Developing trends in nanomaterials and their environmental implications

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Standfirst

Nanotechnology is advancing at an accelerated pace in applications and novel nanomaterials. To become an enabling technology for a more sustainable society, we identify and assess nanomaterials and applications trends with potentially significant environmental implications.

Main text

Although there has already been considerable development of novel nanomaterials and applications in the past two or three decades, nanotechnology continues to be the source of tremendous innovation, with exciting new applications appearing rapidly. Important questions for researchers working on the potential benefits and implications of nanomaterials are: What is the projected growth for different nanomaterials? Which ones will likely become more available in the coming decade? What are the fastest-growing applications? Which applications are more likely to have environmental implications? Where will nanomaterials end up? Will a circular economy develop for nanomaterials?[1]

The global market for nanomaterials has grown from around 100,000 to 150,000 metric tons in 2000, to over 1.6 million metric tons in 2020. It will likely double by 2031 to nearly 3.5 million metric tons.[2] These estimates have considerable uncertainty (± 75%), even for 2020, since there is no required reporting by individual companies. For example, nano-silica (silicon dioxide) has been produced for many decades, although only recently has "nano-silica" been recognized as equal to "bulk silica",[3] based on the definition for nanomaterial in the European Union.[4] These estimates do not include carbon black, a pigment commonly used in tires and other polymeric composites, and nano calcium carbonate, which would likely dwarf these numbers, but is usually a mixture of nanoscale and microscale particles. Nevertheless, these two materials are on top of the list of mandatory nanomaterial registrations in France.[5] Nine nanomaterials have risen to the level of high production commodities (Figure 1), dominated by silicon dioxide and titanium dioxide, while many others are still specialties, produced in very low amounts (< 1,500 metric tons/year).

Commodities represented 99.8% of the market in 2020, while low-volume nanomaterials accounted for only 3,600 metric tons. By 2031, these less employed nanomaterials are expected to grow to 38,000 metric tons, increasing by an order of magnitude. In the past two decades, carbon nanotubes have rapidly grown from a few thousand tons per year to a projected 160,000 metric tons per year by 2031. The use of graphene-based materials is growing rapidly in novel applications,[6] particularly energy generation and storage, making it the leading specialty nanomaterial by 2031. Although gold and silver have been employed considerably in research, they remain a small fraction of the market for nanomaterials. In addition, multi-component nanomaterials are a subgroup of advanced materials expected to grow in importance soon, but currently have yet to be captured in the market study.

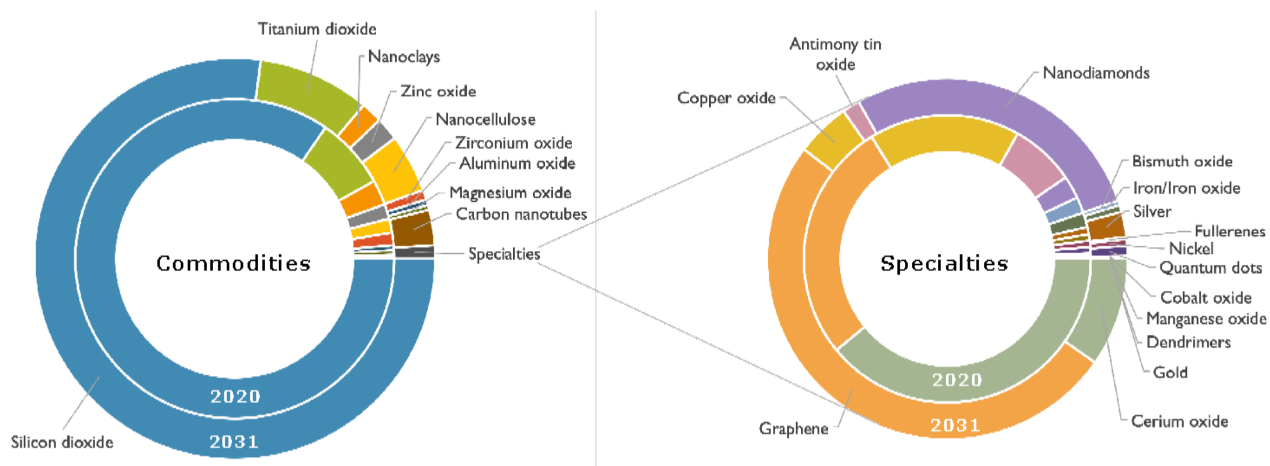

Figure 1. Market distribution of high-production commodity nanomaterials (left) and specialty nanomaterials (right) in 2020 and 2031. Data from [4]

Although market surveys (e.g., Future Markets) provide useful information, a "reality-check" can be made via other sources of information, such as the mandatory French registry of all nanomaterials produced in or imported to France.[5] This registry presents the most detailed inventory of nanomaterials used in a country and reports are available for the years 2013 to 2019. The most striking feature is that over those seven years there was no overall increase in the total production or import of nanomaterials in France. However, the values fluctuate over the years. However, if a nanomaterial is imported within a product or a formulation, it does not have to be reported in the French registry, which may bias the results. This contrasts strongly with the increase in global nanomaterial production published by market research companies. For the same period from 2013 to 2019, Future Markets reported a 120% increase in nanomaterial production. In France, 92% of the production in 2013 (504,000 tons) was attributed to carbon black, silica and calcium carbonate, now considered nanomaterials in Europe. The remaining 40,000 tons produced or imported in France could be upscaled based on GDP to a worldwide production of about 1.3 million tons, which falls within the Future Market estimate of 845,000 to 1.8 million tons in 2013. One advantage of the French data is that they are based on mandatory reporting that has been performed since 2013, so companies are used to the system. Furthermore, reporting is based on a legal definition of nanomaterials, thereby removing any ambiguity on whether a material needs to be considered nanomaterial.

While considering these differences in nanomaterial production and use, a deeper analysis of the market study,[4] with some reclassification of applications to evaluate their potential release, revealed that in 2020, nine major uses of nanomaterials accounted for 98.5% of the total. Still, by 2031 these major uses will account for slightly less (95.7%) as new applications rise faster (Figure 2). Coatings, paints, and pigments, used in many different markets (e.g., automotive, buildings, food, medicines and medical instruments) are the primary use of nanomaterials. They are projected to remain the significant use by 2031. In addition to commodity nanomaterials, 2-D sheets from graphene, boron nitride, molybdenum disulfide, and zirconium phosphate are increasingly being considered for advanced coatings to prevent corrosion and organic and inorganic nanomaterials in surface coatings for viral and microbial control. Other than paints and pigments, automotive applications include nanomaterials incorporated into polymers (i.e., plastics and rubbers), ceramics, other composites, adhesives, aerogels, and other automotive components, and their use will likely double in the coming decade. In addition, carbon-based nanomaterials are increasingly being considered for reducing friction in combustion engines. The fastest growing application by far is energy storage (i.e., batteries, capacitors), which will go from a relatively minor sector in 2020, at around 3,000 metric tons, to over 85,000 metric tons by 2030. Solar panels and fuel cells (i.e., renewable energy generation) will also represent increasingly important applications for nanomaterials. Novel nanomaterials such as yttria-stabilized zirconia incorporated into beta-alumina solid electrolyte may succeed in making sodium-based batteries an option to lithium batteries,[7] reducing environmental concerns about mining for lithium in sensitive habitats.

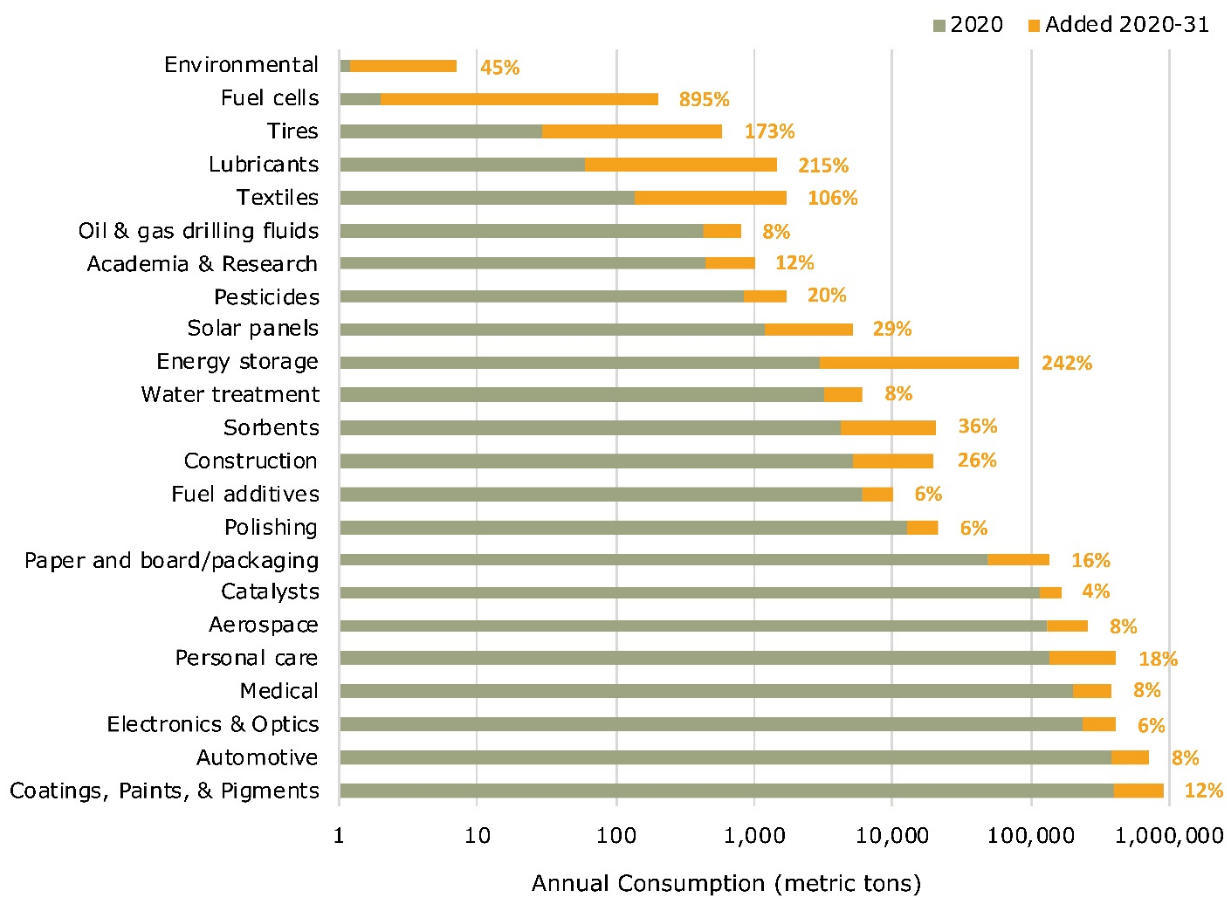

Figure 2. Annual consumption of nanomaterials for different applications in 2020 (in green) and the increase from 2020 to 2031 (in orange). The annualized percent increases from 2020 to 2031 are indicated next to each bar. Data from [4]

In contrast, the use of nanomaterials in water treatment, agriculture, and environmental remediation is still relatively modest, and growth is projected to be slow by 2031. Many research studies have presented the development of a myriad of nanomaterials for water treatment. Still, currently only titanium dioxide and aluminium oxides are used in significant amounts, although carbon nanotubes and graphene are expected to be employed in more significant amounts by 2031. In agriculture, the most widely used nanomaterials are copper-based, as fungicides, but their use is still less than 1,000 metric tons/yr. Bio-based nanocarriers are actively being developed to reduce cost and increase sustainability while minimizing toxicity. Like water treatment, the development of nano-enabled agrochemicals is booming, with many novel particles developed as nanofertilizers, nanopesticides, nanocarriers of active ingredients, nanodiagnostics and other applications. However, their commercial use is still in its infancy. Nano-scale silver and other elements have been developed as antimicrobials, and are considered within the pesticide category, but they are still only used in minimal amounts. For environmental remediation, only nano zero-valent iron although has had significant success, with still only a very small annual production amount.

The growing nanomaterial market has raised some concerns in terms of their environmental implications. In addition to the energy needed for their manufacture and transport,[8] some applications have a direct impact, such as nanomaterials in their primary application, coatings, paints and pigments, particularly for outdoor uses. However, in most cases, these nanomaterials are applied in a polymeric matrix, which significantly reduces their release in nanoscale particles, and their release is over the lifetime of the surface coating.[9] Personal care products, such as sunscreens and cosmetics, have a much more immediate effect. They are washed off within hours of their application and mostly go to wastewater treatment or are directly released to surface water. In some countries, solid waste and wastewater biosolids are incinerated, resulting in condensed waste being sent to landfills or released into the atmosphere. The flow of nanomaterials through the global economy, developed using the methods employed in our previous studies[10] with updated nanomaterial market information;[4] region-specific end-of-life data (i.e., level of wastewater treatment, fraction of solid waste incineration), and nanomaterial removal in wastewater treatment,[11] reveals that the majority (~90%) of these nanomaterials will end up in landfills around the world, with a smaller fraction (~6%) reaching soils as they are released from paints and coatings or from the biosolids after wastewater treatment, as well as 4.5% to surface waters and less than 1% to the atmosphere (Figure 3). Nanoscale therapeutic and diagnostic agents also have a relatively short residence time in their use phase, and mostly pass to wastewater. When all of the nanomaterials are considered, the relative magnitude of the flows from production to application to end-of-life does not change substantially by 2031 (Figure 3a), a focus on the lower volume nanomaterials reveals marked changes by 2031 (Figure 3b). The growing importance of carbon nanotubes and other nanomaterials projected to be used in energy storage is clear, as well as the significant increase in the application of cellulose nanofibers for packaging and many other applications. While the mass flow through wastewater treatment plants will still be relatively small, it is expected to more than triple from 2020 to 2031. Note that the global level of wastewater treatment was considered constant. However, this may change as additional investment in more advanced wastewater treatment, and waste incineration plants are installed in this decade, particularly in some rapidly industrializing countries.

Although the use of nanomaterials in agriculture is minimal, these applications also have direct environmental effects. There is a race to design safer nanopesticides that retain their effectiveness at an affordable cost. At present, the recycling of nanomaterials is minimal, mostly in recycled tires, and there is a need to develop strategies to close the circle.[12]

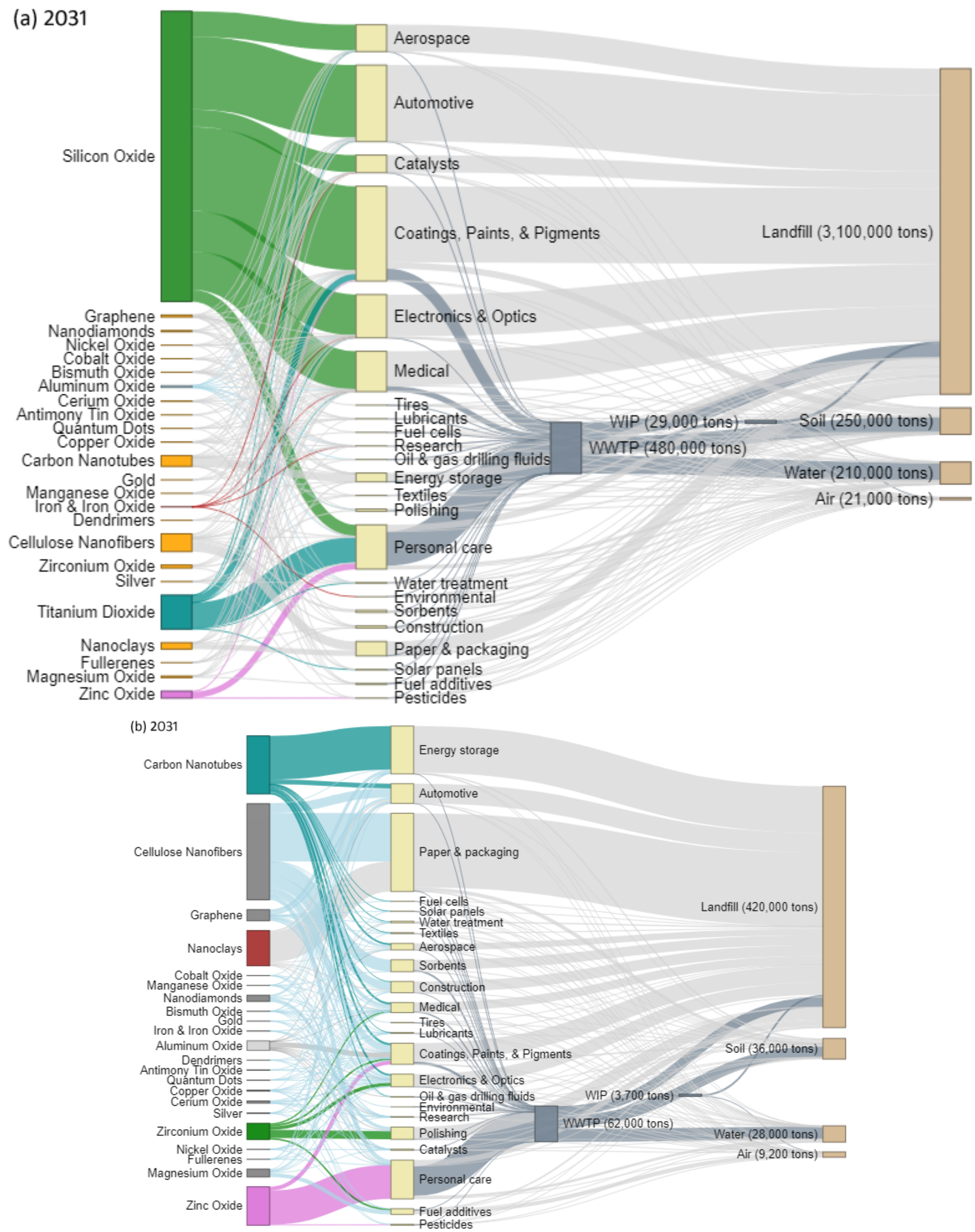

Figure 3. The flow of all manufactured nanomaterials in 2031 through the global economy, from production (left side) to applications (mid-yellow boxes), to final compartments (right side, in brown), with some passing through wastewater treatment plants (WWTP) and waste incineration plants (WIP): (a) All nanomaterials; and (b) lower-production nanomaterials.

From the early days when nanoscale properties were first identified, the production and use of nanomaterials have increased at a mercurial pace. Some nanomaterials (e.g., silicon and titanium dioxides, nanoclays, nanocellulose, aluminium and zinc oxides) have matured into commodity products used in many well-known applications. Nevertheless, the pace of innovation is still ramping up, with the increasing use of specialty nanomaterials for exciting and novel applications, particularly in energy generation and storage, as well as in medicine, electronics, automotive, aerospace, packaging, and construction. In high-value applications, nanotechnology is being increasingly adopted given the high benefit-cost ratio. In other applications, such as water treatment, environmental remediation, and agriculture, there is still a large potential. Still, the high cost of nanomaterials relative to conventional approaches, and regulatory and perception issues are significant obstacles for implementation. A few current and future applications have the potential for significant environmental implications, especially those that result in rapid transfer from use to wastewater, and direct application in the environment, such as in agriculture. Emphasis is needed in these areas to ensure that the promise of nanotechnology does not come at a cost to human and ecological health.

References

(1) Hansen, S. F.; Arvidsson, R.; Nielsen, M. B.; Foss, O.; Hansen, H.; Peter, L.; Clausen, W.; Baun, A.; Boldrin, A. Nanotechnology meets circular economy. *Nat. Nanotechnol. 2022 177* **2022**, *17* (7), 682–685.

(2) Future_Markets, _Inc. *The Global Market for Nanomaterials 2021-2031: Markets, applications, production and producers*; 2021.

(3) Wigger, H.; Wohlleben, W.; Nowack, B. Redefining environmental nanomaterial flows:

consequences of the regulatory nanomaterial definition on the results of environmental exposure models. *Environ. Sci. Nano* **2018**, *5* (6), 1372–1385.

(4) EUR-Lex. Commission Recommendation of 18 October 2011 on the definition of nanomaterial Text with EEA relevance. EUR-Lex - 32011H0696 - EN - EUR-Lex https://eur-lex.europa.eu/eli/reco/2011/696/oj.

(5) MTES. *Éléments issus des déclarations des substances à l'état nanoparticulaire. Rapport d'etude 2019.*; 2020.

(6) Hong, H.; Part, F.; Nowack, B. Prospective Dynamic and Probabilistic Material Flow Analysis of Graphene-Based Materials in Europe from 2004 to 2030. *Environ. Sci. Technol.* **2022**, *2022*, 13798–13809.

(7) Deng, T.; Ji, X.; Zou, L.; Chiekezi, O.; Cao, L.; Fan, X.; Adebisi, T. R.; Chang, H. J.; Wang, H.; Li, B.; et al. Interfacial-engineering-enabled practical low-temperature sodium metal battery. *Nat. Nanotechnol. 2021 173* **2021**, *17* (3), 269–277.

(8) Gilbertson, L. M.; Pourzahedi, L.; Laughton, S.; Gao, X.; Zimmerman, J. B.; Theis, T. L.; Westerhoff, P.; Lowry, G. V. Guiding the design space for nanotechnology to advance sustainable crop production. *Nat. Nanotechnol. 2020 159* **2020**, *15* (9), 801–810.

(9) Wohlleben, W.; Neubauer, N. Quantitative rates of release from weathered nanocomposites are determined across 5 orders of magnitude by the matrix, modulated by the embedded nanomaterial. *NanoImpact* **2016**, *1*, 39–45.

(10) Keller, A. A.; Lazareva, A. Predicted Releases of Engineered Nanomaterials: From Global to Regional to Local. *Environ. Sci. Tech. Lett.* **2014**, *1* (1), 65–70.

(11) Cervantes-Avilés, P.; Keller, A. A. Incidence of metal-based nanoparticles in the conventional

wastewater treatment process. *Water Res.* **2021**, *189*, 116603.

(12) Rajkovic, S.; Bornhöft, N. A.; van der Weijden, R.; Nowack, B.; Adam, V. Dynamic probabilistic material flow analysis of engineered nanomaterials in European waste treatment systems. *Waste Manag.* **2020**, *113*, 118–131.