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# Learning from other Domains to Advance AI Evaluation and Testing

We are grateful to the author of the enclosed expert report, which forms part of a broader series commissioned by Microsoft.

These reports were commissioned as part of Microsoft's effort to draw lessons from other domains to strengthen testing and evaluation as a cornerstone of AI governance.

The insights contained in each report reflect the authors' independent analysis and expertise. The views expressed are those of the authors alone.

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# The regulatory landscape of nanoscience and nanotechnology, and applications to future AI regulation

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## Introduction

The fields of nanoscience and nanotechnology investigate and manipulate matter at the nanoscale (generally defined as having critical dimensions less than 1000nm). At these scales, materials exhibit distinct physical, chemical, and biological properties compared to their bulk counterparts due to their increased surface area, enhanced reactivity, and potential for quantum effects. Nanomaterials include nanoparticles, two-dimensional materials (such as graphene, hexagonal boron nitride, transition-metal dichalcogenides), and their heterostructures, and are pivotal to the development of advanced technologies across numerous industries. These materials have the potential to revolutionize a wide range of sectors, from computing, communications, and catalysis, to medicine and manufacturing, owing to their increased strength, improved conductivity, and/or the ability to interact with biological systems in novel ways. The Nanotechnology Research and Development Act recently celebrated its twentieth anniversary (March 2004-March 2024). As stated in former President Bill Clinton's letter during that celebration, "in the last quarter century, nanotechnology research has contributed to scientific breakthroughs that have changed the way we live and work—from computer chips, to electric vehicle batteries, to COVID-19 vaccines."

While nanoscience is a nascent field - in many ways even younger than the AI field - the applications of nanotechnology are vast and increasingly impactful. In pharmaceuticals, nanomaterials are being used to develop drug delivery systems that target specific cells or tissues with precision, minimizing side effects and enhancing therapeutic efficacy. In chemical manufacturing, nanomaterials serve as catalysts, speeding up reactions and improving energy efficiency. In energy storage, nanomaterials increase the speed of charging, extend the cyclability, and can increase the device capacity and energy density. In automation and robotics, nanomaterials enhance the performance of components such as actuators, sensors, and motors, offering improved strength, flexibility, and responsiveness at the nanoscale. In additive manufacturing, nanomaterials enable the creation of lighter, stronger, and more durable parts, allowing for greater precision and the production of complex, custom-designed structures with enhanced mechanical properties. Nanotechnology is also transforming transportation and construction with stronger, lighter materials, as well as self-healing structures that can extend the lifespan of materials. In the electronics industry, nanomaterials are fundamental to the development of smaller, faster, and more powerful semiconductor chips, enabling the continued miniaturization of devices. Finally, consumer products, such as clothing, cosmetics, and food packaging, also benefit from nanotechnology, with innovations that improve strength and durability, stain resistance, and functionality.

Despite the immense potential of nanotechnology, there is caution regarding its safety and environmental impact. The long-term biological and environmental hazards associated with nanomaterials remain, to a certain degree, uncertain. Modern industries often operate under safety testing requirements that focus on bulk properties, potentially overlooking nanoscale-specific risks. The specialized characterization equipment needed for thorough evaluation of nanomaterials can pose challenges in certain sectors, making regular industrial monitoring both expensive and complicated. For example, techniques like scanning and transmission electron microscopy, x-ray spectroscopy, scanning probe microscopy, and mass spectrometry can reveal the atomic-scale structure and composition of nanomaterials. These tools require considerable up-front capital, as well as expert personnel to operate and maintain these instruments. The semiconducting industry makes frequent use of such tools, to inspect wafers and chips

for quality fabrication. Similarly, the pharmaceutical industry also employs state-of-the-art methods to ensure manufactured product quality control. However, scaling these tools such that they could be used for routine inspection and safety risk assessment would be cost-prohibitive in many industries, and also reveal a scarcity of expertise in nanocharacterization. Because such tools are so specialized, linking the (often heterogeneous) nanoscale composition of nanomaterials with downstream function in applications spanning batteries, catalysis, optoelectronic devices, and even biomedical devices is largely underexplored - requiring multidimensional analysis of physical, chemical, biological properties of nanomaterials.

In addition, the potential for unintended nanomaterial formation also raises safety concerns. For example, while the potential toxicology profile of many nanomaterials is known (particularly those in consumer products), some bulk materials degrade into micro/nanoparticles with highly variable properties. This variability can give rise to distinct functions, and sometimes, distinct safety concerns. One particularly notable example is the degradation of plastics and rubbers into micro and nanoplastics. Recognizing that these particles persist in the environment and have the potential to harm aquatic life and potentially the health of land animals (including humans), the Microbead-Free Waters Act of 2015 in the United States banned the use of plastic microbeads in cosmetics and personal care products. Related, methods to create nanomaterials can have significant environmental impacts, including hazardous waste generation and the depletion of precious materials. Any regulatory framework must not only consider the safety and risks of the nanomaterials themselves, but also their lifecycle analysis, from creation to disposal.

## Current regulatory measures, from R&D to consumer product

Current regulatory measures are aimed at addressing the risks of nanoscience, while ensuring innovation is maintained. The landscape is complex and fragmented; below, we outline how regulation has been implemented and how it might evolve in the future. As of this writing, regulations around nanotechnology remain industry-specific and are not based on a uniform framework for the industry as a whole.

In the US, agencies like the Food and Drug Administration (FDA) and Environmental Protection Agency (EPA) regulate nanomaterials in certain contexts. There is still ongoing debate about whether existing frameworks are sufficient to address the unique risks posed by nanoparticles. The National Nanotechnology Initiative (NNI), through its Environmental, Health, and Safety (EHS) Handbook, along with feedback from organizations like the American Industrial Hygiene Association (AIHA), play an important role in shaping guidelines and research aimed at ensuring the safe development and deployment of nanotechnology across diverse fields. In the European Union, several agencies are involved in the regulation and oversight of nanomaterials. For example, the European Chemicals Agency (ECHA) is responsible for the implementation of the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation. Under REACH, manufacturers and importers must register chemical substances, including nanomaterials, and provide information about their properties, uses, and safe handling. In parallel, the European Food Safety Authority (EFSA) evaluates the safety of food and feed additives. It assesses risks associated with the use of nanomaterials in food products and issues scientific opinions that inform regulations and safety standards for food-related nanomaterials. The European Medicines Agency (EMA) assesses medicinal products, and is responsible for the evaluation of the safety, efficacy, and quality of nanomedicines. EMA provides guidance on the use of nanotechnology in pharmaceuticals and ensures compliance with existing regulations.

Regulation of nanomaterials in Asia varies significantly by country and industry. In China, the Ministry of Ecology and Environment (MEE) oversees environmental regulation, including the management of nanomaterials' safety and environmental impact, while the National Health Commission (NHC) is responsible for health regulations, including those related to food safety and the use of nanomaterials in

food products. Japan, South Korea, Singapore, and India also have their own agencies that regulate the use of nanomaterials in food, pharmaceuticals, and cosmetics, and provide guidance regarding safety assessments. These include the Ministry of Health, Labour and Welfare, Ministry of the Environment, and Pharmaceuticals and Medical Devices Agency in Japan; the Ministry of Environment, Ministry of Food and Drug Safety, and Korea Occupational Safety and Health Agency in Korea; the Food Safety and Standards Authority of India, Central Drug Standard Control Organization, and Department of Biotechnology in India; and the National Environment Agency, the Singapore Food Agency, and the Health Sciences Authority in Singapore.

As highlighted by the above agencies, testing of nanomaterials is generally more pervasive in consumer product regulation, particularly in the pharmaceutical industry, where ensuring human and animal safety is paramount; and in the microelectronics/semiconducting industry. In the pharmaceutical industry, regulatory approval processes, such as those overseen by the FDA and related international agencies, necessitate extensive clinical testing for nanomaterials used in biotherapeutic applications. To provide a few examples, gold nanoparticles are being explored for photothermal tumor ablation, while HDL (aka, 'good-cholesterol')-mimicking nanoparticles are being developed for atherosclerosis therapy. Similarly, lipid nanoparticles (LNPs) are used for drug delivery in diseases spanning autoimmunity, cancer, metabolic disease, and infectious disease; LNPs are also used as prophylactics and in vaccines. In these cases, the nanoparticles undergo rigorous testing in multiple phased clinical trials before approval in humans.

Nanomaterials in cosmetics have more lenient regulations than drugs. Here, ingredients like titanium dioxide and zinc oxide (often in nano-form) are used in sunscreens, lotions, and in make-up. Cosmetic products are not subject to pre-market approval by the FDA. In 2014, the FDA released a draft guidance titled "Safety of Nanotechnology-Based Products." This report indicates that if a product contains nanomaterials, manufacturers should consider the unique properties of these materials, which may differ from their bulk counterparts. This includes potential risks and toxicity considerations. The FDA does not require the term "nano" to appear on labels unless it is part of the name of a specific ingredient or if the ingredient has specific labeling requirements.

In the electronics and semiconducting sector, rigorous testing of nanomaterials is crucial for ensuring reliability and quality control in microelectronics, energy storage, and computing devices. Testing protocols evaluate whether components meet specifications for computing speed, power consumption, processing capabilities and cyclability. Moreover, as technologies evolve, testing becomes crucial to identifying potential cybersecurity vulnerabilities, ensuring that devices can withstand electromagnetic interference and thermal management challenges, and ensuring these devices are not counterfeit.

Beyond these industries, there is relatively little regulation governing standardization of nanomaterials use and safety testing. Lighter-touch governance of nanomaterials in certain industries is both deliberate and desirable. Low-risk nanomaterial applications have minimal testing requirements. For example, nanomaterials as additives in air and water filtration systems - for example as antimicrobials - only need to show improved air and water quality; likewise, nanomaterials as additives in industrial manufacturing (eg, construction and transportation) simply need to demonstrate enhanced performance (eg, durability and strength). In these and other applications, the nanomaterials are assumed to be adequately 'packaged' so that the end-user does not interact with the nanomaterial. Such lighter-touch governance supports innovation while still safeguarding public interests to the best extent possible.

At present, there is strong collaboration between academia, industry and regulatory bodies to maintain a balance between fostering innovation and safeguarding public health. At the research and development (R&D) level, safety is prioritized, ensuring the secure production and handling of nanomaterials. As materials scale from R&D to translation, more emphasis is given to packaging, such that end-users rarely

interact with the constituent nanomaterials (eg, nano-materials are packaged into display technologies, batteries, catalytic reactors; lipid nanoparticles are packed into an injectable medicine; chips are packaged into computers and cell-phones). It is these packaged materials that are most often the subject of industry-specific regulation, creating a framework that ideally protects both human health and the environment. Yet, as consumers increasingly encounter and interact with various nano-enabled products, the industry should consider more transparency in the potential risks, allowing individuals to make more informed decisions in their use of these products.

## The testing landscape: measuring risks and benefits, and developing standards

The testing landscape of nanoscience is multifaceted. As nanotechnology products transition from lab prototype to mass production, testing requirements evolve. In the laboratory, safety-testing objectives focus on ensuring the safety and function/effectiveness of nanomaterials across the full lifecycle (eg, synthesis, deployment, and disposal). By characterizing physical and chemical properties—such as nanomaterial size, solubility, and reactivity—researchers can better understand how nanomaterials behave in different environments and contexts, whether aqueous or aerosolized. At the industrial level, testing is nominally aimed at determining the longevity, degradability, and biocompatibility of these materials. It assesses how safe the nanomaterials are not only in their original forms but also concerning their degradation products. This involves extensive studies on human and animal safety, evaluating risks such as toxicity, flammability, and long-term health effects, as well as environmental considerations, including the life cycle of the nanomaterial in various ecosystems. Conventional regulations necessitate life-cycle testing that evaluates the behavior of nanomaterials in various conditions. This includes assessing the reliability of manufacturing processes, where standards are established to regulate key parameters affecting both performance and safety.

The measurement and assessment of risks and benefits in nanoscience vary significantly across industries. In the pharmaceutical industry, the evaluation of nanomaterials often involves comprehensive in vivo and in vitro studies to assess their biocompatibility, pharmacokinetics and dynamics, cytotoxicity, and long-term health effects (eg, genotoxicity, carcinogenicity, and reproductive health impacts). Quantitative metrics—such as the rate of cellular uptake of nanoparticles, their efficacy in targeted drug delivery, and any potential adverse reactions—are crucial in determining both the safety and effectiveness of nanomedicine applications. Regulatory bodies like the FDA mandate rigorous clinical trials and safety assessments to ensure that nano-enabled medical technologies, including drug delivery systems and nanostructured vaccines, meet stringent safety standards before gaining approval for consumer use.

The electronics and semiconducting industries focus on ensuring that nanomaterials used in devices like microchips maintain performance standards while minimizing potential environmental and human safety risks. Testing protocols often center around evaluating electromagnetic radiation exposure, reliability under operational stress, and the overall longevity of semiconductors that utilize nanotechnology. The standards for the safety and manufacturing of semiconducting chips are established by several key organizations, including the U.S. Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC). The Semiconductor Industry Association (SIA) also works with member companies to develop best practices, technical documents, and policy recommendations that address safety and manufacturing processes. On an international scale, organizations like the International Organization for Standardization (ISO) and ASTM International establish internationally recognized standards that can guide safety practices and manufacturing processes globally. These standards often encompass various facets of chip production, including (nano)materials safety, performance testing, waste management, and environmental impact assessments.

The chemical manufacturing and energy sector, which relies on nanoparticles as catalysts or electrodes, will often assess the performance and environmental impact of nanomaterials. Here, regulatory frameworks require life-cycle assessments that evaluate not only the material's performance in catalysis, batteries, or other applications but also its interactions and reactivity with other materials in the environment. This governance seeks to quantify risks such as toxicity, persistence in ecosystems, and potential pathways for human exposure through mechanisms like soil contamination or wastewater. Governing bodies include the Occupational Safety and Health Administration (OSHA), the Environmental Protection Agency (EPA), the American Chemistry Council (ACC) and the European Chemicals Agency (ECHA). OSHA establishes regulations and standards related to workplace safety that are directly pertinent to chemical manufacturing. These regulations address issues such as handling hazardous materials (eg, most batteries are processed as e-waste), exposure limits, and safety training requirements. The EPA sets standards regarding environmental safety and pollution control for chemical manufacturers. This includes regulations related to waste management, emissions, and water quality, particularly concerning the disposal of byproducts from chemical and catalytic processes. The ACC is an industry association that represents chemical manufacturers in the U.S. and helps set industry standards, guidelines, and best practices for safety and sustainability. In the European Union, ECHA administers the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation, which requires chemical manufacturers to register their substances and assess their safety for human health and the environment.

To summarize, the standards and methods for testing nanomaterials are developed through collaboration among government regulators, academic institutions, and industry stakeholders. Together, these sectors work to update and refine standards to reflect technological advancements and emerging safety concerns. Regulatory bodies like the FDA and organizations such as ISO, OSHA, and EPA craft the criteria based on safety data, testing outcomes, and scientific insights provided by institutions like the National Nanotechnology Initiative (NNI). Additionally, testing may be carried out by academic laboratories, industries seeking regulatory approval, independent laboratories, and even government institutes like NIST, which ensure that manufacturing processes across sectors adhere to established standards. Results from these tests inform consumer safety, regulatory compliance, and best practices in the workplace. Semi-structured frameworks, such as material flow analyses and exposure models, also help quantify the lifecycle impacts of nanomaterials. The resulting insights not only inform regulatory standards but also guide the responsible development and commercialization of nanotechnology.

## The history of safety- and risk-testing in nanoscience and nanoengineering

The testing of nanomaterials began gaining prominence in regulatory frameworks in the early 2000s, coinciding with the commercialization of nanotechnology products. A significant milestone in the US occurred on December 3, 2003, with the 21st Century Nanotechnology Research and Development Act. This act established the National Nanotechnology Initiative (NNI), which aimed to foster research, development, and the responsible application of nanotechnology in various sectors. This act also coincided with several important publications from the international Organisation for Economic Co-operation and Development (OECD), including "Safety of Manufactured Nanomaterials" and "OECD Guidance Manual for the Testing of Manufactured Nanomaterials". These reports detailed the safety of specific types of nanomaterials, provided guidance on testing nanomaterials for toxicity, and emphasized the need for appropriate methods tailored to the unique characteristics of nanomaterials.

Since these publications, core testing guidelines have evolved in response to the increasing interest in and commercialization of nanotechnology. Recommended tests on nanomaterials now include physicochemical characterization (eg, particle size and distribution, surface area, and surface charge), toxicokinetics (eg, absorption, distribution, metabolism, and excretion studies), environmental testing (eco-toxicity and transport and fate studies), in vitro testing (eg, cytotoxicity and genotoxicity), and in-

vivo testing (acute and chronic toxicity, carcinogenicity, and reproductive and developmental toxicity). We note however, that these tests are not always standardly conducted, depending on the industry.

To provide a few industry-specific historical examples, the microelectronics industry has consistently emphasized testing, with comprehensive academic and industry initiatives driving advancements in this area. In the past few decades, safety testing in the microelectronics industry has become more comprehensive and systematic. Formalized testing protocols for assessing material safety, including procedures for evaluating toxicity, stability, and chemical interactions, have been established. The microelectronic industry has also shifted toward adopting risk-based assessment frameworks, which emphasize identifying and managing potential risks throughout the product lifecycle, from material selection through manufacturing and to end-of-life disposal.

Meanwhile, in the food and pharmaceutical industry, regulations have evolved in response to novel nanomaterials. In 2007, the FDA issued draft guidance titled "Nanotechnology Applications in Food." It highlighted the need for manufacturers to consider the implications of nanoscale materials in drug formulation, safety assessments, and efficacy. The guidance recommends that the unique properties of nanomaterials should be considered in the submission of investigational new drug (IND) applications and New Drug Applications (NDAs). The FDA encourages sponsors to provide data specific to the nanoscale properties of their formulations, addressing safety and potential toxicity differences compared to bulk materials.

In the chemical manufacturing industry, nanoparticles for catalysis were developed as early as the 1950s, but it was only after the implementation of environmental regulations, such as the Clean Air Act in the 1970s, that focused testing began. Specific testing of nanoparticles related to catalysis did not significantly emerge until the 2000s. Today, it is customary to monitor aerosol exposure in workplaces handling nanoparticle catalysts, using techniques like filter sampling and electron microscopy to evaluate particle sizes and concentrations. The industry also works to recover precious metals or other valuable materials from spent catalysts through processes like solvent extraction or chemical leaching - not only to protect the environment in response to environmental waste regulations, but also to promote a ‘circular materials economy’ in which reagents can be reused or recycled.

## International coherence

While testing remains industry and country specific, there is a shift towards international coherence in nanoscience safety testing. International coherence in the testing and regulation of nanoscience has historically been challenging due to divergent standards and practices across jurisdictions, particularly among major players like the United States, China, the European Union, Australia, and various African nations. While the U.S. has established its own regulatory framework, it often lacks the stringent requirements seen in the EU, which has a more precautionary approach to chemical safety, particularly in consumer products such as cosmetics. For example, several chemicals deemed safe for use in the U.S. are banned in Europe, creating a patchwork of regulations that complicates product development and potentially exposes consumers to unnecessary risks.

Currently, there is no universally accepted international standard for labeling nanomaterials. In Europe, requirements exist for labeling products that contain nanomaterials, particularly in food and cosmetics. These include Regulation (EC) No 1907/2006 (REACH), under which manufacturers and importers are required to inform the European Chemicals Agency about the presence of chemical substances in their products. If a chemical substance is produced or imported in the nanoscale form, it must be specifically identified as such when it is subjected to registration under REACH. Similarly, Regulation (EU) 1169/2011 on the Provision of Food Information to Consumers outlines the labeling requirements for food products, which includes the use of nanomaterials. If a food product contains nanoscale additives or

ingredients, this must be stated on the label using the term “nano” next to the relevant ingredients. Cosmetic Products Regulation (EC) No 1223/2009 also requires that any nanomaterial used in cosmetic products be explicitly mentioned in the list of ingredients; the term “nano” must be added in parentheses after the name of the ingredient.

In the United States, the regulatory landscape for the labeling of nanomaterials in consumer products is not as clearly defined as in Europe. The EPA administers the Toxic Substances Control Act (TSCA), which requires chemical substances, including nanomaterials, to be reported if they are new chemicals or if they represent significant new uses. While manufacturers may need to register and provide information about nanomaterials, there is no specific labeling requirement for consumer products under TSCA. The FDA does not currently have specific labeling requirements for nanomaterials in foods or dietary supplements, but it has issued guidance for the industry about the use of nanotechnology. Manufacturers are encouraged to notify the FDA if they use nanomaterials in products, particularly in food additives, food contact substances, and cosmetics. However, the FDA does not require manufacturers to explicitly label products as containing nanomaterials. Finally, the consumer product safety commission (CPSC) regulates consumer products for safety but does not have specific labeling requirements for nanomaterials in general consumer products. Manufacturers are expected to ensure product safety, and if nanomaterials pose specific risks, they might need to provide sufficient information to consumers. Some states have enacted their own regulations regarding nanomaterials. For example, California has considered bills regarding the labeling of nanomaterials in cosmetics and other consumer products, though as of this writing, comprehensive statewide regulations have not been universally adopted.

Asia is also somewhat fragmented in terms of its regulation of nanomaterials. China has established guidelines that require the assessment of nanomaterials used in food and cosmetics. These guidelines encourage transparency and safety assessments but do not impose a strict labeling requirement specifically for nanomaterials in all consumer products. However, products categorized as food with nanomaterials often require specific labeling or notification to authorities. Japan has guidelines on the use of nanomaterials, particularly in food and cosmetics. The Ministry of Health, Labour and Welfare (MHLW) has issued notifications regarding the safety assessment of food additives, which include nanoscale materials. However, there is no comprehensive national requirement for general consumer product labeling specifically for nanomaterials. South Korea has specific regulations concerning nanomaterials. Under the Act on Registration and Evaluation of Chemicals (K-REACH), manufacturers are required to register nanomaterials, with guidelines that recommend the labeling of products containing them. However, labeling requirements can vary depending on the product category. In India, regulatory frameworks governing nanomaterials are still evolving. The Food Safety and Standards Authority of India (FSSAI) has indicated the need for guidelines on the use of nanotechnology in food and food products, calling for appropriate safety assessments. However, as in China, Japan, and Korea, there are currently no strict labeling requirements for nanomaterials in consumer products. Finally, Singapore is also developing a framework around nanotechnology regulation. The National Environment Agency (NEA) and other agencies have been actively discussing the safe use of nanomaterials. While specific labeling requirements aren't fully established, there is an emphasis on safety assessments and risk communication.

Several mechanisms exist that promote the movement toward coherent international standards but also pose limitations to interoperability. International coalitions, such as the OECD, have made strides toward establishing agreed-upon testing protocols to address nanotechnology products. However, balancing the urgency of bringing new materials to market with the need for comprehensive safety evaluations often impedes progress. The perception of nanotechnology among the public can shape regulatory approaches, where concerns about potential health and environmental risks may lead to calls for faster regulations. At the same time, the ongoing influx of new nanomaterials and chemicals entering the commercial landscape poses difficulties for coherent regulation. Each country has different priorities and approaches, leading to discrepancies that can complicate the efforts to create harmonized standards. The lack of universally

accepted definitions and methodologies for nanoscience and testing of nanomaterials further exacerbates this issue. To date, most nanomaterials are considered as chemical substances; to the extent that chemical substances are internationally regulated, nanomaterials will be subject to similar regulations.

## Domain lessons learned, and possible implications for AI

Nanoscience is an innovative new field, with many potential benefits, and also some remaining unknown risks. As described above, distinct domains of nanoscience have tailored regulations that address specific challenges and risks unique to each field. Factors that generally accelerate governance maturity in nanoscience applications include potential impact on human and environmental health and national security, as well as commercial opportunity. Some industries, like the electronics, semiconducting, pharmaceutical, and cosmetic industries, are more mature in their governance of nanomaterials. These industries have significant, direct impact on human and environmental health, and so regulation helps ensure public safety. Pharmaceuticals (whether with or without nanomaterials) are distributed only when the benefits outweigh the risks; and nanomaterials in electronics and the semiconducting industry are thoroughly packaged and properly disposed of (eg, as ‘e-waste’). We note however, that these sectors were already regulated prior to the advent of nanomaterials, and so in many ways, nanomaterials are simply subject to the same scrutiny.

Interestingly, these industries also have significant commercial impact, and therefore likely greater private sector investment in research and testing. Such investments can inform potential hazards, often before they are known by the public. For example, the chemical industry was aware of, and suppressed their knowledge of health harms caused by exposure to PFAS (per- and polyfluoroalkyl substances); see Gaber et al, Annals of Global Health (2023) “The Devil they Knew: Chemical Documents Analysis of Industry Influence on PFAS Science.” Rachel Carson’s Silent Spring also revealed the environmental harm of the pesticide DDT, with public officials generally accepting the industry's marketing claims despite industry-known hazards. To avoid related safety concerns with nanoscience (and by extension, AI), it is important that government and private sectors conduct independent investigations, so that commercial interests do not supersede public and national/international safety. In principle, the level of regulation should correspond to the potential and known risk level associated with the application, optimizing for personal, population, and planetary health and welfare.

Finally, we note that AI has the potential to significantly accelerate the testing and future regulation of nanomaterials. For example, AI could streamline the identification and assessment of promising nanomaterials candidates before extensive lab trials. By leveraging machine learning algorithms, researchers could rapidly screen vast libraries of nanomaterials, predicting their safety profiles and performance based on previously gathered data. Moreover, the advent of self-driving labs—automated systems guided by AI—can facilitate real-time experimentation and data collection, ensuring a more agile and efficient research process. Additionally, AI-guided materials synthesis can optimize the creation of nanomaterials tailored for specific applications, further advancing the field while prioritizing safety. While applications of AI to nanomaterials is nascent, and will require improved and/or expanded materials databases, AI could accelerate the discovery of functional nanomaterials while addressing potential health and environmental concerns proactively.