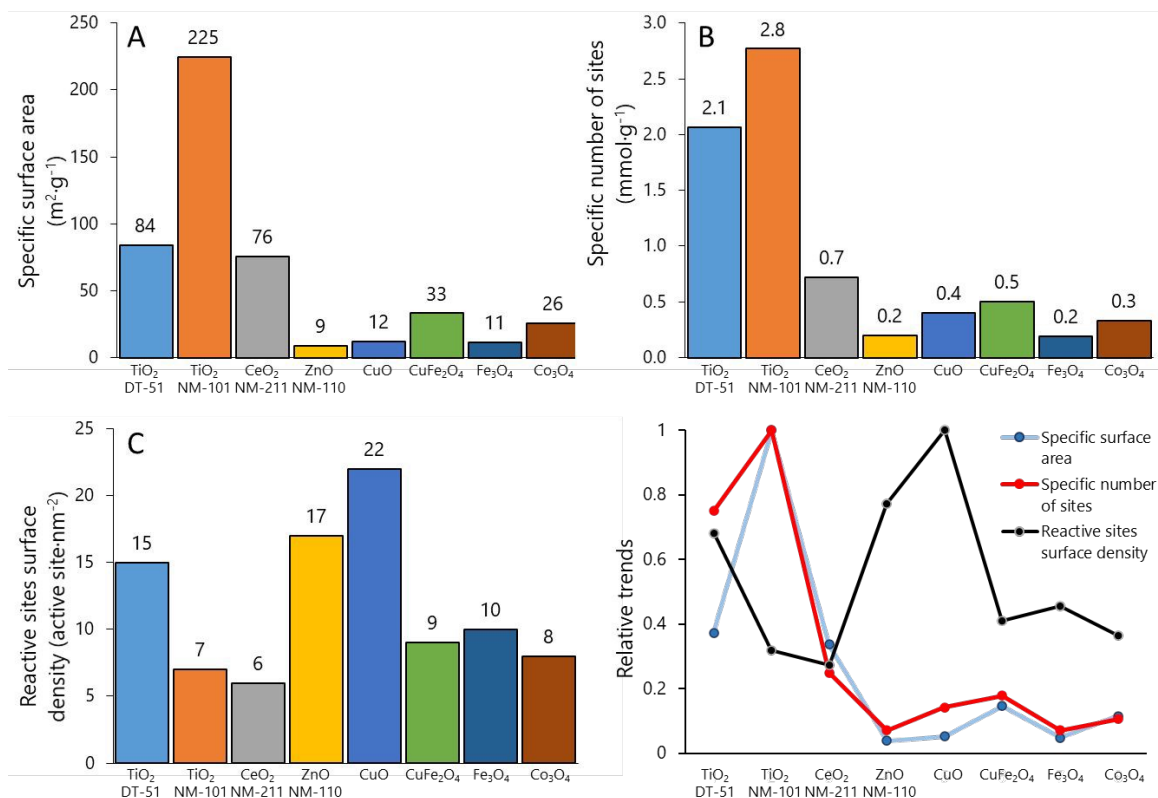


Figure 2. Surface analysis: **A)** Specific surface area obtained by N_2 adsorption isotherm, **B)** Specific number of reactive sites obtained by methanol chemisorption, **C)** Reactive sites surface density obtained by combination of A and B, **D)** Comparison of the three surface descriptors (values normalized to the maximum).

3.2 Reactive profile

The methanol TPSR profiles in **Error! Reference source not found.** provide information on the reactive sites and their reactivity. The typical TPSR products are DME, HCHO and CO_2 .

TiO₂ ENMs (DT51 and NM-101) form mainly **dimethyl ether (Error! Reference source not found. A and D)**, the characteristic product of acidic reactivity. The maximum production of dimethyl ether occurs at 349 °C for NM-101 and at 339 °C for DT51, indicating a weaker acidity of the sites of the latter, which are also fewer, as indicated by the smaller area under the curve. Redox (HCHO) and basic (CO_2) reaction products also form on both titania samples. The redox site is active in a broad temperature range, which indicates a broad

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3 distribution of oxidation reactivities, and that the oxidation capacity is moderate, since rather
4 high temperatures are required to express it.
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8 Oxidative sites produce **HCHO**. Thus, CeO₂ exhibits redox sites where methanol is oxidized
9 to formaldehyde, with a maximum near 259 °C (**Error! Reference source not found.G**);
10 ceria oxidative sites exhibit a narrower peak, which indicates that most oxidizing sites have
11 similar reactivity. This is unlike the broad distribution of oxidative site types on the titanias,
12 in the 150 to 400 °C range. Moreover, ceria has a higher oxidation capacity, for its maximum
13 is at a lower temperature than the average of HCHO formation on the titania samples.

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15 ZnO NM-110, CuFe₂O₄-SA, Fe₃O₄-SA, Co₃O₄-SA and CuO-SA (**Error! Reference source**
16 **not found. C-H**) produce mainly **CO₂**, but the temperatures at which CO₂ reaches a
17 maximum differs significantly, for some it is near 220-250°C, and for others above 300°C.
18 The significantly higher maximum temperature for CO₂ production is indicative of basic
19 materials, where methoxy species adsorb strongly and can only desorb at very high
20 temperatures, thus being combusted (ZnO NM-110 and Fe₃O₄-SA). Instead, the easier
21 formation of CO₂ (some 100 °C lower temperatures) is indicative of a high oxidation capacity,
22 leading to total oxidation CO₂ rather than to partial oxidation formaldehyde (CuO-SA,
23 CuFe₂O₄-SA and Co₃O₄-SA).⁴⁹ Evaluated as a reference, micrometric Co₃O₄ (Figure S5)
24 showed a similar reactive profile than Co₃O₄ nanoparticles. Thus, the nature of the surface
25 sites in nano and micro CuO remains essentially alike, with the critical difference that a
26 minimum part of the reactive sites is exposed in the larger CuO particles, hence the risk of
27 exposure to larger CuO particles is minimized. In summary, *methanol TPSR reactive profiles*
28 *may classify materials based on a linear combination of their acidic/basic reactive profile vs.*
29 *its oxidation profile* (**Error! Reference source not found.I**). In this categorization, the X-
30 axis qualitatively indicates how oxidizing the material is, while the Y-axis moves from acidic
31 to basic character. Thus, TiO₂ DT51 and NM-101, ZnO NM-110, and Fe₂O₃-SA have a
32 moderate oxidation capacity, being Fe₂O₃-SA and ZnO NM-110 more basic and both TiO₂
33 more acidic. On the other hand, CeO₂ NM-211, Co₃O₄-SA exhibit increased oxidation
34 capacity, and the highest is for CuO-SA and CuFe₂O₄-SA.
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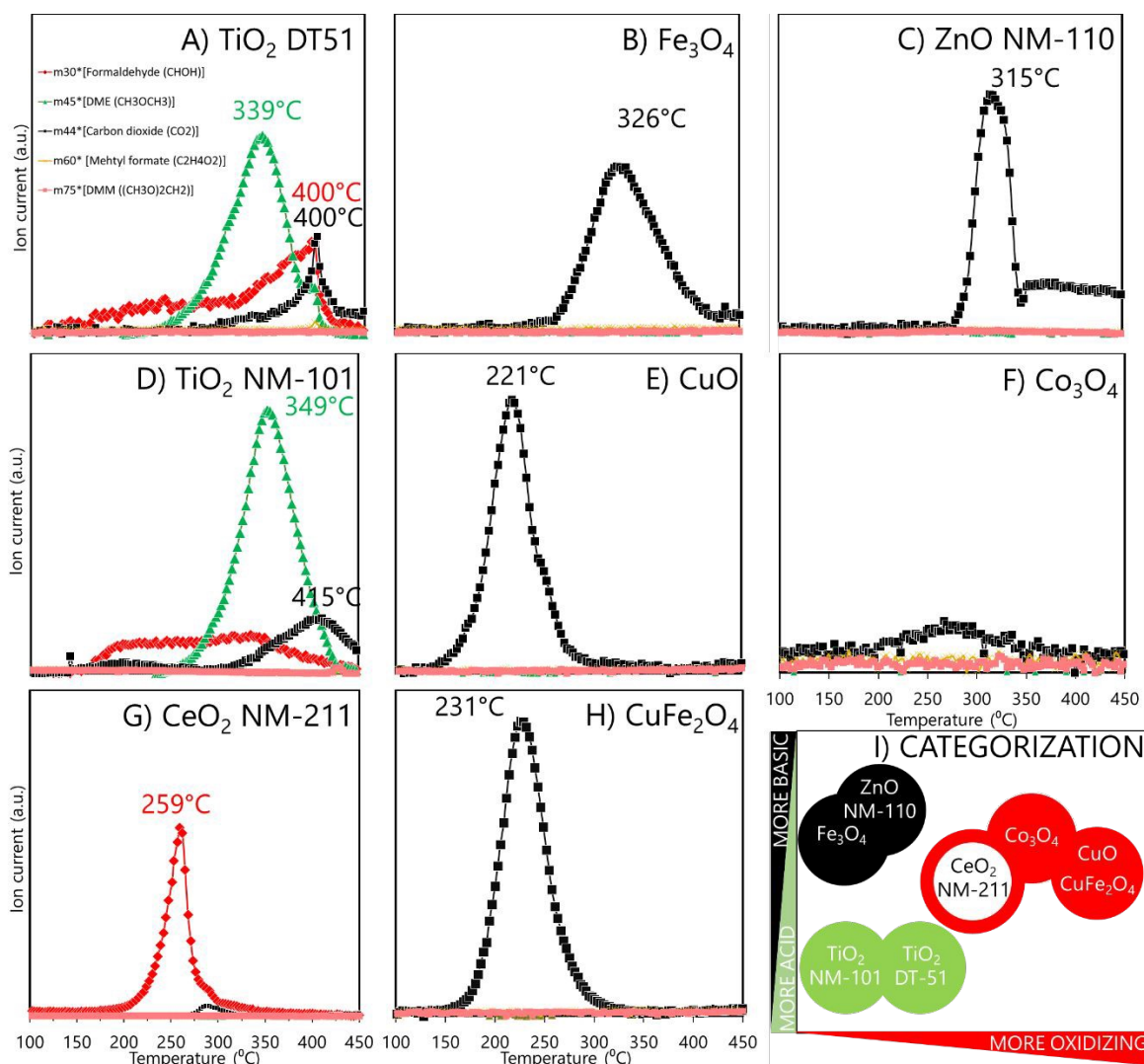


Figure 3. Temperature-programmed surface reaction products of pre-adsorbed methanol analysed by mass spectroscopy for two different anatase TiO₂: DT51 (A) and NM-101 (D), for Fe₃O₄-SA (B), for ZnO NM-110 (C), for CuO-SA (E), for Co₃O₄-SA (F) for CeO₂ NM-211 (G), and for CuFe₂O₄-SA (H). Formaldehyde signal (red) is obtained for redox sites, dimethyl ether signal (green) for acid sites, and carbon dioxide (black) for basic or high reactive redox sites. ENMs classification by MeOH-TPSR results is shown in I) with the same colour code. For a given colour, filled circles are more reactive than empty circles.

3.3 Oxidative potential

Error! Reference source not found. illustrates DDT catalytic oxidation results for 1h reaction, normalized vs. different descriptors; the corresponding classification of the ENMs based on Tukey's test using the logarithm of OP_{mass} , OP_{area} and OxTOF are provided on the right side of the plots. ZnO NM-110 was not included in the analysis because it dissolves in

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the reaction media and Zn cations get complexed by DTT,⁶⁶ so no free and uncomplexed DTT is available for interaction with the ZnO NM-110 surface, and thus the results are close to the negative control.⁶⁶ The relative oxidative potential of the other ENMs significantly depends on the descriptor. The positive control normalization has little impact on the relative conversion trend (*Figure S6*), which is similar to that of the specific reaction rate shown in **Error! Reference source not found. A**: CuO-SA \approx CuFe₂O₄-SA \gg Co₃O₄-SA \approx TiO₂ NM-DT-51 \approx TiO₂ NM-101 \approx CeO₂ NM-211 $>$ Fe₃O₄-SA; according to Tukey's test, only CuO-SA and CuFe₂O₄-SA are classified as significantly highly reactive ENMs. The differences between these ENMs' reactivities are clearly amplified when the oxidation rate is normalized to the ENM surface area (**Error! Reference source not found. B**), which underlines that CuO-SA surface, being small (**Error! Reference source not found. A**), is significantly more reactive than other ENMs' surfaces in the series. Actually, Tukey's test reveals three reactivity groups of ENMs according to OP_{area} descriptor: CuO-SA $>$ Co₃O₄-SA \approx CuFe₂O₄-SA $>$ TiO₂ DT-51 \approx CeO₂ NM-211 \approx TiO₂ NM-101 \approx Fe₃O₄-SA. *Mass or BET normalizations cannot tell how reactive each site is, so this trend stands on assuming that all physical areas are equally populated by equally reactive sites, which is not the case.* Normalization per reactive site (**Error! Reference source not found. C**) delivers the OxTOF, which shows that CuO-SA and CuFe₂O₄-SA sites are the most oxidizing ones, followed by Co₃O₄-SA, and ca. fourfold more reactive than ceria sites. The remaining group of materials exhibit significantly lower oxidation activity, according to Tukey's test: CeO₂ NM-211 $>$ TiO₂ DT-51 \approx TiO₂ NM-101 \approx Fe₃O₄-SA. A larger amount of sites can make up for individual site lower reactivity; therefore, both pieces of reactivity information, global (per material dose) and individual (per site), are important to understand and classify ENMs. Among these descriptors, only OxTOF can identify with statistical significance that ceria has more reactive redox sites than titania ENMs. *From a chemical perspective, turnover frequency values may allow a better quantitative comparison of oxidative potential and provide a more accurate insight into reactivity at a molecular scale.*

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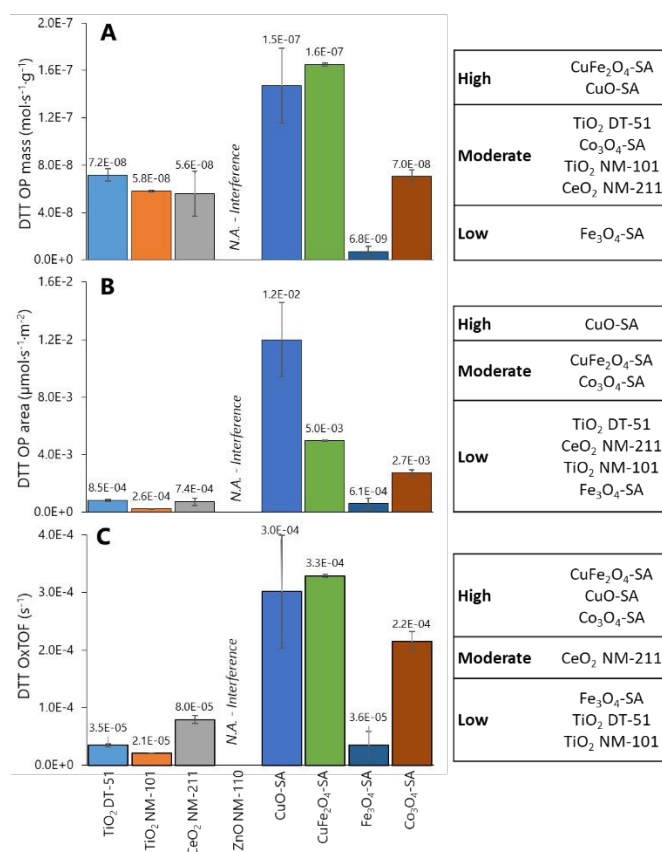


Figure 4. Oxidative potential evaluated by DTT assay and expressed as: reaction rate per mass (A), reaction rate per surface (B), oxidative turnover frequency (reaction rate per reactive site) (C). Left: Averaged OP values ($n=3$) with error bars indicating the standard deviation. Right: Statistical analysis for classification of the ENMs by OP based on Tukey' test comparison.

Size dependence of reactivity was evidenced via comparison of Co₃O₄ nanoparticles vs microparticles, which exhibited a DTT depletion of $6.7 \pm 4.2\%$ of DTT depletion, equivalent to a NIOG of 0.08 ± 0.04 , that is, around 7 times lower oxidative capacity than its nanoparticle counterpart. This is essentially due to the significantly smaller fraction of reactive sites that are exposed.

3.4 Dose metrics applied to bibliographic toxicological data

Bibliographic toxicity information for TiO₂ NM-101, CeO₂ NM-211, ZnO NM-110, CuO-SA, Fe₃O₄, CuFe₂O₄ and Co₃O₄ was extracted from eNanoMapper^{75,76} and the literature to



investigate possible correlations of the surface reactivity with in vitro toxicity descriptors (**Error! Reference source not found.**).

CuO-SA is highly toxic to pulmonary cells, causing cell death and impairing cell functions after 24-hour exposure.⁷⁷ The mechanism involves ion release, autophagy activation, and increased lipid peroxidation.^{78 79 80} Animal models support its lung inflammatory effects but do not show teratogenic potential.^{81 82} In terms of dose metrics, this ENM, the most oxidant in the series, exhibits significant effects on A549 cell viability at 5, 10 and 17.75 µg/mL gravimetric doses, equivalent to 2, 4 and 7.1 µmol/L sites doses, in different studies.⁷⁸


CuFe₂O₄-SA cytotoxic effects on human lung (A549) and liver (HepG2) cells were analyzed, illustrating a dose-dependent toxicity within a concentration range of 10–100 µg/ml (*i.e.*, 5–50 µmol site/L). Key observations include mitochondrial membrane potential (MMP) depletion, upregulation of the caspase-3 gene, and increased caspase-3 enzyme activity, suggesting apoptotic cell death as a consequence of exposure to these ENM. Furthermore, an imbalance in cellular redox status was evident through the induction of ROS and depletion of glutathione (GSH), indicating oxidative stress as a potential underlying mechanism of cytotoxicity.⁸³

ZnO NM-110, extensively studied in vitro, exhibits adverse effects in multiple cell lines, with immune system alterations observed in Raw 264.7 and MH-S macrophages (EC50: 10-25 µg/mL, *i.e.*, 3-7.5 µmol/L sites doses), pulmonary cell lines displaying cytotoxic and genotoxic effects (LC50: 76 µg/mL, that is, 22.8 µmol sites/L),^{84 85} and respiratory and male reproductive cell lines affected (EC50 < 20 µg/mL, so less than 6 µmol sites/L).⁸⁶ Hepatic damage in C3A was evidenced by WST-1 test.⁸⁷ Proteomic analysis in NRK-52E reveals pronounced effects, particularly in actin carbonylation; this ENM is classified as highly cytotoxic and a protein carbonylation agent.⁸⁸ Caco-2 cell lines exhibit cytotoxicity due to dissolved Zn²⁺, and HUVEC cell lines show reduced mitochondrial viability attributed to intracellular Zn ions and ROS. In contrast, TiO₂ NM-101 shows no cytotoxicity or inflammatory markers.^{89 90}

TiO₂ NM-101 exhibited no significant cytotoxicity in A549, HepG2, HK-2, and C3A cell lines. However, C3A cells showed IL-8 release, indicating inflammation.^{87,91} BEAS-2B cell viability

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was unaffected by TiO₂ at concentrations of 1-100 µg/mL, i.e., 2.8-280 µmol sites/L, but DNA damage and IL-6 release were observed at 10 (28 µmol sites/L) and 100 µg/mL, respectively. RAW 264.7 macrophages exposed to TiO₂ NM-101 released IL-6 and TNF-α at higher concentrations (100 µg/mL).⁹²

The toxic mechanism of **CeO₂ NM-211** remains unclear, but protein aggregation and fibrillation are proposed hypotheses.^{93, 94} CeO₂ NM-211 induced moderate pro-inflammatory cytokine release in rat precision-cut lung slices (PCLuS) at 100 µg/mL, which represents a sites concentration of 70 µmol/L. It is in line with other In vivo studies, where inflammatory markers increased in the bronchoalveolar lavage fluid (BALF) after 14 days of exposure.^{95,96} In vitro, A549 cells exposed to similar cerium oxide nanoparticles at concentrations up to 100 µg/mL showed no cytotoxicity.⁹⁷ In contrast, NR8383 alveolar macrophages exhibited cytotoxicity at 90 µg/mL (63 µmol site/L) along with signs of inflammation, including TNF-α release, after CeO₂ NM-211 exposure.⁹⁸ These results will be analyzed in section 4.2 with respect to our in chemico method, as gravimetric, surface, and reactive site-based concentrations offer insights into the diverse doses of ENMs in toxicology.

Fe₃O₄-SA showed no adverse effects on A549 cell viability for 24-72 h for concentrations up to 100 µg/mL (equivalent to 20 µmol site/L), even after being internalized within the cells following 12 h exposure. Furthermore, an increase in lysosomal activity was not detected after 6 h. However, a concentration-dependent decrease in mitochondrial membrane potential at 100 µg/mL was statistically significant. There was no induction of pro-inflammatory cytokine secretion, including IL-1β, IL-6, IL-8, and TNF-α. This evidence suggests that iron oxide exhibits low cytotoxicity.⁹⁹

Cyto-genotoxic and inflammatory responses of **Co₃O₄-SA** in human alveolar (A549) and bronchial (BEAS-2B) cell lines was evaluated at concentrations ranging from 1–40 µg/ml, equivalent to 0.3-12 µmol site/L. Notably, A549 cells exhibited no cytotoxicity, while BEAS-2B cells showed reduced viability at 40 µg/ml and early membrane damage at 1, 5, and 40 µg/ml. Significant direct and oxidative DNA damage was observed in A549 cells at 20 and 40 µg/ml, with no impact on cytokine release. Conversely, BEAS-2B cells exhibited significant direct DNA damage at 40 µg/ml and notable oxidative DNA damage at lower concentrations, coupled with increased TNF-α and IL-8 release at specific concentrations

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and exposure times. These results underline the differential cellular responses to cobalt oxide nanoparticles, highlighting the enhanced sensitivity of BEAS-2B cells to cytotoxic, genotoxic, and pro-inflammatory effects.¹⁰⁰ The genotoxic effects of cobalt oxide in Chinese hamster lung fibroblast (V79) cells, primarily mediated by reactive oxygen species, were used to compare with the bulk counterparts: Co₃O₄-SA nanoparticles exhibit pronounced genotoxic effects compared to bulk Co₃O₄ macroparticles, due to significant cytotoxicity and DNA damage, attributed to enhanced ROS generation. The mitigation of genotoxic effects with N-acetylcysteine, a ROS scavenger, further confirms the central role of ROS in nanoparticle-induced toxicity. The nano-sized particles facilitate closer cellular interactions, leading to significant cytotoxicity and DNA damage from ROS, unlike the minimal interaction and impact observed with bulk materials.¹⁰¹

4 DISCUSSION

4.1 ENMs' surface sites and reactivity

The exponential increase in surface-to-volume ratio as particle size decreases to a few nanometers is crucial; additionally, quantum confinement and discrete energy levels alter electronic states and surface reactivity. We focus on the phenomenological consequences of this, not its origins. A comprehensive categorization of ENM requires an understanding of their reactivity characteristics; namely, the number of reactive surface sites, their reactive nature and relative reactivity. Nanomaterials can oxidize molecules directly or generate ROS through interactions with biological systems, which may also alter their properties. These interactions depend on the surface properties of the nanomaterials, including reactive sites beyond physical surface area. While oxidative potential is often highlighted, acidic and basic sites also significantly impact molecular interactions. Our method maps all reactive sites to provide a comprehensive description of nanomaterials and enable more reliable grouping based on their chemical surfaces. According to our data, reactivity-triggered nanotoxicity not only depends on the number and reactivity of redox sites but also on sites of basic and acidic nature. Their interplay determines how ENM's interact with the environment and with our physiology. Parameters like site-specific numbers and TOF (e.g., DTT OxTOF) are essential in elucidating the reactive potential of ENMs and linking them to potential adverse effects. Additionally, TPSR profiles provide insights into these sites' relative presence and reactivity, influencing toxicity profiles. OxTOF tendency in Figure 4C shows CuO-SA \approx CuFe₂O₄-SA > Co₃O₄-SA >> Ce₂O₃ NM-211, in line with oxidation capacity assessed by methanol-TPSR;

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also following this correlation, the titanias, Fe₃O₄-SA and ZnO NM-110 exhibit very little methanol oxidation. Therefore, DTT probe reaction is an oxidative dehydrogenation forming a disulfide group that appears to run mechanistically parallel to the oxidative dehydrogenation of methanol to formaldehyde in TPSR experiments. The use of chemisorption avoids interference from ion release, buffer reactivity (as observed with some probe reactions in phosphate medium),¹⁰² or agglomeration that would take place in liquid-phase assays.

Reactive site surface density quantified by methanol chemisorption in our series is consistent with values reported in the literature for oxide ENMs, ranging between 0.4 and 22 sites/nm², but typically up to ca. 7 sites/nm², corresponding to a monolayer.³⁹ The high number of reactive sites on CuO-SA (22) and ZnO NM-110 (17) surfaces must be related to a highly reactive interaction with chemisorbed methoxy groups. Multilayer formation is likely on ZnO NM-110 basic sites, as suggested for La₂O₃, MgO or Cr₂O₃,³⁹ whereas CuO-SA is a highly oxidizing material that transforms surface methoxy groups into formate groups^{103,104,105}. This is consistent with the extensive CO₂ desorption profile during MeOH-TPSR. Hence, the chemisorption temperature was set to 50 °C in these materials. CO₂ formation at low temperatures on highly reactive CuO-SA is characteristic of formates decomposition, while the formation of CO₂ at high temperatures on the alkaline ZnO NM-110 is associated with the decomposition of carbonates.¹⁰⁴ The determination of reactive sites provides complementary insight to ROS determination probes, which sensitivity depends on different features. For instance, the basic character of ZnO NM-110 and its high reactive site surface density correlates with the ferric reduction ability of serum (FRAS) assay, an indirect measurement of ROS by total antioxidant depletion, and protein carbonylation assay.¹⁰⁶ In another study, electron spin resonance (ESR) spectroscopy with 3-carboxy-2,2,5,5-tetramethylpyrrolidine 1-oxyl (CPH) and 5,5-dimethyl-1-pyrroline N-oxide (DMPO) probe molecules quantifies the oxidative potential of ENMs by determining the ROS production.¹⁰⁷ Less ROS were produced by CeO₂ NM-211 and ZnO NM-110 when compared with CuO,¹⁰⁶ which agrees with our reactive ranking based in OxTOF data, and the higher number of reactive surface sites of the latter; the CPH spin probe (more sensitive to singlet oxygen, superoxide radicals, and peroxy nitrates) revealed higher ROS production by ceria than by zinc oxide, whereas the DMPO spin trap (more sensitive to hydroxyls and superoxide radicals) showed the opposite trend. Raman spectroscopy, which is highly

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3 sensitive to peroxide-related species, can be used to further analyze this. *In situ*^{108,109} and
4 *operando*¹¹⁰ Raman spectra show that superoxide and peroxide species are generated at
5 the surface of different ceria materials by interaction with molecular oxygen, but there are
6 no reports of superoxide species formed at the surface of ZnO and TiO₂. Thus, reactive
7 superoxide species would only account for DMPO and CPH by CeO₂ NM-211, but not by
8 ZnO NM-110 or titania; therefore, ZnO NM-110 must generate more hydroxyls than CeO₂
9 NM-211 to account for the DMPO probe results.
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predicting the overall toxicological profile, comparisons are not straightforward, and correlations with physicochemical properties of ENMs can only be done as a first approximation.^{77,120} The *in vitro* toxic effects of ENMs that over-oxidize methanol to CO₂ in TPSR and show redox surface reactivity (Co₃O₄-SA, CuFe₂O₄-SA and CuO-SA) significantly affected different cell lines,^{83,101,120} underscoring the implication of reactive surface sites in nanotoxicity field. When comparing CuO-SA and ZnO NM-110, the higher reactive sites surface density and the lower temperature of maximum methanol conversion to CO₂ of the former are indicative of a higher reactivity of CuO-SA, which correlates with the higher toxicity reported by cell viability assays with A549 line: EC₅₀ for 24 h exposure was 17.75 for CuO-SA and 76 µg/mL for ZnO NM-110.^{84,120} Site-based dose metrics underlines the higher *in vitro* toxicity of CuO-SA sites. DTT OxTOF could not be evaluated for ZnO NM-110; still, the physical-chemical properties reported in the literature -oxidation number, ionic potential, surface reducibility and redox reactivity- are consistent with its high *in vitro* toxicity.¹²¹ Nevertheless, ZnO NM-110 is a complex ENM, because its surface reactivity has biocidal properties,¹²² but its mode of action is essentially by dissolution.¹²¹

CuO-SA has the highest reactive sites surface density in the series, though not the most sites per gram, and shows the highest OxTOF (Figure 2D, Figure 4E) along with CuFe₂O₄-SA. This correlates with their inflammatory effects, commonly associated with ROS generation and oxidative stress, making these ENMs the most toxic in the series.¹²³ CuO-SA's oxidative damage was evaluated in HepG2 cells, with endocytosis transporting nanoparticles to endo/lysosomes, leading to lysosome disruption and copper ion overload.¹²⁴ This mechanism may involve surface reactivity, initially overlooked due to lack of information on reactive sites. CuO-SA induced oxidative changes in A549 cells, increasing protein carbonylation, oxidizing protein thiols, and decreasing cell viability, with no effects from dissolved copper ions.¹²⁵ These effects were more pronounced in CuO-SA with higher crystalline defects and ROS production, likely due to higher reactive sites surface density.¹²⁵ Other studies reported CuO-SA's distinct cytotoxicity in A549 and HeLa S3 cells from direct interactions with cellular components, facilitated by greater surface area and reactive sites density compared to microparticles. This parameter could facilitate the surface interactions of CuO-SA with their surroundings. For that reason, elevated intracellular levels can disrupt copper homeostasis, leading to pro-oxidative reactions¹²⁶ produced at the surface of CuO-SA nanoparticles.¹²⁷

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Co₃O₄-SA nanoparticles exhibited higher reactivity for DTT depletion than bulk material, reflected in genotoxic effects V79 cells, primarily mediated by reactive oxygen species. This indicates that nano-sized Co₃O₄-SA induces significant cytotoxicity and DNA damage, unlike larger particles.¹⁰¹ The toxicity of TiO₂ NM-101 is not fully understood due to inconsistent evidence across different tests.

In the case of CeO₂, the literature has typically linked its toxicity with reactive oxygen species generation and the Ce³⁺/Ce⁴⁺ ratio,¹²⁸ related to the exposed phase of ceria^{129,130} and its defects, which is also key for catalytic activity.¹⁰⁸ These properties can be easily determined by several techniques^{131–135} CeO₂ NM-211, with redox surface sites and moderate oxidative capacity, causes cell death by apoptosis and DNA damage in pulmonary cell lines.^{136,137} The OxTOF of CeO₂ NM-211 is between those of the titania ENMs and of CuO-SA, despite its low BET. This is consistent with the intense formaldehyde production in MeOH-TPSR, maximum at 259 °C, and with characterization reported in the literature: CeO₂ NM-211 surface contains 22% Ce (III) (XPS), indicative of redox sites, which induce ROS generation, as detected by ESR.^{131–135} CeO₂ is highly oxidizing, while defect-rich CeO_{2-x} has antioxidant properties. This versatility is used to engineer ceria nanoparticles by tuning its properties.^{138,139} and, thus, its performance e.g. in catalysis, from combustion to selective oxidation^{131,140,141}, and in biomedical applications, from biocidal to antioxidant^{138,139,142}. The dynamic states of ceria nanomaterials in aqueous media¹⁴³ or biological media^{132,144,145} resulting in defective ceria are extensively investigated¹⁴⁶.

ZnO NM-110, which induces protein carbonylation,¹⁴⁷ has high reactive site surface density, facilitating the formation of a protein corona. This aligns with reports on BSA-ZnO interactions, which demonstrate that protein adsorption on ZnO NM-110 surface is higher compared to other ENMs like TiO₂ NM-110.⁸⁴ Despite TiO₂ NM-110 having a larger surface area, its reactive sites surface density is lower than that of ZnO NM-110.

Titania and iron oxide exhibit the lowest reactivity. Fe₃O₄-SA showed no adverse effects even after being internalized within the cells following 12 h exposure. Similarly, both titania samples convert methanol into carbon dioxide, but above 400 °C and to a limited extent, as they are essentially acidic. This low redox reactivity is consistent with their low DTT OxTOF.

In line with our hypothesis, the high BET area of TiO_2 NM-101 does not directly correlate with adverse effects. While it has a high surface area (a physical feature) its chemical reactive profile counterpart does not run in parallel. The number of surface reactive sites is low, and their reactivity is moderate. TiO_2 NM-101 is a relatively safe ENM, with no cytotoxicity for cell viability in immune, hepatic, reproductive and pulmonary cell lines such as A549, HepG2, HK-2 or C3A. There are no toxicological data for TiO_2 -DT51, but the lower number and reactivity of its sites predicts that DT51 would be safer than NM-101. Fe_3O_4 , classified as low redox reactive via DTT OxTOF, is described as a safe ENM in terms of *in vitro* evaluation in the literature.⁹⁹

An *in chemico* classification of ENMs can thus be proposed based on methanol chemisorption, reactivity of surface sites and DTT Oxidative Turnover Frequency that may correlate with *in vitro* toxicity sites-based dose metrics: $\text{CuO-SA} \approx \text{CuFe}_2\text{O}_4\text{-SA} > \text{Co}_3\text{O}_4\text{-SA} \approx \text{ZnO NM-110} \gg \text{CeO}_2 \text{ NM-211} \geq \text{Fe}_3\text{O}_4\text{-SA} \approx \text{TiO}_2 \text{ NM-110}$

4.3 Reactive surface site-based dose metrics

Recently, some works emphasized the critical importance of adopting dose metrics that reflect the relevance of surface and particle number when assessing the nanotoxicity of ENMs, as traditional mass-based dose metrics are insufficient for evaluating the unique toxicological responses of nanoscale particles.^{148,149} These studies collectively underscore the need for more accurate dose metrics to assess the potential risks associated with ENMs. Due to the assumption that not all physical areas are equally populated by equally reactive sites, the reactive sites concentration is proposed as a tool to better quantify the ENMs exposition. For example, TiO_2 NM-101 has 4 times higher specific number of reactive sites than CeO_2 NM-211 (2.8 vs 0.7 mmol/g), but also 3 times higher surface area, so the reactive sites surface density is only slightly higher for the titania (7 vs. 6 sites/nm²), and therefore the comparison is similar by DTT OxTOF and by OP_{area} : TiO_2 NM-101 has 3-4 times less oxidative potential than CeO_2 NM-211. A different impression is provided by OP_{mass} . Hence, while mass or physical surface area do not provide a site-relevant dose metrics, the number of reactive sites connects with reactivity-triggered effects. This may serve as a new possible dose metrics as an approach to assess the exposure to nanomaterials. The differences are greater when TiO_2 NM-101 is compared to CuO-SA , with very low specific surface area, and thus high reactive sites surface density. These are much more reactive than those of titania

and ceria, as observed by DTT OxTOF; but not as much as OP_{area} indicates. Moreover, a dose metrics based on reactive sites underscores that CuO-SA, with a dose of sites of 4 $\mu\text{mol/L}$, is capable of producing a significant adverse effect in A549, while 280 $\mu\text{mol/L}$ of titania sites did not significantly decrease cell viability.

5 CONCLUSIONS AND OUTLOOK

Reactive-based nanotoxicity is primarily governed by the surface chemistry of engineered nanomaterials, making catalysis science principles highly relevant to describing the reactive nature of ENMs. Our findings conclude that 1) The specific surface area does not reliably correlate with nanomaterial reactivity, necessitating consideration of surface sites quantity, nature, and reactivity for categorization and site-specific dosing; 2) this can be achieved by a new approach methodology that quantifies and describes reactive surface sites by chemisorption and reaction tests with probe molecules. 3) Methanol offers a triple benefit: it quantifies surface sites through chemisorption, characterizes surface reactivity (acidic, basic, or redox) via temperature-programmed surface reaction, and overcomes limitations of liquid-phase reactions, such as possible ion release, pH-dependent agglomeration, effects of the dispersion protocol, or stability issues, providing insights into the primary reactivity of thermally-stable nanomaterials such as metal oxides. 4) Combining site quantification with physiologically relevant oxidation reactions, like DTT, allows for calculating site-specific oxidative reactivity (OxTOF), aiding nanomaterial classification: CuO-SA, CuFe_2O_4 -SA, Co_3O_4 -SA are the most oxidizing ENMs, according to a higher *in vitro* toxicity, while less reactive ENMs does not produce adverse effects in *in vitro* models.

CuO-SA, CuFe_2O_4 -SA, Co_3O_4 -SA, Fe_3O_4 -SA, ZnO NM-110, CeO_2 NM-211 and two TiO_2 ENMs (DT51 and NM-101) are ranked into three categories with statistically different reactivity based on DTT. This fundamental site-specific reactivity information is a relevant descriptor to group ENMs and, ultimately, understand nanotoxicity. Moreover, the behavior of a given material not only depends on its specific nanoform (e.g., crystallinity, size, band gap, solubility, hydrophobicity, surface charge, aspect ratio or shape), but also on its chemical reactive features, like the number of surface reactive sites, their nature, their reactivity and their relative populations. In another cases, the adverse effect would not appear related to the reactivity but to other features, like in multiwalled carbon nanotubes.¹⁵⁰

This new methodology offers a complementary *in chemico* approach to unravel nanomaterial modes of action. To validate its effectiveness, further testing with additional reference and real-life ENMs and relevant and comparable toxicity information is essential. On a broader vista, the correlation with cellular assays will help establish molecular insight into the reactive basis of nanotoxicity. There are, however, significant structure, reactivity and toxicity data gaps to connect adverse effects with chemical reactivity. This approach aims to elucidate the specific pathways impacted by ENMs, highlighting their role in achieving a comprehensive understanding of nanomaterial toxicity and advocating for safe-by-design principles. Filling these data gaps is in the mission of nanoinformatics and nanosafety projects, supported by platforms like eNanoMapper. Mapping all reactive properties enables a more relevant grouping of nanomaterials since the acidic, basic and redox properties not only reflect their reactivity for adverse effects but also for interaction with species and molecules in biological systems.

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