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Editorial for *Environmental Science: Nano* themed collection on Advanced Materials

Are advanced materials a progress towards sustainability?

Guest edited by Wendel Wohlleben (BASF), Jerome Rose (CEREGE), Mark Wiesner (Duke University), and Peter Vikesland (Virginia Tech)

Advanced Materials reflect the latest advancements in materials science, and as such they contribute to the planetary burden as “novel entities”. Advanced materials are created through deliberate design, allowing for precise manipulation of their composition and internal structure using advanced manufacturing techniques (Kennedy et al., 2019; Schwirn et al., 2021). Advanced materials differ from conventional materials as they possess superior mechanical, electrical, optical, or magnetic characteristics, but may also enable unusual functionalities such as self-repair, degradability, responsive shape changes, energy transformation, or various emergent phenomena. While not all advanced materials incorporate nanoscale structures, many rely on nano-sized particles or nanoscale phenomena to achieve their desired performance. During the last three decades, societal research focus has evolved from pristine nanoparticles (buckyballs, carbon nanotubes, metal particles, etc) towards more complex systems, combining surface treatments of nanoparticles and/or their incorporation into complex materials (Wohlleben et al., 2017). The advanced materials concept introduces a heightened level of complexity, thus necessitating a global approach to understanding the effects and interactions among various components, matrices, their structures at different scales, and their properties. The synergy between the different elements of advanced materials is at the heart of their appeal. Some experts argue that the innovation with advanced materials exceeds the global capacity for risk assessment and monitoring. Indeed Persson et al (2022) consider that the safe operating parameters of the planetary boundary for “novel entities”, including advanced materials, are being surpassed due to the rapid increase in annual production and releases. However, this perspective overlooks progress and new paradigms in the design of advanced materials and innovation methodologies, such as the “safer by design” (SbD) and “safe-and-sustainable-by-design” (SSbD) approaches (Bottero et al., 2017; Sánchez Jiménez et al., 2020; Trump et al., 2020; Rose et al., 2021). In particular, the SSbD approaches employ flexible, agile methods to facilitate comprehensive assessment of the risks associated with advanced materials and their sustainability throughout the entire lifecycle. “Novel entities” developed by SSbD principles reduce planetary burdens.

Not all societal needs can be fulfilled by materials that are inherently safe for humans and the environment. But pursuing such a goal from the outset of the innovation process offers significant advantages across various dimensions, such as reducing uncertainty regarding risks, enhancing value, increasing stakeholder confidence, and ensuring readiness for future regulatory requirements. Several large collaborative research projects, such as SERENADE, NANoREG2, SAByNA, SUNSHINE, HARMLESS, focused on the safe and sustainable development of nanomaterials and advanced materials across various application domains. These projects employ a selection of interdisciplinary case studies representing different technology readiness levels (TRLs) and life-cycle stages. At the same time, innovation processes that integrate assessments of hazard, exposure, end-of-life, and performance in the intended use and overall sustainability have been described both from industry and from policy (WBCSD 2023; JRC, 2023). However, methods that are fit-for-purpose, valid and applicable to advanced materials are only emerging, and more case studies of SSbD innovation are needed. Experience gained from case studies with nanomaterials has shown that, rather than a sequential SbD approach that focuses only on hazard and exposure issues for the nanomaterial

component, a SSbD procedure is preferable that focuses on the final product as a whole and considers the field of application (Rose et al., 2021a). Such approaches developed in the specific context of nanomaterials should be applicable to more complex advanced materials. It is essential to comprehend the intricate chemical, physical, and textural interplays among the diverse components within a complex product. To fully elucidate the complexity inherent in such systems such understanding must encompass both synergistic collaborations and antagonistic interactions.

The explicit consideration of the balance of the intended use and the different SSbD dimensions is a common feature of all contributions to the present themed collection. A tiered framework providing design principles and assessment recommendations during the earliest stages of the development of advanced materials is proposed by Wohlleben et al. (<https://doi.org/10.1039/D3EN00831B>). The themed collection comprises research into advanced materials that strive for enhanced sustainability, and which are created through deliberate design with precise manipulation of their multiple components, some with internal structure, some by using advanced manufacturing techniques. Several sectors of application are covered:

- **Sensors** that are biobased (Hijazi et al., <https://doi.org/10.1039/D3EN00376K>), partially biobased, partially biodegradable (Carboni et al., <https://doi.org/10.1039/D3EN00263B>), functional in their application due to multiple components (Babulal et al., <https://doi.org/10.1039/D3EN00808H>, Priya et al., <https://doi.org/10.1039/D3EN00804E>), or self-healing in biomedicine applications (Venkateswaran, et al., <https://doi.org/10.1039/D4EN00235K>)
- **Catalysts** that are internally nanoporous (Asati et al., <https://doi.org/10.1039/D3EN00752A>), deliberately designed (Jin et al., <https://doi.org/10.1039/D3EN00776F>), functional in their application yet challenging in their lifecycle due to multiple components (Liu et al., <https://doi.org/10.1039/D3EN00820G>; Di Battista et al., <https://doi.org/10.1039/D3EN00685A>),
- **Energy conversion & storage materials** that explore the SSbD options (Shah and Gilbertson, <https://doi.org/10.1039/D3EN00633F>; Di Battista et al., <https://doi.org/10.1039/D3EN00338H>)
- **Biologically active materials** including **agricultural products** interacting with plants or their pests (Pandey et al., <https://doi.org/10.1039/D3EN00939D>, Singh et al., <https://doi.org/10.1039/D4EN00053F>), and **consumer products** with antimicrobial and fungicidal functionality (Sipe et al., <https://doi.org/10.1039/D3EN00888F>)
- **Sorbents** that are partially biobased (Rivadeneira-Mendoza et al., <https://doi.org/10.1039/D3EN00843F>) deliberately designed (Fablet et al., <https://doi.org/10.1039/D3EN00962A>), produced by advanced manufacturing techniques (Hwa et al., <https://doi.org/10.1039/D3EN00780D>), more sustainable by substitution (Liu et al. <https://doi.org/10.1039/D3EN00849E>),

We hope that the present collection contributes to the wider adoption of principles of the safe and sustainable development of advanced materials, including those with nanostructures, and exemplifies pragmatic approaches for academia, industry, and regulators.

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