POLICY AREA:
2030 Agenda

Nanowaste: Need for Disposal and Recycling Standards

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Abstract

Nanotechnology is expected to gain significant market share among emerging technologies. It has been forecast that the global nanotechnology industry will grow to reach $75.8 billion by 2020. However, nanotechnology brings new challenges to human health, ecosystems, and biodiversity. We recommend that the G20 member states (a) work together to develop efficient and unified policy efforts to regulate the field of nanotechnology, (b) apply Precautionary Principle to all nanotechnology developments, and (c) establish protocols to respond to potential threats of this new and poorly understood field in order maintain and combat unexpected or intentional hazards of nanotechnology to human health and well-being, environment and biodiversity. Priority should be given to (i) commercialization pathways of nanotechnology and related products, (ii) a comprehensive toxicity and health-related studies on the effects of any new nanotechnology development, (iii) comprehensive and effective pathways for safe disposal and combating of unwanted or unexpected effects of nanoproducts, and (iv) the policy coherence set-up within the G20.

Challenge

Nanotechnology is a multidisciplinary field of science that deals with manipulation of objects with at least one of the dimensions smaller than 100 nm (10^{-9} meter). The emergence of nanotechnology in the 1980s was caused by the convergence of experimental advances such as the invention of the scanning tunneling microscope in 1981 and the discovery of fullerenes in 1985 (*1*).

The field was subject to growing public awareness and controversy in the early 2000s, with prominent debates about both its potential implications as well as the feasibility of the applications envisioned by advocates of molecular nanotechnology, and with governments moving to promote and fund research into nanotechnology. The early 2000s also saw the beginnings of commercial applications of nanotechnology, although these tended to focus on applications relevant to consumer products (i.e. carbon nanotubes for lightweight sporting equipment or nanosilver for enhanced shelf life packaging or odorless clothing) (*2*).

Nanosilver coated urethral and central line catheters and other implantable medical devices such as infusion ports, orthopaedic protruding fixateurs, endovascular stents, urological stents, endotracheal tubes, contact lens coatings, endoscopes, electrodes, peritoneal dialysis devices, subcutaneous cuffs, surgical and dental instruments are also used to prevent the growth of slime-containing biofilms that promote bacterial infection and sepsis.Nanosilver also is incorporated for its anti-bacterial, anti-viral and anti-fungal properties in a growing range of modern domestic or household items. It has the highest degree of commercialization of nanoparticles in consumer products, more than 260 nanosilver products, including household appliances and cleaners, clothing (including socks and underpants), cutlery, children's toys and personal care products (such as menstrual pads) being currently on the market in the US. Similar estimates have been made in the UK. A typical example is Samsung's "Nano Silver Health System," which uses nanosilver in refrigerator trays, filters, air conditioners and tubing to kill bacteria and the odors they produce. Particularly widespread household uses of nanosilver include cosmetics, clothing de-odorisers, paints, disinfectants and cleaning products.

Nanotechnology offers numerous advantages. It allows for miniaturization, cost reduction, more sustainable use of resources among many others. Due to all its promises, nanotechnology has found an application across the fields of science and technology, ranging from materials science, electronics through energy, cosmetics, and agriculture to medicine, implants, and sensors.

According to RNCOS Nanotechnology Market Outlook (*3*), the nanotechnology market is expected to grow exponentially in the coming years, reaching $75.8 billion by 2020. This rapid growth offers countless opportunities for industrial and economic growth and development. It has the potential to provide many new solutions to old problems, such as those that affect the areas of water purification, medicine, food and consumable energy. Progress in these fields will be instrumental in achieving sustainable economy and sustainable development *(4)*, especially when the human population is expected to increase to 11.2 billion by the year 2100 *(5)*.

However, further development and commercial accessibility to nanotechnology-based solutions bring with it many challenges that must be addressed before this technology can be widely available. These challenges include issues related to the monitoring, safe use, disposal and, where possible, effective recycling of nanomaterials and nanoparticles.

One of these challenges is related to the small, nanometer size of the product, which makes it difficult to track and monitor both in the environment and human body. Furthermore, preliminary studies related to toxicity and chemical reactivity of nanoparticles show serious concerns that require new, tailor-made disposal and recycling procedures. Every year hundreds of millions of dollars are spent on nanotechnology-related research, however much less money or attention is given to develop tools to facilitate use and disposal of nanowaste. In 2010, the International Organization for Standardization (ISO) developed a series of standards (ISO/TS 80004) (*6,7,8,9*), which describe vocabulary for nanotechnology and its applications. The standards are motivated by health, safety, and environmental concerns. The ISO/TS 80004 (*6,7,8,9*) was one of the very first attempts to unify the field and introduce uniform standards and legislations. The ISO/TR 13121:2011 *(10)*, which relates to *Nanomaterial risk evaluation,* was developed in 2011 to aid in identifying, evaluating, addressing, making decisions about, and communicating the potential risks of developing and using manufactured nanomaterials, in order to protect the health and safety of the public, consumers, workers and the environment. To date, there are no standards that relate specifically to the safe disposal or recycling of nanomaterials. This is predominantly due to the large variety of nanomaterials and nanoparticles that exist and the varying approaches required for each.

Several nanomaterials and nanoparticles that are widely used in industry or commercial products are likely to prove highly toxic when introduced into ecosystems or when attempted to be recycled. For example, nanoparticles of titanium dioxide (TiO_2) are used in sunscreens, paints, and electronic

circuits. Reports show that TiO_2 can penetrate diseased or damaged skin in significant amounts and enter the bloodstream, where it can affect the central nervous system resulting in permanent damage through intranasal instillation *(11)* and neuroinflammation in the brain *(12)*. Moreover, titanium dioxide dust is classified by the International Agency for Research on Cancer (IARC) as a Group 2B carcinogen, meaning it is *possibly carcinogenic to humans (13)*. Other research shows that TiO_2 waste when present in the environment can kill beneficial soil microbes and bacteria completely changing the ecosystem balance *(14, 15).* Carbon nanotubes, fullerenes, graphene and carbon nano-dots are carbon-based nanomaterials that have applications in electronics and other fields. Several reports have proposed the use of these materials in applications such as medicine, drug delivery, and implantable sensors. However, other reports suggest the potentially hazardous, toxic or even carcinogenic nature of these materials, making them incompatible for use in biological applications. Indeed the use of carbon nanotubes for lightweight strengthening of building materials such as pavers could create asbestos-like problems when those materials are cut with electric saws and the particles inhaled (*16,17,18*).

In 2010, nanosilver in waste water was listed by a team of public health experts as one of 15 nascent issues that could deleteriously affect the conservation of biological diversity (*19,20,21*).

The volume of waste containing residue nanosilver is increasing proportionally with its utilization in domestic products and medicinal applications. Nanosilver released in domestic wastewater may have a variety of fates, including being converted into ionic silver, complexing with other ions, molecules or molecular groups, agglomerating or remaining in nanoparticle form. Its potential for significant environmental toxicity revolves around its biocidal and catalytic effects on a wide range of organisms in the soil, including bacteria, fungi, and earthworms, along with reaction with other toxic substances, a toxic effect on groundwater and accumulation along the food chain. Wastewater treatment relies on heterotrophic micro-organisms for organic and nutrient removal, while autotrophic microorganisms play an important role in nitrification. Nitrifying bacteria in sewerage systems are especially susceptible to inhibition by silver nanoparticles.

Recent research shows that synthetic nanowaste does not disappear even when exposed to harsh environmental conditions. For example, nanoparticles of cerium oxide do not burn or change in the heat of a waste incineration plant. They remain intact on combustion residues or in the incineration system. Scientists sprayed ten kilograms of cerium oxide particles measuring eighty nanometers in diameter onto communal refuse to be incinerated in a waste incineration plant equipped with modern filters and fly-ash separation systems based on electrostatic filters and a wet scrubber. Up to eight tons of waste was incinerated at the plant per hour. In a second experiment, the particles were sprayed directly into the combustion chamber, thereby simulating a future “worst case scenario” with massive nanoparticle release during incineration. In both cases, treatment didn’t remove the nanoparticles(*22*).

Not enough is known about the properties of nanomaterials and nanoparticles. Not all nanomaterials are hazardous or toxic, however these nanosized objects differ from bulk (non-nano) objects of the same material. One example is gold, commonly used in jewelry among many other products. In its bulk form gold is not harmful, but scaled-down to nano-size it becomes chemically reactive in particular upon light illumination. The photocatalytic properties of gold nanoparticles can facilitate certain chemical reactions; such as oxidation reaction and degradation of organic compounds; making it potentially dangerous*(23,24)*.

Learning from the past policy failures

The Organisation for Economic Co-operation and Development (OECD) was one of the first international bodies to acknowledge and investigate the issue of potentially hazardous nature of

nanomaterials and nanowaste to environment and human health. Recently, OECD released five new reports that describe their efforts. Other national and international organizations have joined the effort. The International Union for Conservation of Nature (IUCN), European Commission (EC), United Nations Environmental Programme (UNEP), as well as the US Environmental Protection Agency (EPA) and ISO, among others, are working independently to investigate the issue and propose a solution.

The EPA, US Occupational Safety and Health Administration (OSHA) and World Health Organization (WHO) are funding studies on the health and environmental risks posed by nanomaterials. The UK's Royal Society of Engineering and the European Commission are currently developing rules to protect humans and the environment from nanomaterials and nanowaste. Many big multinational companies and corporations have also joined the effort, putting more attention into their products and performing more evidence-based studies to evaluate hazards. However, there is still much to be done. Currently, the EPA does not require health testing on new materials and particles before releasing them to the market or environment. This rule doesn't apply solely to nano-products, but to any new chemical. In addition, very few safety efforts have been implemented by OSHA. In fact, the US Occupational Safety and Health Administration instructs manufacturers and technology users to handle all carbon-based materials alike, which is a cause for concern. While graphite is non-hazardous, carbon nanotubes, fullerenes, and carbon dots have all had several health concerns raised in regards to their use. In the US only about 4% of the federal nanotechnology research budget goes into studying the health and environmental effects of nanomaterials. To change the situation and make the field more sustainable and safe, experts project around 10% of the nanotechnology budget should be spent on these types of endeavors. Industry experts agree that rules should be changed and that companies should be made responsible in terms of evaluating hazards of their products, to prove they are safe to manufacture, use, and dispose of.

Proposal

Based on our expertise in nanomaterials and nanotechnology, we recommend simple steps that should be considered when developing nanowaste policies and regulations. The purpose of this paper is to support policy and decision makers in developing such policies or regulations by providing a basic conceptual model that can be further expanded into full policy.

Inventor's responsibility

Whose responsibility it is to evaluate the toxicity of newly developed nanomaterials, how they will behave in the contact with environment or human body, and how to safely dispose of them remains a debate. Whether the responsibility should be given to inventor or a company that is willing to commercialize the product based on specific and new nano-invention and release it to the market remain the ongoing debate, which needs to be clarified. However, taking into consideration the limited funds, manpower and laboratory capabilities that often face the researchers who are developing new materials solely for research purposes (e.g. in small amounts), it places an undue burden on the shoulders of these researchers to be charged with the responsibility of going through an expensive and time-consuming process that may require specialized facilities to complete. On the other hand, inventors of the new nanomaterials or nanoparticles are experts on that particular material; during the development process, these individuals are like to have discovered numerous important pieces of information that might be used for further environmental and health evaluation, as well as support the development of disposal and neutralization procedures. Taking both these factors into account, it follows that in cases where inventor is not going to use their nano-invention for commercial applications, they should be released from the obligation of performing the evaluation. It

is the author's opinion that it should not be the inventor's responsibility as long as it is used in small quantities for non-commercial purposes. In cases where (consistent) toxicity studies and safe disposal protocols don't exist, the company or individual who wants to use nanomaterial or nanoparticle should be charged with the task of completing the toxicity evaluation as well as the development of disposal procedures specific to that product.

There are specific ISO standards describing toxicity evaluation protocols for nanomaterials and nanoparticles. The ISO/TR 13121:2011 — *Nanotechnologies — Nanomaterial risk evaluation (10)* provides internationally recognized standards and good practices for identifying, evaluating, addressing and making decisions about the potential risks of developing and using synthetic nanomaterials, in order to protect the health and safety of the public, consumers, workers and the environment. However, to the date, there are still no standards in place regarding safe disposals of these new developments.

More funding into nanotechnology life-cycle and safe nanowaste disposal

Experts and stakeholders involved in the nanotechnology field agree that not enough funds are dedicated to toxicity evaluation and development of safe disposal practices. One common recommendation is that the governments or grant funding bodies should spend more money studying the health and environmental effects of nanomaterials.

There are two simple ways of addressing this issue. The first option assumes that the inventor should make preliminary evaluation and each nanotechnology development grant should allot 10 to 15% of the total grant amount specifically for this purpose. However, this would collide with the aforementioned proposed rule of releasing the inventor from responsibility in cases where the invention is used in small quantities for non-commercial purposes. The second funding option would be to develop funds specifically devoted to the purpose of evaluation and development. Groups that focus solely on evaluation of hazards and toxicity of nanomaterials already exist, however due to the highly competitive grant awarding process, in many cases their work is second category (considered less important compared to development projects). Existence of dedicated funds would completely change the research landscape, rewarding the existing teams focused on the topic and encouraging more researchers to pursue this area in the field. Special research funds may possibly be the fastest way to develop the toxicity library of nanomaterials and safe disposals protocols and standards. Another issue with this kind of research is its '*impact factor*'. Currently, the work produced by the field of environmental and health evaluation of nanomaterials is not considered as important and impactful as developing new materials. This attitude, which can be seen by examining how research funds are being distributed and the impact factors of the articles, must also change in order to make a progress in the field.

Commercialization procedures

The process of nano-product (nanomaterials, nanoparticle, etc.) approval should exist and be controlled in every country by a governmental regulatory agency. We recommend a simple approval sequence for nanotechnology in a similar fashion to that of drug approval procedures in the US, however the time required for each of the steps should be minimized. The regulatory procedures for nanomaterials commercialization have to be designed to protect the environment and human health while progressing the development. The steps listed below are brief and limited recommendations

and in order to be applied they must be further developed in regards to detail. Timeframes are also flexible and can be adjusted based on current needs.

- Literature review: This step involves compiling knowledge from a variety of sources on toxicity and environmental impact of the specific product. In cases where the literature is conflicting or inconsistent, the Preliminary Testing step is required to be eligible to submit an Investigational New Nanotechnology Application. Otherwise, the Preliminary Testing step can be skipped in cases where enough supporting literature evidence is available.

- *Preliminary Testing:* In this step, the development company conducts specific studies before the future nanotechnology-based product is released for further environmental and toxicity evaluation. Laboratory and/or animal studies must be done to demonstrate either a lack of biological activity or that biological activity is non-hazardous and non-toxic to the target. The product must also be evaluated for safety in regards to various environmental conditions (i.e. acidity levels, various types of radiation, temperature, etc.). These tests should take place over the course of 1 to 2 years on average.

- *Investigational New Nanotechnology Application:* The development company files an application to the national regulatory agency to begin the approval procedure. The application must include the following information: description of the material and chemicals used to produce it, the chemical structure of the compounds, MSDS of used chemicals, the results of all preliminary tests and how they were conducted (procedure description) and/or literature review, description of planned studies and their extent, possible applications of the product, description of possible or suspected negative effects on human health and ecosystems, as well as any toxic effects found in all completed animal studies. The application must be reviewed and approved by the governmental regulatory agency before next steps of the evaluation can be conducted.

- *Phase I Trials:* Phase I studies are usually the first tests of a nanotechnology under strict and unified experimental procedures. The tests determine a technology's safety profile, including the safe quantity range and environmental conditions, whether the material or nanoparticle is absorbed, distributed, metabolized and excreted by the human body and in the environment, and the duration of its action. Additionally, safe disposal measurements and procedures are developed in this step. Phase I trials are expected to take place over the course of one year, on average.

- *Phase II Trials:* This phase is designed to further study and clarify any concerning properties that have been identified in Phase I. In cases where solid evidence gathered in Phase I shows no additional concerns, Phase II can be skipped. Phase II is expected to take place over one year, on average.

- *Phase III Trials:* These are the definitive, large-scale, randomized trials that are submitted to the regulatory agency in order to obtain approval of the new development. This phase examines the effectiveness as well as the safety of the product in relation to random, very extreme cases that may occur during use of the technology. These may include, but are not limited to, the study of the material or nanoparticle in high temperatures or very acidic conditions. It is recommended that the tests in Phase III are performed by an independent

third party. Phase III is expected to take place for the duration of six months to one year. The outcome of Phase III is an official extensive report that broadly describes the material, its chemical structure, and the manufacturing procedures including the necessary chemicals used. Moreover, it describes testing procedures used to evaluate toxicity and environmental impacts of the material, as well as all findings that have been collected during these tests. Lastly, the report recommends safe manufacturing, use, disposal, and where possible recycling procedures, as well as any recommendations in case of contamination.

- *New Nanotechnology Application:* Following the Phase III Trials, the manufacturer analyzes all the data from the studies and files the final report to the regulatory agency. The final report contains all of the data gathered to date about the nanomaterial. The report is then reviewed by internal experts to the regulatory agency and either approved or rejected. In special cases where approval is given by more information is need to proceed, the regulatory body may request that Phase IV studies take place.

- *Phase IV Studies:* The regulatory agency may give approval with the requirement that the approval must be reviewed 5 to 10 years from the introduction of the new material or nanoparticle to the market. Phase IV is any organized collection of data from case studies, concerns, reports and user complaints related to the product that has already received approval from the regulatory agency.

National and international standards

It is clear that standards have to be developed in order to tackle the escalating issue of nanowaste in these early stages. One of the main questions remains unclear, which is whether national standards are sufficient or if unified international standards should be developed to guide creation, supervise development and production, and further normalize safety standards and disposal of nanowaste.

It is the author's opinion that each country should develop their own standards based on their individual needs, capabilities, and geographical conditions. Some nanomaterials or nanoparticles might be specifically chemically active or toxic under particular environmental conditions occurring in specific parts of the world. Freedom of safe disposal and neutralization of nano-refuse should also remain in the hands of national regulatory agencies. However, to properly tackle this escalating, complex and poorly understood issue, stakeholders from different parts of the world must be required to share their opinions, expertise and case studies. International stakeholder engagement can result in bigger and unified international policies and guidelines. It will also enhance exchange of new facts, issues and solutions.

It is clear that international bodies, such as ISO, have already started investigating the issue at hand and that they will develop standards related to safe disposal and/or recycling on nanowaste. Additionally, the OECDs presence and attempt to address the issue is expected to drive the change to safe use of nanotechnology at every point of its lifetime. This is currently done by releasing statements, reports, and guidelines, however more active science diplomacy is needed to regulate the issue at this early stage of the technology development.

Unified standards for all materials?

Currently, our knowledge on the issues related to nanotechnology and nanowaste is too immature and poorly understood to decide whether all nanomaterials and nanoparticles can be treated the same way in terms of safe disposal and neutralization. It is true that many materials within the same material classification group behave in a very similar way and have similar properties. However, it is also clear that there are different classifications of nanomaterials and nanoparticles (i.e. organic and inorganic, natural and synthetic, spheres and clusters, nanofibers, wires and rods, thin films and plates, bulk nanomaterials, etc.). Depending on the type of the material, they can have very dissimilar physical and chemical properties, including melting point, size, hardness, etc. Due to these differing properties, procedures used for one type of material may not necessarily be applicable to other groups of nanomaterials. Another concerning issue is that allotropes *(25)* of the same element may behave very differently and poses very diverse chemical and physical properties depending on its crystal structure. Carbon is a perfect example of this case. Graphite is a mechanically soft and optically black form of carbon widely used in pencils, while diamond, one of the hardest materials known to man, is white in color and also based on carbon elements. Disposal procedures for these two elementally identical materials will have to be very different due to their chemical and physical properties. This demonstrates that not all carbon-based materials can be treated the same way, and nor can all allotropes of the same element. Another issue lies in derivatives of the same material. Base material may not be toxic, but the derivatives may be. For example, attaching functional groups (functionalization) to nanoparticles in certain cases can result in an incredibly toxic and chemically active product. A good example of such a behavior are fullerenes. Available data shows that pristine C60, which is found in a large variety of living organisms from bacteria and fungus to human leukocytes, mice, and rats, as well as guinea pigs, is non-toxic *(26,27)*. In contrast, to chemically; either covalently or noncovalently; modified fullerenes, some C60 derivatives can be highly toxic. *(27)*

These two issues related to the chemical and physical nature of materials and their physical properties force us to identify tailor-made disposal, neutralization and recycling techniques for each material individually. In numerous cases there will be procedural overlaps and similarities in the treatment, however it is too simplistic and a risk to safety to assume that procedures are transferable without proper testing. It cannot be assumed, for example, that disposal procedures developed for silver nanoparticles will be transferable to titanium dioxide. Nanowaste disposal requires extensive research and evaluation; it also requires that very strict and clear norms and procedures be adopted. Scientists, policy makers, and other involved stakeholders must work together and learn from each other in order to make effective and viable standards.

Further evaluation

Due to the lack of information at this time and the complexity of the issue, toxicity and safe disposal evaluations of nanomaterials and nanowaste should be performed and updated ongoing basis. As previously stated, the same material can behave chemically in a very different manner when exposed to disparate physical and chemical conditions. Moreover, there may potentially be hundreds of derivatives of the same compound, molecule or nanoparticle, some of which may be very hazardous, reactive and toxic. Hence, it cannot be assumed that since the pristine material has been identified non-toxic and non-hazardous, modified versions of that material can fall under the same category. Derivatives and materials modified on a molecular level require further studies and evaluation.

Preliminary evaluation and procedures used for pristine materials can, in this case, serve as guidelines for further studies.

Closing remarks

The grand challenges for nanowaste regulation are:

- develop instruments to assess exposure in air and water;
- develop and validate methods to evaluate the toxicity;
- develop models for predicting the potential impact on the environment and human health;
- develop robust systems for evaluating the health and environmental impact of engineered nanomaterials over their entire life;
- develop strategic programmes that enable relevant risk-focused research.

There is a growing consensus in the EU, the UK, and Australia that regulatory definitions of bulk substances cannot accurately represent their nano-equivalents and the existing toxicity testing methods cannot effectively determine the toxicity of nanosilver. As such the different regulatory gaps can be bucketed into two categories. The first category deals with gaps relating to whether existing definitions and threshold requirements are applicable to nanoproduct waste. The second category deals with gaps arising from a lack of toxicological data, life-cycle studies or knowledge of optimal environmental exposure limits regarding nanowaste.

To address the first category of regulatory gaps, regulators should provide clear guidance to the industry for classifying nanoscale materials as “new” for legal, regulatory and safety purposes. The existing statutory threshold levels for quantity of manufactured nanomaterials are high and unlikely to be triggered in many cases where risks could eventuate.

Where appropriate legislation should be amended to explicitly deal with nanotechnology products and to simplify the existing legislative provisions. For example, introducing a category of nanopesticides in the different jurisdictions may assist in avoiding the circuitous route currently adopted to regulate non-traditional pesticidal products that utilize nanosilver such as washing machines.

Pre-marketing approvals are a good regulatory strategy because they not only allow the government to screen any potentially harmful materials and products, but to facilitate products targeted at public goods. They should be extended to nanoproducts regardless of whether they currently belong to a category of products exempt from such approvals. REACH for all its faults (regulatory triggers based on high levels of manufacture) in probably represents a better model of oversight law than the TSCA because it puts the burden on the manufacturer to prove safety rather than on the government to prove the risk. This safety data so required should not be limited to the physical, chemical and toxicological properties; instead, it should (as standardized measures for determining these parameters become progressively available) include the shape of the nano-formulation, particle size range and mean, aggregation characteristics, expected lifetime in various states, biopersistence, synthesis method, crystal structure, surface area and charge, anti-microbial claims, concentration and associated novel chemical characteristics and properties.

Post-marketing surveillance should be extended to all nanosilver products. Additionally, the regulators should look to provide guidelines on disposing of nanowaste in order to provide oversight encompassing the entire life cycle of nanosilver. There is a need for the various governments to internally and internationally consolidate their knowledge bases and work with scientists, producers, users of nanosilver to develop protocols and guidelines that are consistent and ensure responsible development.

Given that the voluntary reporting programs were a failure in the US, the UK, and Australia, it is recommended that mandatory reporting schemes be introduced. Claims that this would compromise confidential business information or constitute an unconscionable financial or administrative burden seem unreasonable in the face of public necessity to facilitate the availability of information across the various sectors.

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25. Allotrope or allotropism is the property of some chemical elements to exist in two or more different forms, in the same physical state. Allotropes are different structural modifications of an element, where the atoms of the element are bonded together in a different manner.

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