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Voices

Responsible nanotechnology for a sustainable future

Nanotechnology has accelerated groundbreaking solutions at the molecular scale to help address many grand sustainability challenges. However, there are also growing concerns about the known and unknown health and environmental risks associated with the production and application of nanotechnology. This Voices asks: what and where are the opportunities, and what must be taken into account, to enable functional and safe nanotechnology for a sustainable future?

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Flexible, lightweight PV prospect for sustainability

Nanotechnology has undoubtedly revolutionized the field of flexible photovoltaics (flexPV), enabling more efficient solar energy conversion per weight (∼370W/kg is attainable presently), thus providing opportunities to reimagine the application space as well as the established residential solar installation standards.

Solution processing is one of the most cost-effective deployment routes for large-area flexPV fabrication. However, the manufacturing process often involves the use of regulated chemicals, including solvents and dopants. While these materials offer advantages for photovoltaic performance, in some cases there may be concerns regarding their potential toxicity and impact on human health. Some of these materials may contain hazardous nano-substances that could pose risks in case of exposure to workers during the manufacturing or end-users if not encapsulated properly.

To assure mitigation of the environmental risks associated with mass production, sustainable practices have to be adopted throughout the flexPV fabrication and recycling processes. This includes minimizing the use of harmful chemicals; designing effective, application-tailored waste treatment methods; exploring alternative flexPV materials that are environmentally friendly or biodegradable; and developing efficient byproduct recycling and end-of-life management strategies, thus reducing the need for raw material extraction and making it a more sustainable approach for the future of renewable energy.

Potential benefits of nanotechnology in flexPV are immense; by implementing environmentally conscious practices and regulatory oversight, the production and application of flexPVs will contribute to a greener future without compromising the well-being of our planet.

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Roadmap for nanotechnology in sustainable agriculture

Humans are facing universal food security challenges due to increasing populations worldwide and climate change. The utilization of smart and engineered nanomaterials in agroecosystems has the potential to address these challenges. Nanotechnology may deliver efficient techniques for precision farming, plant genetic engineering, maintaining soil health, food processing, and packaging. For example, recent innovations in nano-sensors suggest they may be cost-effective diagnostic tools to improve crop and soil health. In another example, nano-agrochemicals may improve the efficiency, accuracy, and targeting of agrochemicals like fertilizers and pesticides and thus reduce environmental pollution.

However, a better understanding of the ecotoxicological consequences of the nanomaterials, their ecotoxicological sustainability, general health risks to those using and deploying nanoproducts, and risks to the workers who manufacture nanoproducts is required. Improvement to the policy and regulatory environment is also needed.

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Non-animal innovation in nanosafety assessment

The nanomaterial revolution is producing incredible numbers of new materials across many applications. These new materials are often rapidly incorporated into consumer products. However, the safety of advanced nanomaterials and composites (ANMCs) and their long-term effects on human and environmental health is not well understood and not assessed prior to market entry. This is at odds with the growing body of evidence that some nanoparticles have toxic effects. For example, titanium dioxide (TiO2) nanoparticles, a common food additive, change the diversity of gut microbiota and promote undesired inflammatory responses. Altered gut microbiota can lead to many effects on the body, even cognitive impairment. TiO2 nanoparticles have therefore recently been banned in Europe. In another example, silicon dioxide consumption has been shown to accelerate tumor growth and metastasis in animal models.

Researchers, industry, and regulatory agencies are currently grappling with suitable methods to realistically and efficiently investigate the toxicity of ANMCs. The emergence of models that mimic the human microenvironment, such as organ-on-a-chip, micro-physiological systems, or "mini organs," is likely a solution. These models enable high-throughput/high-content analysis and harmonize *in vivo*–*in vitro* assessment. They can replace animals in research, promoting humane and ethical research. These models can also account for organ crosstalk and the co-existence of cells and microorganisms, both essential aspects of physiology. Attention to models that facilitate adequate assessment of nanomaterials safety is key for the sustainability of nanomaterials and a nano-enabled sustainable future.

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Nanotech in sustainable healthcare

Globalization has increased medical accessibility, technology exchange, and the rapid spreading of scientific knowledge, but it has also increased the transmission of infectious diseases and contributed to the exposure of populations to previously unknown harms. In this scenario, there is a need for fast and efficient screening methods for disease diagnosis and management, as well as the monitoring of air, water, and food. Nanotechnology has a central role in creating new analytical methodologies and enhancing the performance of existing ones. For example, gold- and carbon-based nanostructures (e.g., nanotubes, graphene) are commonly used for improving the sensitivity of (bio)sensors. In another example, the use of fluorescent, electrochemical, and/or colorimetric properties of nanomaterials has potential for large-scale and efficient (bio)chemical detection even in low-resource settings, leading to more effective treatments. The applications are numerous, but in order for nanotechnology to provide sustainable long-term solutions, there is still work to be done: (1) the nanomaterials and processes used in production of diagnosis devices should be affordable and accessible, assuring the decentralized application of technologies even in low resource settings; (2) the raw materials used in the overall production of devices should be sustainable, assuring non-depleting of non-renewable sources and key natural resources; (3) devices should produce minimal waste and the use of nanomaterials harmful for the environment or health should be avoided. Last, the regulation of technologies should be active, assuring safety and performance.

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Encourage sustainable nanotech with academic programs

Nanotechnology holds great promise for catalyzing development in food, energy, healthcare, and other areas. As with the emergence of any transformational technology, there have been many questions about long-term implications, mainly whether the technology will be safe and sustainable. Key among these concerns is the possibility of unintended consequences. For example, there might be environmental health and safety issues resulting from accidental inhalation or the release of nanomaterials that contaminate soil and migrate into surface and groundwaters. So far, significant steps been taken to address these concerns, including the US-Nanotechnology Initiatives (NNI), the creation of the Sustainable Nanotechnoloy Organization, extensive nano-environmental health and safety (nanoEHS) research & developments, and numerous conferences worldwide.

These efforts have shifted the perspective from "nano is dangerous" to "nano can be made safe," which has positively impacted nanomanufacturing, nanoEHS, and nano-medicine. One notable example is the infusion of nanomaterials as vehicles in the Moderna and Pfizer COVID-19 vaccines. However, for nanotechnology to continue its stride and promise, significant steps must be taken to advance awareness of its continual sustainable development, incorporate safe-by-design principles, and train future scientists and engineers. Although nanotechnology degree programs already exist in some institutions of higher learning, the development of sustainable nanotechnology as an independent academic department or its recognition as a field is still lacking. Thus, sustainable nanotechnology could catalyze economic developments in the 21st century as we develop purposeful nanoscale educational programs that incorporate societal, economic, and environmental aspects.

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Feeding the world with nanomaterials

The field of nanotoxicology emerged in the early 2000s with concern about novel safety risks that might emerge with increased use of engineered nanomaterials. Scientists working in nanotoxicology aimed to understand if the size or unusual properties would present any challenges that are distinct from traditional molecular toxicants. In brief, nearly 20 years of intense research has not uncovered any previously unaccounted for modes of toxicity; as such, our current toxicity assessment and regulatory systems are sufficient to account for nanoparticle safety (though this could change with nanomaterials developed in the future). With that, the field has turned toward aggressively developing nanomaterials that fulfill sustainability goals related to air, water, energy, and food.

Nanomaterials have particularly exciting promise when it comes to tackling imminent food security challenges. Given the increasing global population, climate change, and the limitations of current agrochemicals, nanomaterials designed to increase crop production will likely play a critical role in achieving global food security. Particularly promising are nanoparticles designed from earth-abundant elements that transform after entering a plant to release nutrients that help crop-producing plants become drought- and disease-resistant or deliver cargo targeting particular crop-compromising entities. These nanoparticles will facilitate plant growth when there is less water and survival when pests attack; they may also support the longevity of produced crops. Overall, there is great promise of increased crop yields using inexpensive nanomaterials that also decrease the use of precious and problematic agrochemicals, and that promise is backed up by decades of toxicity considerations—now is the perfect moment to translate laboratory knowledge into sustainability solutions.

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Mobilizing sustainable nanotechnology inventions

Nanotechnology researchers have the opportunity to invent and design novel materials and attributes to advance the clean energy transition, provide abundant clean water, and develop and deliver therapeutics and vaccines to combat disease. Sustainability, durability, safety, and circular recovery and re-use can be designed into new products. All of these valuable advances, however, will not be realized in practice without the consideration of the pathways to commercialization. Nanotechnology innovations can take 10–15 years of development, and tens (or even hundreds) of millions of dollars of investment to de-risk before a first commercial application. This development lag time is only partly due to technological development hurdles. Because nanotechnology inventions are often generic in nature, meaning that they have broad applicability across many different markets, the problem of identifying viable applications requires the confluence of deep technical understanding with the capacity to identify, prioritize, and protect market opportunities. This process of technology-market matching is a critical aspect of the translation of science-based research out of the lab. Scientists and engineers with the world-leading technical skills required to develop nanotechnology inventions can be taught the innovation skills to make early-stage decisions that will increase the commercial viability of their sustainable inventions, mobilizing research sorely needed to combat climate change and to enhance human wellbeing.

DECLARATION OF INTERESTS

C.L.H. declares no competing interest beyond her position as an inventor on several nanomaterial-related patents, patent applications, and patent disclosures.