Estimates of Upper Bounds and Trends in Nano-TiO_2 Production As a Basis for Exposure Assessment

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An upper bound is estimated for the magnitude of potential exposure to nano-TiO_2 with the purpose of enabling exposure assessment and, ultimately, risk assessment. Knowledge of the existing bulk TiO_2 market is combined with available nano-TiO_2 production data to estimate current nano-TiO_2 sources as a baseline. The evolution of nano-TiO_2 production as a percentage of the total TiO_2 market is then projected based on material and market information along with a method that combines observations from scientific articles and patents as predictive indicators of the rate of innovative transformation.

Introduction

With the growth of nanotechnology, engineered nanomaterials are produced and incorporated into products and processes across a broad spectrum of industries and will inevitably enter the environment. The novel properties resulting from their nanoscale size, which are the basis of their advantage, may also cause nanomaterials to interact with the environment and living organisms in ways that differ from their bulk scale counterparts (*1*−*3*). Assessing the impacts and risks posed by nanomaterials requires estimates of potential environmental exposure to these materials. In turn, an understanding of the variety and physical magnitude of nanoparticle sources is the starting point for estimating environmental exposure to nanomaterials and interpreting exposure predictions for the purposes of formulating possible regulation and risk management strategies. Relevant exposure estimates are particularly urgent for those materials already finding their way into industrial and consumer products.

Titanium dioxide (TiO_2) is one of the most widely used nanoscale materials to date; it is incorporated into consumer products such as sunscreens and toothpastes, industrial products like paints, lacquers, and papers, and photocatalytic processes such as water treatment (*4, 5*). Its bulk form is traded in a mature commodity market. This work brings together materials science and engineering knowledge with business and economic modeling approaches to determine upper bounds for the production of titanium dioxide engineered with greater precision in terms of size distribution and crystallinity at the nanoscale (nano-TiO_2). Knowledge of the existing bulk TiO_2 market, in terms of sources and product segments, is combined with available nano-TiO_2 production data to estimate current TiO_2 sources. The evolution of nano-TiO_2 production as a percentage of the total TiO_2 market is projected, employing a method that combines observations from scientific articles and U.S. patents as predictive indicators of the rate of innovative transformation (*6*).

Potential for environmental impact by TiO_2, either the bulk-scale or nanoscale, occurs at multiple stages of the material's life cycle. The boxes in Figure 1 represent stages within the journey from raw material to final product and potential releases of TiO_2 to the air, water, soil, and biosphere, which in turn affect the environmental exposure.

Our scope primarily encompasses the stage backlit in gray: production of nano-TiO_2. Though we incorporate some information regarding bulk and nanoscale end products into understanding how much nano-TiO_2 is produced now and how much may be produced in the future, our study differs from some other exposure estimates in that we consider this production amount as the upper bound of potential environmental impact. While recent studies have estimated environmental TiO_2 exposure based on release from end use products (*7, 8*), our approach looks further upstream in the life cycle to create an upper limit of nano-TiO_2 exposure, identifying how much nano-TiO_2 may be produced prior to incorporation into end use products. Three pieces of information are necessary to project sources of nano-TiO_2 exposure over time: current nano-TiO_2 production volumes must be known to provide a baseline, or *y*-intercept, of our projection function; the maximum potential production volume is considered here as the total TiO_2 market, although we explain why this is probably an overestimate; and the growth rate over time (slope) must be estimated to describe how the production magnitude might increase from the baseline toward the maximum potential level. This work estimates these values.

Methods

Estimation of a nano-TiO_2 production function included a conservative bias toward the highest potential source terms that might be applied to subsequent exposure assessments. This effort amounts to an estimate of the penetration of nanoformat TiO_2 into the current TiO_2 market.

Current TiO_2 Production. Information was collected from nano-TiO_2 production patents, academic publications, and company interviews to estimate current nano-TiO_2 production volumes. One source of uncertainty in estimating this value is the proprietary nature of these emerging technologies. Current nano-TiO_2 production was estimated by applying available production data across all known producers.

The maximum potential nano-TiO_2 production was then determined based on information culled from United States Geological Survey (USGS) reports and company interviews. The physicochemical properties of bulk TiO_2 that make it competitively advantageous in traditional markets were reviewed from literature and evaluated with respect to potential enhancements or changes from a shift to the nanoformat. Integrating current known bulk production volumes, estimates of which market segments might shift to an alternative nanoscale product, and current U.S. nano-TiO_2 producer data, we defend the position that most applications of bulk TiO_2 would be able to utilize, and frequently be improved by, the adoption of nano-TiO_2 given the appropriate market conditions. The true degree of nanoscale penetration into the bulk market will be determined by trade-offs between improved performance in products incorporating nano-TiO_2 and additional costs. We

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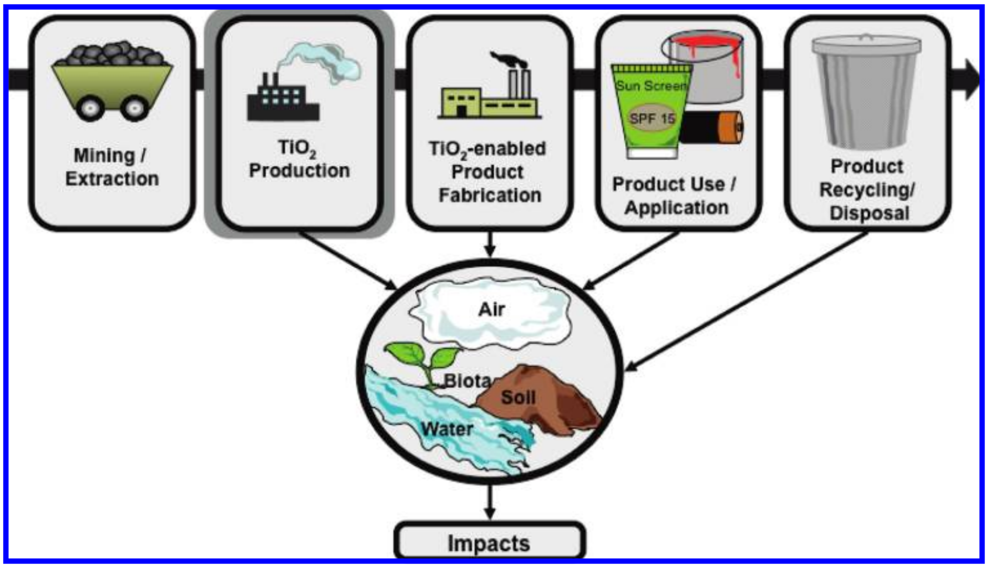

FIGURE 1. Life cycle of TiO_2 and opportunity for environmental impact.

acknowledge that in a few cases, the properties of nano-TiO_2 would make it unsuitable for the current bulk application. However, here we take the current bulk TiO_2 industry as a generous upper bound for future sources of the nanoengineered product. A few scenarios of the resulting cumulative environmental load are then presented, representing various fractions of this upper bound being produced and thus theoretically available for release to the environment.

Estimates of Future Trends. Methodology developed in previous studies to predict trends in conversion of the biotech industry from traditional to newer technologies (*9, 10*) was applied to estimate the rate of change in nano-TiO_2 commercialization over time. Parallels in the development of biotechnology markets with developments in the nanotechnology domain are not immediately obvious; while biotechnology is relatively well-defined as a market sector, nanotechnology spans multiple sectors (including biotechnology). Nonetheless, both represent technological leaps born out of revolutionary discovery and inventions; biotech from the historic research on recombinant DNA by Cohen and Boyer in 1973, and nanotech from the groundbreaking inventions of the scanning tunneling microscope (STM) by Binning and Rohrer in 1981, as well as the development of the atomic force microscope (AFM) in 1985 (*6*). The publishing, patenting, geographical concentration of innovative activity, and commercial entry by new firms in nanotech all show significant similarities to the patterns in biotech (*6, 11−13*).

Of particular interest for our purposes is the similarity in publishing and patenting trends between the two scientific areas. Since we postulate that these are key indicators in establishing the future rate of transformation in emerging industries, using the biotech transformation process as a template for nanotech development will only be valid to the extent that the two sets of indicators follow similar patterns at similar points along the growth process of their respective fields.

To investigate trends in nano-TiO_2 related innovation, relevant records were identified within the various data sets of scientific articles and USPTO patents. Text from titles, abstracts, and patent claims was used to search for nanotechnology and TiO_2-specific indicators. In this search, we employed information retrieval (IR) methods developed by the open source search engine library Xapian (*14*). One such method ranks the observations in a data set according to relevancy using probabilistic methods from formulas developed by Robertson and Jones (*15*). A detailed accounting of the relevant search terms, variables, and calculations involved in this investigation is available in the Supporting Information. Nanorelated observations have also been identified by Nanobank (*16*). Nanobank uses a sophisticated version of the method referred to above and explained in the SI, letting the data set dictate potentially relevant terms by applying the formula iteratively. By taking into account the changing nature of the most relevant terms with time, this methodology allows different decision criteria for different time periods. The algorithm is applied separately to USTPO patents and scientific articles, with resulting nano subsets available at http://www.nanobank.org. The combined trends drawn from the patent and publication data are used to quantify the rate of increase in nano-TiO_2 innovation and arrive at a slope for our exposure function.

A scenario for the upper bound on cumulative release of nano-TiO_2 to the environment is then estimated by summing the production amounts over time, as the nanoscale share of the TiO_2 market grows. It is important to note that these values are based on the nano-TiO_2 production portion of the life cycle; this method differs from some other recent exposure estimates in the literature in that we do not estimate nanomaterial release from products into which they are incorporated (*7*). The purpose of the approach presented here is to examine the effects of broad, very explicit assumptions regarding nanomaterial exposure potential. These assumptions are independent of product life cycle and other pathway-specific factors that may be highly speculative given the rapidly evolving nature of these markets.

Results and Discussion

Estimated Baseline Current Nano-TiO_2 Production. Current production estimates for nanomaterials are inherently uncertain due to the rapid evolution of the industry and proprietary nature of processes used at this early stage. At least seven companies are known to be actively producing nano-TiO_2; however, the production volumes are typically guarded as proprietary information. The only nano production data being incorporated into the titanium dioxide mineral reports of the USGS is from DuPont, the only established bulk TiO_2 producer also producing at the nanoscale, as it is presumably included in its reported bulk volumes. DuPont produces nano-TiO_2 using an undisclosed plasma process acquired from Nanosource Technologies (Oklahoma City, OK); Nanophase (Romeoville, IL) uses physical vapor synthesis; NanoGram (Milpitas, CA) uses laser pyrolysis; Advanced Nanotech (New York, NY) uses mechanical milling; the German company Nanogate (Göttelborn, Germany) uses a sol−gel process; and Degussa (Evonik) uses yet another proprietary process. Altairnano uses a hydrochloride process with additional control steps such as spray hydrolysis, calcining, and milling to control the TiO_2 crystal size. As its patent was released in a detailed paper wherein production capacities were reported (*17*), the Altair process provides the most detailed information of all nano producers, and forms the basis of our nano-TiO_2 projections. The small number of producers and proprietary nature of the processes introduces significant yet unavoidable uncertainty to current nano-TiO_2 production estimates. A single very effective production method could rapidly affect the landscape of this new portion of the industry. This happened with DuPont in the bulk TiO_2 industry in the early 1980s, when they developed an updated chloride process that so dramatically improved their economies of scale that they priced competitors out of the market and effectively controlled the prices of bulk TiO_2 (*18*).

Estimated Maximum Nano-TiO_2 Production. The landscape of the established TiO_2 commodity market offers insight for the future of nano-TiO_2, with the current magnitude and types of demand for the bulk material shedding light on potential future uses and magnitudes at the nanoscale. The estimated annual global production of TiO_2 is 4 million metric tons (*19*).

1. The Centralized Bulk Industry Is Poised for a Rapid Shift to the Nano Scale. a. Production Methods. Titanium dioxide has been produced via essentially the same two production methods for over fifty years. The older of the two, the sulfate method, is a batch process whereby sulfuric acid is mixed with the ferric titanium oxide to yield TiO_2, water, and ferric sulfate. The significant ferric acid waste stream and high capital cost have led many producers to move away from this method. The second process used in bulk TiO_2 production is the chloride process. Licensed by DuPont in the 1940s and later developed into a continuous production process, it has become the preferred process for new plant construction. The technology proved to be highly scale-sensitive, leading to a 2-fold reduction in manufacturing costs upon doubling of the production capacity as compared with the sulfate process. The aging infrastructure of the sulfate process, along with its the environmental and economic drawbacks, could potentially warrant upgrades or retro-fitting with new processes in the near term.

b. Geographical Distribution. Global titanium mining and TiO_2 production occur in a limited number of relatively centralized locations. All United States operations and most new facilities being built worldwide are chloride plants, with the exception of China, where virtually all plants use sulfate processes. There is notable potential for TiO_2 production growth in places such as Australia and South Africa, which boast ample raw material sources yet to date have practically no manufacturing. Of particular relevance to nano-TiO_2 is the Vietnam production, where a plant has recently been built using the Altairnano licensed process. Its capacity represents the majority of Vietnam's total national TiO_2 production, and is said to have a capacity of 5,000−10,000 annual metric tons; if operating at capacity, this plant would represent the majority of the global nano-TiO_2 capacity. See Supporting Information for a map of worldwide ore sources and TiO_2 production operations.

c. Organizational Centralization. There are only four companies producing bulk TiO_2 in the United States at a total of eight locations, all of which utilize chloride processes. The total production capacity is about 1.3 million metric tons per year, making the average plant capacity 200,000 t per year and meaning that the U.S. is responsible for more than 25% of the global production. That such a large percentage of the world's TiO_2 is fabricated by such a small number of companies and sites could indicate a relatively rapid potential response time to change the whole industry, should a new technology be introduced.

2. Most Product Sectors Could Use and Benefit from Nano-TiO_2. Historical data of TiO_2 use by product sector exists for the past 30 years, compiled by the USGS. There is no method of specifically tracking any nano-TiO_2 portion of these products yet, so to the extent that any currently reporting producers are manufacturing nano-TiO_2 (DuPont), they are assumed to be included in these numbers. From a volume standpoint, the market size driver has been and still is the paint, pigment, and lacquer segment at nearly 57% of the market, followed by the plastics segment at 26%, and paper with another 13%. The remaining 4% is comprised of the "other" segment including applications such as catalysts, cosmetics, coated fabrics, ceramics, printing inks, roofing granules, welding fluxes, and glass (*19*). A figure tracking the relative percentages of TiO_2-based products since 1975 is shown in Supporting Information.

Titanium dioxide is advantageous in applications that require high opacity or whiteness, corrosion resistance, or photocatalytic activity. As a pigment in paints, inks, plastics, and paper, the extremely high refractive index (RI) of titanium dioxide (anatase = 2.55, rutile = 2.73) offers the pure whites, brilliant colors, and high opacity that are desired in those industries. When engineered using the methods that enable nanoscale TiO_2 production, the tight control of particle size increases both the refractive index and light scattering of the resulting material because of the uniform particle size distribution and additional surface area (*20*). On the other hand, the smaller size can reduce the opacity and may thus mean that bulk TiO_2 remains the most appropriate option for some applications. Though the lack of opacity and whiteness may render nano-TiO_2 inapplicable for some of the bulk TiO_2 uses, there is evidence that the nano scale is being incorporated into some of these traditional uses of the bulk material, such as paints and coatings, where the high degree of particle size control allows increased contrast ratio and hardness to offset the loss in opacity (*21*). In addition, the procedures used to make tightly controlled small particles may also be useful in larger particles with a high degree of opacity.

Engineering at the nanoscale is particularly interesting because of the fact that the smaller particles, when matched properly with the suspension medium, are less opaque. This makes them desirable in applications such as sunscreens and UV-resistant surface coatings or lacquers. As part of sunscreen creams and lotions, TiO_2 absorbs the UV rays, shielding the skin from absorbing them and incurring cell damage. A similar phenomenon helps lacquers and paints to resist UV degradation. In such applications, the high RI of nano-TiO_2 is needed but the photocatalytic activity of these nanoparticles is undesirable and must be suppressed. Radicals created by exposure to sun and water could pose either health risks or potential degradation of the material. The particles in these applications are often coated with an organic layer and a metal oxide to mitigate radical formation while still allowing the refractive properties to function.

Applications for which the desirable photocatalytic activity of TiO_2 is exploited include water treatment processes and self-cleaning surfaces. Absorption by these particles of ultraviolet rays from sunlight or an engineered source results in the generation of reactive oxygen species, which in turn may be used to break down contaminants in water, degrade organic compounds that foul surfaces or adhere to windows. Nano-TiO_2 has shown to have higher reactivity than its bulk counterpart. As higher reactivity may make a nanoscale version more desirable than its bulk counterpart, high reactivity plus low opacity will likely lead to new uses of TiO_2 requiring transparent, reactive surfaces in addition to displacing applications of bulk TiO_2 in current markets.

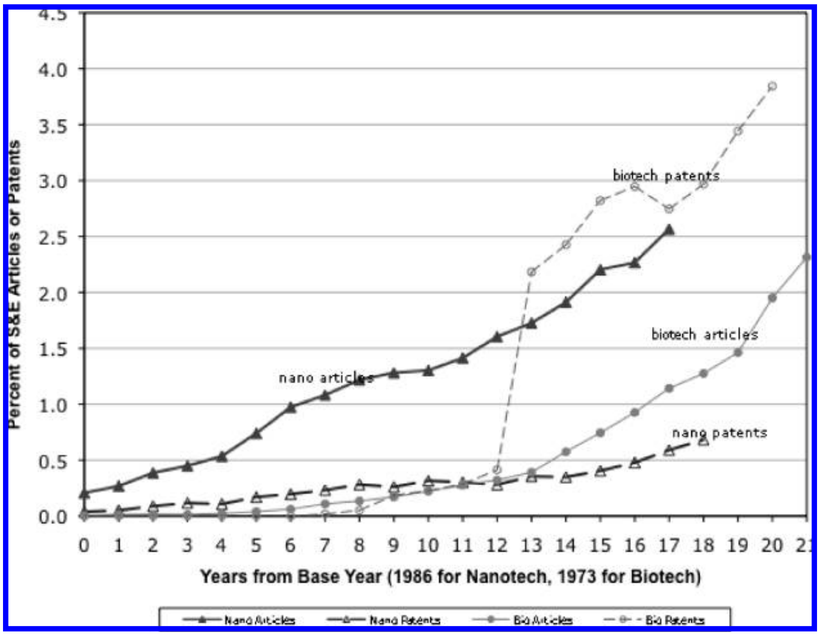

FIGURE 2. Comparing nanotech (1986–2004) and biotech (1973–1994) publishing and patenting trajectories, as adapted from Zucker and Darby (*11*).

Most current applications for nano-TiO_2 fall into the small category of "other" at this time, which has historically represented a small percentage of the total use (*19*). However, given the many advantages of the nanoscale and the centralization of the industry with respect to geography, ownership, and technology, it could be argued that once a change to nanoscale TiO_2 production is warranted for some products, there may not be sufficient reason to preserve or update the older bulk scale facilities.

3. Pricing Differential Is in Favor of Producing Nano-TiO_2. Raw titanium ores currently trade at between \$0.09 and \$0.51/kg. Processing them to bulk TiO_2 adds an order of magnitude of value, as it trades at approximately \$2.21/kg (*19*). Manufacturing nano-TiO_2, which is still a specialty chemical, increases the value by two additional orders of magnitude; according to company inquiries, nano-TiO_2 is sold for \$176 to \$198/kg. This pricing structure will of course change as more nanoscale production facilities are established and economies of scale are realized. As manufacturing costs and market prices fall, nano-TiO_2 use will increase in existing applications and new applications may arise. Moreover, the present added value of nano-TiO_2 may make investing in nanoscale production infrastructure more attractive, especially for suppliers with aging facilities that need retrofitting or replacement. A complete table of comparative pricing is available in Supporting Information.

4. Upper Bound Nano-TiO_2 Projection. Based on the current landscape of the TiO_2 commodity market, including the geography, organizational centralization, homogeneity of production methods, and advantageous specialty pricing of nano-TiO_2, an upper bound of nano-TiO_2 production corresponding to the entirety of the TiO_2 market would appear to be large, but perhaps not far from realistic. Since the DuPont chloride process revolutionized the entire market in the 1980s, perhaps another rapid industry-wide shift could produce a large-scale shift from bulk to nano-TiO_2 (*18*). Thus, the maximum potential U.S. production of nano-TiO_2 is taken to be the size of the current U.S. TiO_2 market, or 1.4 million metric tons annually, projected into the future at historical growth rates. Though we acknowledge this projection is likely an overestimate of the upper bound, it is presented knowing that several sources of inaccuracy exist, including the possibility that some uses of the product may never incorporate the nanoscale, that new applications of nano-TiO_2 will continue to develop, and that the bulk TiO_2 market may or may not continue to grow at historical rates observed over the past 25 years. Moreover, assuming that a fraction of the nano-TiO_2 transiting through each stage of its commercial life cycle (Figure 1) becomes a source for environmental exposure, assuming a large upper bound on nano-TiO_2 production is prudent from the standpoint of estimating maximum possible exposures.

Estimated Rate of Conversion from Bulk to Nano-TiO_2. While the upper bound assumed for nano-TiO_2 production may be a useful end point, the rate at which this upper bound is reached must also enter into estimates of potential sources. As a basis for forecasting the penetration of nano-TiO_2 into the bulk TiO_2 market, we postulate parallels in the evolution of the biotechnologies and nanotechnologies as indicated by publishing and patenting trends, two key indicators in establishing the future rate of transformation in an industry (*11, 13*). Using the biotech transformation process as a baseline for nanotech will only be valid to the extent the two sets of indicators follow similar patterns at similar points along the growth process of the respective fields.

Figure 2 shows a comparison of how nanotech and biotech publishing and patenting activity have changed with time beginning with the base years of 1973 and 1986 for biotechnology and nanotechnology, respectively, for each industry. Other than lack of patenting in the first 7-year period of the biotech area, due to the legal constraints in issuing patents for gene-sequence discoveries (which were not allowed until 1980), the two sets of data show similar trends regarding rates of publications and patents. However, biotech articles probably suffer from undercounting, since they are only considered to be those that report a genetic sequence discovery. We have previously concluded that "*Taken as a whole, the scientific and patenting growth of nanotechnology is of at least the same order of magnitude as biotechnology at a similar stage of development* (*11*)."

It should be noted that the observations counted as nano in Figure 2 result from a Boolean search, only including those that contain the string "nano" in the searchable parts of the observation. (Titles and abstracts, to the extent available, in scientific articles; titles and abstracts in patents). A similar exercise is repeated with the results from Nanobank, which determines the results via a probabilistic search, based on the popular terms used in nanorelated research as well as the certainty samples (like the articles contained in VJNano, the Virtual Journal of Nanoscale Science and Technology). Those results support the previous conclusions that biotech serves as an appropriate template for nanotech in investigating the rates of transformation in innovative processes.

1. Nano Innovation Indicators: Articles and Patents. Forecasting the future usage of a nanomaterial, particularly in the early stages of transformation, is difficult due to certain properties inherent to the field. Nanotech, like biotech before it, is an innovation driven field, where the changes in the related industries do not come gradually. Rather, the new materials, products, and production methods usually represent a radical change from the previous ones, often completely overhauling industries. As a result, making estimations based on the past trends of production and consumption that correspond to preinnovation or early revolution periods may be hugely misleading, since such a method cannot take into account the changes coming from innovations that are in the early phases of being utilized, or even just being discovered. Estimating the complete overhaul of a sizable industry like pharmaceuticals would not have been possible by just looking at the share of biotech in the early stages of development.

Instead, indicators of transformation in such industries can be found by paying attention to the whole innovative process. Innovations that are currently driving the transformation in an industry (i.e., products and areas of use in production) can be traced back to their earlier stages, from an abstract concept to a concrete idea to a promising product (*10, 11*). Conversely, current trends in various innovative stages provide valuable information for estimating the future state of the industry; the transformation in production is likely to follow these transformations in innovation, subject to certain lags based on the innovative process.

To investigate the rate of transformation in the nano-TiO_2 industry, we propose two indicators. First, we consider scientific articles published in peer-reviewed journals as collected by ISI. These represent the birthplace of innovations, where fundamental principles are established or new, novel concepts are introduced. They are also the farthest innovative indicator from the actual industrial production, with the lag between the rate of transformation to nano in scientific articles and the actual production expected to be among the largest. The second indicator is the patent applications granted by the USPTO. As these represent more concrete ideas with clearer paths to innovation and commercialization, their lag is expected to be shorter than that of published articles. For each of these indicators we find the number of TiO_2-related observations and evaluate the trends. Furthermore, we determine the number of nanospecific TiO_2 related observations and investigate how the ratios of nano observations change over time. If a transformation toward nano is to shape the TiO_2 industry in the future, we expect to find traces of this movement in current innovative indicators, as seen in Figure 2.

We also assessed the share of nano in TiO_2 related academic articles as well as the share of nano in TiO_2 related USPTO patents, counted by grant year. A graph showing that the share is steadily increasing can be found in SI Figure 3. In 2005, 35% of all TiO_2 articles and 50% of all patents were nanorelated; though this clearly does not mean that 35% or 50% of the TiO_2 industry is expected to convert to nano in a couple of years, the trends are certainly indicative of the direction of the industry. In addition to serving as estimators for the rate of transformation, these ratios also seem to verify our previous conclusion that the size of the whole TiO_2 market is a reasonable upper bound for nano-TiO_2 usage in the long term. This is also compatible with the idea that TiO_2-related industries are environmentally relevant for study and that they are particularly good candidates for nano transformation.

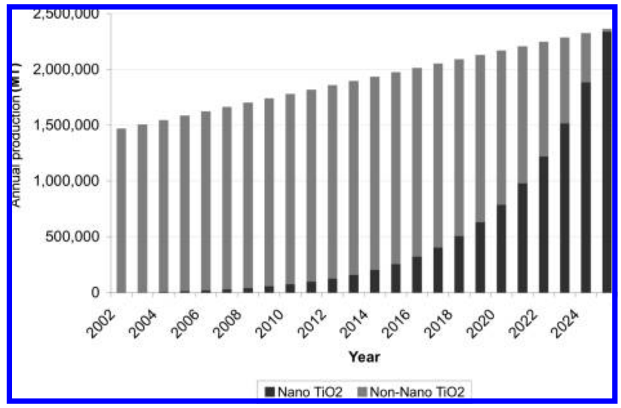

FIGURE 3. Forecasted nano-TiO_2 production as a portion of total U.S. TiO_2 production.

2. Final Conversion. The rapidly changing nature of the industry means that future trends in nano-TiO_2 development depend on a number of factors that cannot easily be identified beforehand, such as how quickly innovations appear in major TiO_2 areas, what will be the cost associated with these innovations, and whether the technologies will be strictly proprietary. However, since our aim is to find an upper bound for potential nano-TiO_2 exposure, we consider the limiting scenario, using biotech as a good benchmark because that industry converted entirely to a new technology within two decades. While nano-TiO_2 is unlikely to follow that pattern exactly, this scenario serves as a reasonable upper bound with the right order of magnitude based on the previously outlined factors that suggest a high rate of conversion.

In this scenario, we make three assumptions. First, we draw on the previously explained estimate of current nano-TiO_2 production, extrapolating the characteristics of one producer (Altair) to the four other known U.S. nano-TiO_2 producers under the assumption that all producers generate the same volume of materials. This assumption is not likely to yield an underestimate of production since of the 4 U.S. manufacturers (Nanogate is a European company), Dupont and Altair seem to be the front-runners over Nanophase and Nanogram; Altair representing 1/3−1/4 of U.S. nano-TiO_2 production is a plausible assumption. Second, we consider the case where the entire industry eventually converts to nano-TiO_2. As mentioned in section 2, there are some caveats that we expect to preclude every current bulk application converting to the nanoscale; however, the bulk market is used as a generous upper bound, and in recognition of the fact that new applications will develop that had not been represented in the previous bulk industry. Finally, we consider a rapid time frame for the shift, comparable to that of biotech.

A relatively stable trend is seen in TiO_2 production over the last several decades, with some aberrations in the period from 1950 to 1982 but a straight trend from 1982 onward. We use the production data from 1982−2004 to estimate the trend and forecast the total TiO_2 production through 2025, which is shown in the upper function of Figure 3. Bulk TiO_2 production data in that time frame start with a value of 598,000 t at year 1982 and follow a linear trend, upward to 1,400,000 t in 2006. Linear regression results in an estimated increase of 38,830 t per year in the total TiO_2 production from year 1982 through 2025, with an R^2 value of 0.96. A graph of this estimated total production is shown in Supporting Information.

To estimate nano-TiO_2 production, we fit three points from past Altairnano production to the exponential function $Y = a \cdot e^{g \cdot (t-2002)}$; this assumption of exponential growth is in line with both standard economic practice and with typical patterns of increasing economies of scale. In this function, Y is the nano-TiO_2 per year in metric tons, t is the year to be

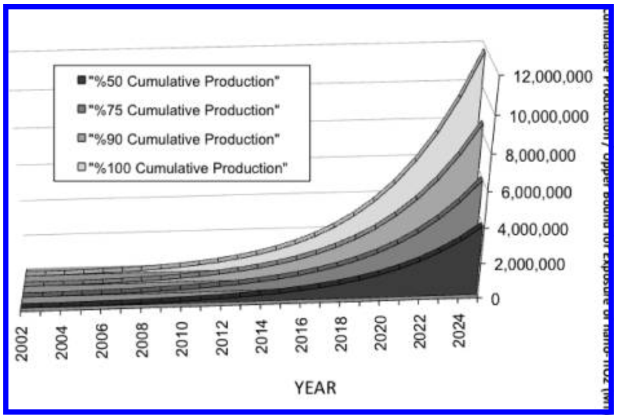

FIGURE 4. Total cumulated nano-TiO_2 production, with various scenarios for percent released to the environment.

estimated, and *g* is the exponential growth factor. We estimate the scenario where 2002 is the start year (zero production), the total nano-TiO_2 capacity in 2006 for all four known U.S. nano-TiO_2 producers is 4 times the claimed 10,000 MT of production for Altairnano at the capacity of its largest facility to date (in Vietnam) in that year, yielding 40,000 MT. Assuming that this upper limit of complete conversion occurs at the fastest possible time, which we take to be the same amount of time in which the biotech industry converted, complete conversion to nano would occur in 2025 with a production of nearly 2.5 million metric tons per year. This is shown as the lower curve in Figure 3 as a portion of the total TiO_2 production.

This scenario suggests that while the share of nano in total TiO_2 production was a negligible 3,000 MT or so in 2002, it may plausibly have increased to a current 2.5% (around 44,400 MT of estimated nano production out of the 1,700,000 estimated total). The potential growth scenario would result in a share of nano in the TiO_2 industry surpassing 10% (~260,000 MT) by 2015 and a completely converted industry the industry by 2025 (which would be ~2.5 million MT at the current growth rate). This represents a true upper bound; the amount of nano-TiO_2 production that we believe will not be surpassed.

3. Potential Environmental Load. Estimates for nanomaterial production can be used as the basis for calculating possible exposure scenarios or environmental loads. While much more information is needed to obtain meaningful estimates of exposure, we assert that before detailed assessments exist to predict the release mechanisms and quantities from nano-TiO_2 enabled products, another method of estimating potential environmental load is to consider the total amount produced as the upper limit of potential exposure. It is then possible to consider multiple scenarios under which less than that full amount would be released, as the potential environmental load of the material. Thus we present here several scenarios of possible nano-TiO_2 release to the environment based on arbitrarily assumed percentages of environmental "leakage" of nanomaterials, which represent averages across sources occurring over the entire lifecycle of the material (Figure 4). As highlighted in the Introduction, our upper bounds are projected solely based on the nano-TiO_2 production stage of the life cycle. The exposure estimates provided by Mueller et. al are not directly comparable to estimates presented here because they are based on release from end-use products via different environmental pathways specific to Switzerland; however, it is notable for comparison that they base their current exposure numbers on total global nano-TiO_2 production numbers (5000 MT/year on the low end (*21*), and ~64,000 MT/year on the high end) that are considerably smaller than our upper bound suggests, given that we claim current U.S. production alone could be as high as 40,000 MT/year. Considerable work is required to hone more accurate maximum exposure projections, details of nanomaterial fate and transport in the environment are needed to translate production estimates to actual exposures, and both human and ecosystem end points studies are needed to determine the significance of exposure levels.

Innovations stemming from the nano format of TiO_2 coupled with the current landscape of the bulk TiO_2 market suggest that the industry could be both pushed from a production standpoint, given the consolidated and aging nature of the bulk TiO_2 market, and pulled from a demand standpoint, given the high value and advantageous properties of nano-TiO_2, to rapidly transition this mature market to the nanoscale. If the expectations regarding nanotech becoming significantly more prominent in the near future are realized, any potential negative impacts may have enormous medical, economic, legal, and policy related effects. In the face of such certain growth and such uncertain effects, it is essential to produce toxicity and exposure risk assessments for nanomaterials, even if they begin as approximations, to frame the issue and understand the size of the potential problem.

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Supporting Information Available

Additional data as referenced in this article. This information is available free of charge via the Internet at http://pubs.acs.org.

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