Physicochemical Characteristics of Two Prototypical Home-Use Consumer Products Containing Engineered Nanomaterials

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Abstract

The extensive use of nanomaterials in new products for the building envelope is expanding rapidly and continues to influence materials science and environmental health. However, there is still uncertainty around the safety of these novel materials to humans and the environment; therefore, more life cycle data is needed. One analytical technique to gather information critical to the development of safe nanomaterials is to characterize the physicochemical properties of the nanoparticle-bearing product throughout various stages of the product life cycle. This research investigates two different products fortified with nanoscale titanium dioxide (TiO2) nanoparticles. Three brands of commercially available titanium dioxide (TiO2) nanoparticles were incorporated into lab- formulated powders and lacquered matrices for all three nanoparticle-types. Cell viability and reactive oxygen species (ROS) generation was measured in immortalized human lung epithelial cells (A549). Results from bioassays showed that ROS generation between unincorporated TiO2 particles and TiO2 incorporated lacquered powders showed little difference, but, the TiO2 incorporated lacquered powders demonstrated significantly lower ROS generation and cell death. Thus, the polymer-based lacquer mitigated tissue damage.

Keywords: Nanocomposites; Nanomaterials; Titanium dioxide; Physicochemical characteristics; Cytotoxicity; Material characterization

Introduction

Engineered nanomaterials offer great advantages to the building industry by supporting sustainable development. It is well documented that the physical and chemical properties of nanometer-sized materials offer specific benefits over the same material in bulk form [1,2]. For example, in the building industry, engineered nanoparticles can increase resistance to ultraviolet damage, prevent degradation and fouling, and improve the rheology, hardness, and strength of construction materials [3]. In many cases, individual engineered nanoparticles are incorporated into large composite products (e.g., cements, concretes, plastics, metal, or ceramics) which provide the benefits of nanotechnology, but with a generally-regarded decreased risk of direct particle exposure. To date, more than 250 products produced by over 100 companies incorporate nanocomposites into building or renovation plans with estimated revenues surpassing $1 billion [6]. Although nanocomposites have been hypothesized to substantially decrease the potential for direct exposure to nanoparticles [4,5], the potential for human and environmental risk along the various stages of nanoparticle incorporation into complex matrices, such as paint and lacquer formulations. More importantly, changes in physiochemical characteristics, potential exposure scenarios, and hazards of the intermediate materials are unknown and are in need of research emphasis [16]. The identification and characterization of engineered nanoparticles in complex matrices is a prerequisite to fill data gaps in risk assessments of human and environmental safety of nanomaterials in real world scenarios [12-14].

While several studies have heavily investigated the physicochemical characteristics and material toxicity of pristine or unincorporated TiO2 nanoparticles [15], little is known about the effects of TiO2 nanoparticles incorporated into complex matrices, such as paint and lacquer formulations. The global use of TiO2 for paint and surface applications alone exceeds 2.5 million tons annually with the specific use of nanoscale TiO2 conservatively estimated around 30,000 tons [9-11]. As a result, human exposure to these engineered nanoparticles is inevitable. The route and extent of particle exposure, however, is dependent upon the application and use of the nano-enabled product in real world scenarios [12-14].

The paint and lacquer industry, in particular, uses tons of engineered nanomaterials, annually. Titanium dioxide (TiO2) nanoparticles have traditionally been incorporated in paint and lacquer formulations as a whitening agent and to provide properties such as improved durability, water repellence, and scratch resistance [8]. The global use of TiO2 for paint and surface applications alone exceeds 2.5 million tons annually with the specific use of nanoscale TiO2 conservatively estimated around 30,000 tons [9-11]. As a result, human exposure to these engineered nanoparticles is inevitable. The route and extent of particle exposure, however, is dependent upon the application and use of the nano-enabled product in real world scenarios [12-14].

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the development of safe nanomaterials is employing a product life cycle approach [17-20] which integrates product development with manufacturing and consumer/occupational exposure. Potential exposures in the form of precipitated particles from water waste or airborne particles from aerosolization processes are examples of by-products from nano-enabled goods that could cause potential adverse health effects [21].

This research characterizes pristine, unincorporated, bulk TiO₂ material and degraded, incorporated, nanoparticle-enabled by-products. Three commercially available TiO₂ nanoparticles were mixed into paint and lacquer formulations and applied onto industry standard substrates: paint on drywall and lacquer on hardwood panels. Simulated wear-and-tear scenarios were performed on each of the substrates. Pristine and worn-and-torn powders were then exposed to immortalized human lung epithelial cells to investigate the effect on cellular viability and reactive oxygen species (ROS) generation. The impact of this research will help enable sustainable opportunities of nanotechnology in the built environment.

Materials and Methods

Nanoparticles used in the study

Three commercially available TiO₂ nanoparticles currently used for applications in industrial coatings were used. These pristine nanoparticles differed in surface treatment and were designated as TiO₂-1, a silica/alumina-treated rutile pigment, TiO₂-2, a zirconia/alumina-treated rutile pigment, and TiO₂-3, an aluminum hydroxide/silica-treated rutile pigment. Materials TiO₂-1 and TiO₂-2 were obtained from Tronox Limited with trade names CR-826 and CR-828, respectively. The third material, TiO₂-3, was acquired from Cristal Global with trade name Tiona 596. All TiO₂ nanoparticles were multipurpose grade rutile pigments having excellent optical properties and high durability. The properties of the three focal TiO₂ nanoparticles used in this study are listed in Table 1.

Nano-enabled products

To mimic real word applications, the three TiO₂ nanoparticles were incorporated into paint and lacquer coatings. The laboratory-formulated coatings were prepared as described below.

Paint on drywall: The paint formulation used included base paint (with and without TiO₂) mixed via commercial specifications [22]. EcoVAE Interior Quality Flat formulation was used as a reference for applications in industrial coatings. The steps involved in the paint formulation and subsequent wear-and-tear process on the drywalls are depicted in Figure 2 in the Supporting Information. The worn-and-torn paint powders were designated as base paint (i.e., no TiO₂), base paint plus TiO₂-1, base paint plus TiO₂-2, and base paint plus TiO₂-3.

Wear-and-tear process

The steps involved in the paint formulation and subsequent wear-and-tear process on the drywalls are depicted in Figure 1 in the Supporting Information. The worn-and-torn paint powders were designated as base paint (i.e., no TiO₂), base paint plus TiO₂-1, base paint plus TiO₂-2, and base paint plus TiO₂-3.

Material characterization

The following material characterization techniques were used to analyze the pristine, unincorporated TiO₂ nanoparticles (as described in Section 2.1) as well as the worn-and-torn TiO₂-enabled paint and lacquered wood powders (as described in Section 2.3).

Transmission Electron Microscopy (TEM): Samples were suspended in ultra-pure water in preparation of TEM analysis. Microscope grids were prepared by dropping 3 µL of each suspended sample on to a 200 mesh copper grid (Ted Pella, Inc., Redding, CA) and dried overnight. Samples were imaged using Hitachi H-7000 electron microscope operated at an accelerating voltage of 100 kV. Images were recorded using a Gatan CCD camera and 4pi Revolution® software.

Scanning Electron Microscopy (SEM): Samples for SEM analysis were deposited onto a carbon adhesive surface affixed to SEM stubs and coated with gold/palladium for 2 minutes using a Hummer® sputtering system (Anatech, Ltd., Battle Creek, MI). Samples were imaged using a FEI Quanta 200 environmental scanning electron microscope. Images were recorded using high vacuum mode, typically 15 kV, spot size 2.5, and a working distance of 10 mm. Elemental analysis was performed...
for each sample using the attached X-ray detector and Inca X-sight software (Oxford Instruments X-ray Technology) was used to process the EDX spectra.

**Fourier Transform Infrared Spectroscopy (FTIR):** Chemical compositions of samples were probed using a Thermo-Fischer Smart Orbit-Single Bounce ATR (Thermo Scientific, Madison, WI) using a Nicolet 6700 FTIR in the 400–4000 cm⁻¹ range. Spectra were recorded in transmission mode with a resolution of 4 cm⁻¹. Thirty-two scans were collected and averaged for each spectrum.
Generation of reactive oxygen species

Cell cultures: Cellular response studies were probed using immortalized human lung epithelial (A549) cells (ATCC, Manassas, VA). Cells were maintained in F-12K medium supplemented with 10% fetal bovine serum and 1% penicillin and streptomycin. Cells were cultured at 37°C in a humidified atmosphere with 5% CO2 and passaged every 3 days. Passage numbers 2–10 were used in the experiments.

Cell viability: A549 cells were seeded with 1 × 10⁴ cells/cm² in 24 well plates in complete growth medium and allowed to proliferate for 48 hours until 80% confluent. Cells were gently washed with phosphate buffered saline (HyClone, Logan, UT), followed by exposure to increasing concentrations (0, 0.1, 1, 10, 100, and 1000 ppm) of the three pristine TiO₂ nanoparticles in complete medium and incubated for 24 hours. Cell viability was assessed using trypan blue exclusion assay via the Countess® Automated Cell Counter (Invitrogen) as per the manufacturer’s instructions. The purpose of performing a dose-response cytotoxicity study using the pristine TiO₂ samples was to determine a relevant concentration to subsequently perform reactive oxygen species measurements.

Intracellular ROS measurement: DCFH-DA (2',7'-dichloro-fluorescein diacetate) was used to measure the levels of intracellular reactive oxygen species (Cell Biolabs, Inc.) after exposure to TiO₂ in pristine and incorporated form (dosing concentration was 50 ppm or µg/L). Cells were seeded with 1 × 10⁴ cells/cm² in a 96-well plate in complete growth medium. Upon reaching 80% confluency, cells were gently washed with PBS followed by treatment with 100 µM DCFH-DA and incubated at 37°C for 30 min. Cells were then exposed to pristine unincorporated TiO₂ nanoparticles, worn-and-torn paint samples, or worn-and-torn lacquered wood samples and incubated for 24 hours. Hydrogen peroxide (1000 µM) was used as the positive control. Unexposed cells in complete medium served as a negative control. After the 24-hour incubation, fluorescence was measured at 480 and 530 nm (excitation and emission, respectively) using a fluorescence plate reader (Synergy Mx Multi-Mode Microplate Reader, BioTek Instruments, Inc., Winooski, VT). The study was designed for an n=8 replicates per treatment and each experiment were performed in triplicate.
Simulation was designed to mimic a consumer sanding a surface (Stage subjected to simulated wear-and-tear scenarios. This wear-and-tear lacquer formulations, applied to drywall and wood, respectively, and TiO this study are currently used in paint products. Designated as TiO oxidation testing using appropriate model test systems depending on the type of identification of potential hazards from such sources requires toxicity of the coating determines the degree of photoactivity [34]. From a dictate the photoactivity of titania pigments and the effectiveness of these minerals [32]. Surface modifications with inorganic hydrates ability in different media (water, solvent, and polymer) and improved decrease the photoactivity of titania pigments by increasing electron-hole recombination sites [33]. Hence, the surface treatment technique of TiO nanoparticles (i.e., base paint plus TiO) indicate TiO nanoparticles embedded in the matrix. The micrographs also show the presence of TiO nanoparticles. Micrographs suggest aggregate particle size to be approximately 600 nm for all three TiO nano-enabled paint products. Additionally, the EDX spectra confirm the absence of TiO in the reference material and the presence of TiO in other samples with characteristic peaks of Ti (0.45, 4.5 and 4.9 keV). The background material also shows representative peaks for carbon and oxygen. The strong Si peak in samples can be attributed to the paint ingredient Diahil 525, which contains silicon and silica. The calcium (Ca) peak is present in native drywall in the form of calcium carbonate. Taken together, these analytical techniques confirm the presence of TiO2 nanoparticles embedded in the resin matrix, the EDX peaks are not as strong as the paint samples (16 wt% TiO2) but the micrographs confirm the presence of the nanoparticles. In addition to electron microscopy, unincorporated and incorporated TiO2 nanoparticles were analyzed using Fourier transform infrared spectroscopy (FTIR). The fundamental vibrations of TiO2 appear in the in the low energy region of the infrared spectra. A peak in the 500-520 cm\(^{-1}\) range can be attributed to the presence of TiO2 in the samples [36-39]. Additionally, bands in the low energy region between 340-520 cm\(^{-1}\) can be assigned to the stretching vibrations of the Ti-O-Ti bonds [36,40,41].

**Statistical analysis**

Each value represents the mean of at least three separate analyses plus or minus the standard error of the mean. Multiple comparisons were performed using analysis of variance (ANOVA) followed by post-hoc testing if \( p < 0.05 \).

Differences between treatment groups were analyzed via the Turkey-Kramer Multiple Comparisons test, a parametric analyses, comparing all pairs of columns to untreated cells.

Probability values of \( p < 0.05 \) were considered to be statistically significant. Statistical analyses were performed using INSTAT software v 3.0 (GraphPad, Inc., San Diego, CA).

**Results and Discussion**

**Physicochemical analyses of TiO2-enabled products**

TiO\(_2\) particles primarily exist in two morphological crystalline forms, rutile or anatase, with each phase possessing a unique crystal structure [29,30]. The differences in crystal structures cause differences in mass densities and electronic band structures, and consequently affect their photoactivity [30]. In general, rutile is claimed to be less photoactive than anatase due to surface defects and thus commonly used as a white pigment in the coating industry [29,31]. To improve pigment dispersion, the surface of TiO\(_2\) is treated with alumina, silica, zirconia, aluminum phosphates of other metals or often a combination of these minerals [32]. Surface modifications with inorganic hydrates decrease the photoactivity of titania pigments by increasing electron-hole recombination sites [33]. Hence, the surface treatment technique dictates the photoactivity of titania pigments and the effectiveness of the coating determines the degree of photoactivity [34]. From a toxicological point of view, surface modifications physically inhibit the diffusion of oxygen and thereby reduce the generation of free radicals. Other advantages of surface treatments include improved wetting ability in different media (water, solvent, and polymer) and improved compatibility with binder and color stability [35].

The life cycle or product value chain for engineered nanomaterials incorporated into paints and other coatings has four main stages in which human exposure may occur: (1) manufacture/production of raw materials, (2) product formulation, (3) product use, and (4) product demolition and disposal. The exposure risks in these stages include the release of pristine particles or formulated composites as industrial air emissions, wastewater processes, or trash. In regard to human exposure, release from worn-and-torn formulated composites, as in the case of natural weathering or “do-it-yourself” home projects, into aerosolized particulate matter in the breathing zone or solid particulates that deposit on the skin’s surface are major sources of concern. Further identification of potential hazards from such sources requires toxicity testing using appropriate model test systems depending on the type of exposure.

The three pristine, unincorporated TiO\(_2\) nanoparticles chosen for this study are currently used in paint products. Designated as TiO\(_2\)-1, TiO\(_2\)-2, and TiO\(_2\)-3, these particles were incorporated into paint and lacquer formulations, applied to drywall and wood, respectively, and subjected to simulated wear-and-tear scenarios. This wear-and-tear simulation was designed to mimic a consumer sanding a surface (Stage 4), which are analyzed and compared to the pristine particles (Stage 1) [16].

**Material characterization**

Images from electron microscopy reveal critical information about the particle size, shape, aggregation, and morphology. Energy dispersive X-ray spectroscopy (EDX) confirms the elemental composition of each sample. Figure 1 shows the transmission and scanning electron micrographs of the three pristine TiO\(_2\) samples. These micrographs confirm primary particle size to be 200 nm for all three TiO\(_2\) nanoparticle-types.

Figure 2 shows the TEM, SEM and EDX spectra of the worn-and-torn paint powders. Micrographs of the base paint formulations mixed with TiO\(_2\) nanoparticles (i.e., base paint plus TiO\(_2\)) indicate TiO\(_2\) nanoparticles embedded in the matrix. The micrographs also show the presence of TiO\(_2\) particles. Micrographs suggest aggregate particle size to be approximately 600 nm for all three TiO\(_2\) nano-enabled paint products. Additionally, the EDX spectra confirm the absence of TiO\(_2\) in the reference material and the presence of TiO\(_2\) in other samples with characteristic peaks of Ti (0.45, 4.5 and 4.9 keV). The background material also shows representative peaks for carbon and oxygen. The strong Si peak in samples can be attributed to the paint ingredient Diahil 525, which contains silicon and silica. The calcium (Ca) peak is present in native drywall in the form of calcium carbonate. Figure 3 shows the TEM, SEM and EDX spectra of the worn-and-torn lacquered wood samples. As shown in the micrographs, the reference sample (i.e., uncoated wood) does not have any characteristic TiO\(_2\) particles while all the other samples (lacquered wood with TiO\(_2\)) show TiO\(_2\) nanoparticles embedded in the complex wood matrix. Micrographs reveal aggregate particle sizes are approximately 200 nm and approximately 600 nm for all three TiO\(_2\) nano-enabled wood samples. Samples with incorporated nanoparticles clearly indicate the presence of TiO\(_2\) nanoparticles in the EDX spectra. Because only 2 wt% TiO\(_2\) was included in the resin matrix, the EDX peaks are not as strong as the paint samples (16 wt% TiO\(_2\), but the micrographs confirm the presence of the nanoparticles.

In addition to electron microscopy, unincorporated and incorporated TiO\(_2\) samples were analyzed using Fourier transform infrared spectroscopy (FTIR). The fundamental vibrations of TiO\(_2\) appear in the in the low energy region of the infrared spectra. A peak in the 500-520 cm\(^{-1}\) range can be attributed to the presence of TiO\(_2\) in the samples [36-39]. Additionally, bands in the low energy region between 340-520 cm\(^{-1}\) can be assigned to the stretching vibrations of the Ti-O-Ti bonds [36,40,41].

Figures 4a, b and c show the FTIR spectra of the pristine TiO\(_2\) nanoparticles, the worn-and-torn paint samples and the worn-and-torn lacquered wood samples, respectively. On analyzing the spectral peak positions, the characteristic structure of TiO\(_2\) in the 340-520 cm\(^{-1}\) range is observed in all three pristine TiO\(_2\) samples (Figure 4a).
Figure 4b shows the FTIR spectra of the worn-and-torn paint samples. The FTIR spectrum of the base paint with no TiO$_2$ is also shown. The characteristic structure of TiO$_2$ in the 340-520 cm$^{-1}$ range is present in all three worn-and-torn paint samples but absent in the base paint spectrum. In order to further quantify this TiO$_2$ peak, the worn-and-torn paint samples were corrected for background using the base paint sample as the reference spectra. Figure 3 in the Supporting Information overlays the FTIR spectra of the three pristine TiO$_2$ nanoparticles to the corresponding worn-and-torn paint plus TiO$_2$ samples. The peak at approximately 500 cm$^{-1}$ is clearly visible in all three worn-and-torn paint samples and matches the pristine sample spectra. Therefore, in addition to microscopy techniques such as TEM and SEM, and elemental analysis via SEM-EDX, these FTIR spectra further confirm the presence of TiO$_2$ in the complex worn-and-torn paint matrix. At 16 wt% TiO$_2$ included in the paint formulations; FTIR is able to detect the presence of the characteristic TiO$_2$ peaks in all the worn-and-torn paint samples.

Figure 4c shows the FTIR spectra of the worn-and-torn lacquered wood samples. The FTIR spectrum of the wood with no TiO$_2$ is also shown. From these spectra it is evident that the characteristic peak of Ti at 520 cm$^{-1}$ is not prominent in any of the worn-and-torn lacquered wood samples. Because the samples contain only 2 wt% TiO$_2$ in this formulation, the signal appears to be below the detection limit of the FTIR system. As a result, the signal from the TiO$_2$ in the worn-and-torn lacquered wood matrix is not visible by FTIR, but is detectable by other material characterization techniques such as TEM, SEM and SEM-EDX which confirmed the presence of TiO$_2$ in the complex worn-and-torn matrix.

Generation of reactive oxygen species

As with any new technology, the identification of potential health risks is a prerequisite for a cost-benefit analysis of new products. Studies suggest some nanomaterials can affect biological behaviors at
the cellular level (e.g., decreased viability, increased reactive oxygen species (ROS) generation). Human and environmental health risks can be determined through assessment of the hazards posed and the potential for exposure to the nanomaterials in various life cycle stages. The most likely route of exposure to nanomaterials used in consumer products is inhalation by the occupational worker [42,43]. As the wear-and-tear simulation of this study produced airborne powders in the so-called use stage, inhalation is also a likely route of consumer exposure. A549 cells (a model lung system used to gauge the differential toxicological responses within a large set of material samples) were exposed for 24 hours to increasing concentrations of all three pristine TiO$_2$ nanoparticles (0, 0.1, 1, 10, 100, and 1000 ppm). Based on the cellular response to these doses, a medium dose was chosen as the primary dosing concentration for subsequent ROS generation evaluation. The results of the trypan blue exclusion assay are summarized in Figure 5a. Cells exhibit a fairly monotonic dose-response relationship upon exposures to all three nanoparticle-types.

Cellular viability is significantly reduced (<0.01) as compared to untreated cells at the highest dose of 1000 ppm for all three TiO$_2$ types. Since cellular viability was unaltered at doses of 0.1, 1 and 10 ppm (and significantly altered at the highest dose of 1000 ppm), the 100 ppm dose was selected as the primary dosing concentration for ROS evaluation.

Recent evidence indicates that the possible mechanism of TiO$_2$ nanoparticle-induced toxicity involves DNA damage via oxidative stress [21]. ROS production of TiO$_2$ nanoparticles in their unincorporated and incorporated forms was tested in vitro. Cellular generation of ROS was measured after a 24-hour exposure to pristine TiO$_2$, worn-and-torn paint samples, and worn-and-torn lacquered wood samples. Data were normalized to the appropriate control values and these results are summarized in Figures 5b, c and d. Statistically significant increase in oxidant production as measured via increased DCF fluorescence was observed with all three pristine TiO$_2$ nanoparticles (Figure 5b). The ROS generation in the TiO$_2$-1, TiO$_2$-2 and TiO$_2$-3 samples was 1.72, 1.96, and 1.65 fold greater than the unexposed control, respectively. The calculated TiO$_2$ particle component after exposure of worn-and-torn materials to these cells was 8 µg/L (16% by weight of 50 µg/L for the paint product and 1 µg/L (2% by weight of 50 µg/L for the polymer material). The results of the ROS production from the worn-and-torn paint and lacquered wood samples are shown in Figure 5c and d. Only two out of the three worn-and-torn paint samples containing TiO$_2$ (i.e., base paint plus TiO$_2$-2 and base paint plus TiO$_2$-3) exhibited significant increase in intracellular oxidants compared to the control. This may be due to differential adhesion, chemical attraction, or wetting of the paint matrix to the TiO$_2$ nanoparticle surface. The water-based paint emulsion wets particles differently based on surface chemistries, thus the different particle-types may reside in different phases of the emulsion. When the paint dries, one particle-type may be "coated" with organic phases and thus not cause ROS generation while other particles may have simply dried as a mixture and still have active sites. In contrast, the worn-and-torn lacquered wood samples containing TiO$_2$ did not cause any significant ROS generation in comparison to the control; however there was a significant difference among the three worn-and-torn lacquered wood samples as wood plus TiO$_2$-3 showed lower ROS generation compared to wood plus TiO$_2$-1 and wood plus TiO$_2$-2 (Figure 5d).

**Commercial paint**

An off-the-shelf commercial paint was purchased and used in this study. This product was a water-based interior flat paint (Valspar White ColorStyle Interior Flat Wall Paint, 44-26300) and served as a comparison to our formulated nano-enabled paints. Paint on drywall samples were made, allowed to cure, and underwent the wear-and-tear simulation in the same fashion as the laboratory-formulated versions. The transmission electron micrograph, scanning electron micrograph and elemental analysis confirm the presence of TiO$_2$ in the worn-and-torn commercial paint particles (Figure 6). The TiO$_2$ nanoparticles were also of a similar particle size as compared to the nano-enabled paint formulated products in Figure 2. Furthermore, the ROS generation in A549 cells upon exposure to this commercial paint sample exhibited a statistically significant intracellular oxidant increase as compared to the control cells. These physicochemical characterization results suggest that the lab formulated paint products are a suitable surrogate of typical nano-enabled consumer products that could be used as a standard material for bridging studies, predictive studies, and simulated studies.

In conclusion, electron microscopy and elemental analysis as analytical chemistry characterization tools were able to detect the
nanoparticles in the worn-and-torn complex paint and lacquer matrices. FTIR, on the other hand, proved to be a useful tool for the nano-enabled lacquered wood samples warrant further investigation. These results validate the usefulness of TEM, SEM and EDX as part of a suite of predictive tools ready to analyze nano-enabled products. FTIR as a material characterization technique, however, is only valid when relatively high concentrations (greater than 15% w/w) of the nanoparticles are incorporated into the products. Furthermore, in vitro ROS generation of both of pristine and worn-and-torn powders provides a more realistic platform for data interpretation and the identification of risk triggers. Thus, the application of a product life cycle approach will help provide critical information to evaluate potential health and environmental risks and benefits of a nano-scale technology.

Figure 5: (A) Cell viability of pristine TiO$_2$ nanoparticles as measured using trypan blue exclusion assay. (B) ROS generation after exposure to 100 ppm of pristine TiO$_2$ nanoparticles. (C) ROS generation after exposure to 100 ppm of powders collected after wear-and-tear of paint on drywall and (D) ROS generation after exposure to 100 ppm of powders collected after wear-and-tear of lacquered wood. Data were normalized to the control values (i.e. measured data divided by control measure for that same time point or concentration) and are represented as the mean ± SEM (*: P<0.05; **: P<0.01; ***: P<0.001).

Figure 6: Material Characterization and ROS generation of particles collected after wear-and-tear of commercial paint on drywall. (A) TEM, (B) SEM, (C) SEM-EDX spectra and (D) ROS generation after exposure to 100 ppm worn-and-torn commercial paint particles.

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