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Advanced Materials

Cornerstones for a Safe and Sustainable Life Cycle

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1 Background

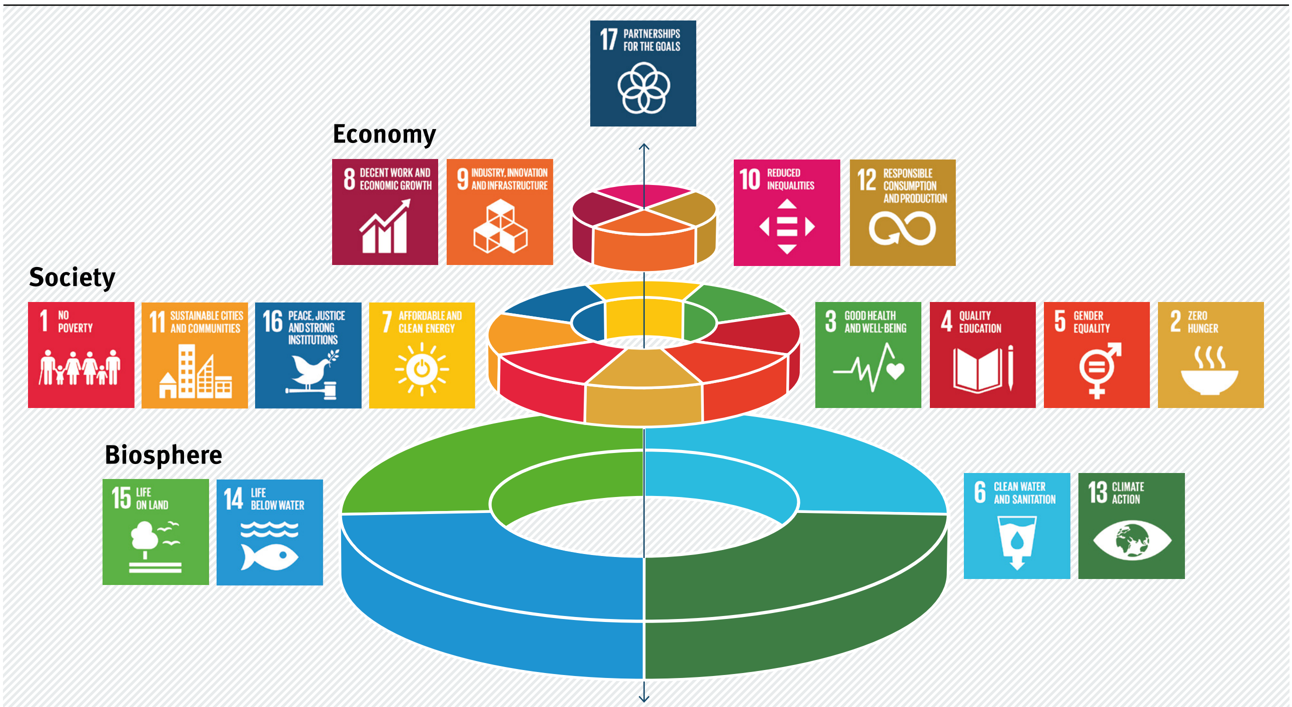
Global society is facing unprecedented challenges. Man-made climate change, the increasing loss of biodiversity and resources as well as increasing chemical pollution threaten human existence as we know it. Climate change and biodiversity loss are interrelated, mutually reinforcing and must therefore be tackled jointly. Today's prosperity, especially in industrialised countries, is based on the use of natural resources, such as the use of fossil fuels and an increasing global use of land, as well as on the increasing use of chemicals. This also has an impact on climate change, biodiversity loss, pollution and human health.

The ability of present and future generations to meet their needs[1] presupposes being able to operate within a safe space, recognizing and respecting the ecological limits of the earth. This idea forms the basis for the concept of planetary boundaries[2]. It defines the conditions for sustainable development by describing and quantifying the planetary boundaries that human activities must not exceed in order to avoid unacceptable and irreversible environmental changes. The United Nations 2030 Agenda for Sustainable Development with its 17 Sustainable Development Goals (SDGs, Figure 1)[3], 169 targets and 231 indicators contains a vision for a future global society based on the principles of sustainability. The 2030 Agenda covers the environmental, economic and social dimensions of sustainability in an integrated manner and provides principles and references for local, national, regional and business decision-makers.

To transform the EU's current economy into a greener and more sustainable one, the European Commission has presented the European Green Deal[4]. The Green Deal includes various action plans, strategies and initiatives to minimise or, where possible, eliminate the (harmful) effects of chemicals, materials, products and services on human health, climate and the environment in order to ensure a sustainable circular economy. This is done, among other things, through action plans for the circular economy, climate neutrality, pollution prevention, as well as strategies such as the Chemicals Strategy for Sustainability, the Farm-to-Fork Strategy, the Initiative for Sustainable Products or the Bioeconomy Strategy.

Figure 1

The 17 Sustainable Development Goals of the UN, divided into biosphere, society and economy



Source: Jerker Lokrantz/Azote for Stockholm Resilience Centre, Stockholm University

Chemicals and materials are essential for the provision of low-CO_2, pollution-free, energy- and resource-efficient techniques, materials and products. They are indispensable for the digital and green transformation of society and the economy. Advanced materials promise the potential to offer technical solutions for the transition of energy system and transport, resource conservation, digitisation or health care[5] in order to meet the urgent global challenges. For example, the European Commission's Chemicals Strategy for Sustainability addresses this potential of advanced materials to support green and digital transformation and announces the promotion of research and development of advanced materials for use in various fields[6].

In order to support the development towards a more sustainable society, it is a basic prerequisite that advanced materials themselves are safe and sustainable over their entire life cycle. From UBA's point of view, it is therefore of great importance to identify and avert challenges for environmental protection and sustainability through the use of advanced materials at an early stage. Therefore, UBA aims to support shaping the safe and sustainable development of advanced materials and their applications over their life cycle. Although chemical safety is seen as an inherent component of sustainability, this paper explicitly focuses on chemical safety and the sustainability of advanced materials and their applications. This serves to clarify the position that chemical safety is a basic condition for achieving sustainability, which must be met and cannot be compensated by other aspects of sustainability. Thus, an advanced material or application cannot be considered sustainable if there is a material risk to humans or the environment[7].

This position paper describes, from UBA's point of view, the possible opportunities and risks of advanced materials and their use in terms of sustainable development. The focus is also on the field of tension between the promising use and potential challenges for environmental and health protection and other sustainability dimensions, illustrated by various examples, as well as on the resulting cornerstones for the development of safe and sustainable material innovations.

Advanced Materials

UBA has been dealing with the opportunities and risks of nanomaterials since 2006[8]. Over the years, it has become increasingly clear that the consideration of material innovations cannot be limited to an upper limit of 100nm. UBA has therefore broadened its perspective to include other advanced materials. Advanced materials are those materials which, through the precise control of their composition and their internal and external structure, are deliberately structured or designed in such a way that they meet new functional requirements[9]. This rough description includes a variety and diversity of materials with different structures, properties and functionalities of varying complexity, which can be widely applied. The OECD Working Party on Manufactured Nanomaterials (WPMN) has developed a working description for advanced materials[10], on the basis of which questions of chemical safety and sustainability are addressed. Examples of advanced materials can also be found in Giese et al. 2020[11].

2 Advanced materials in the field of tension between climate, environmental and health protection, and circular economy

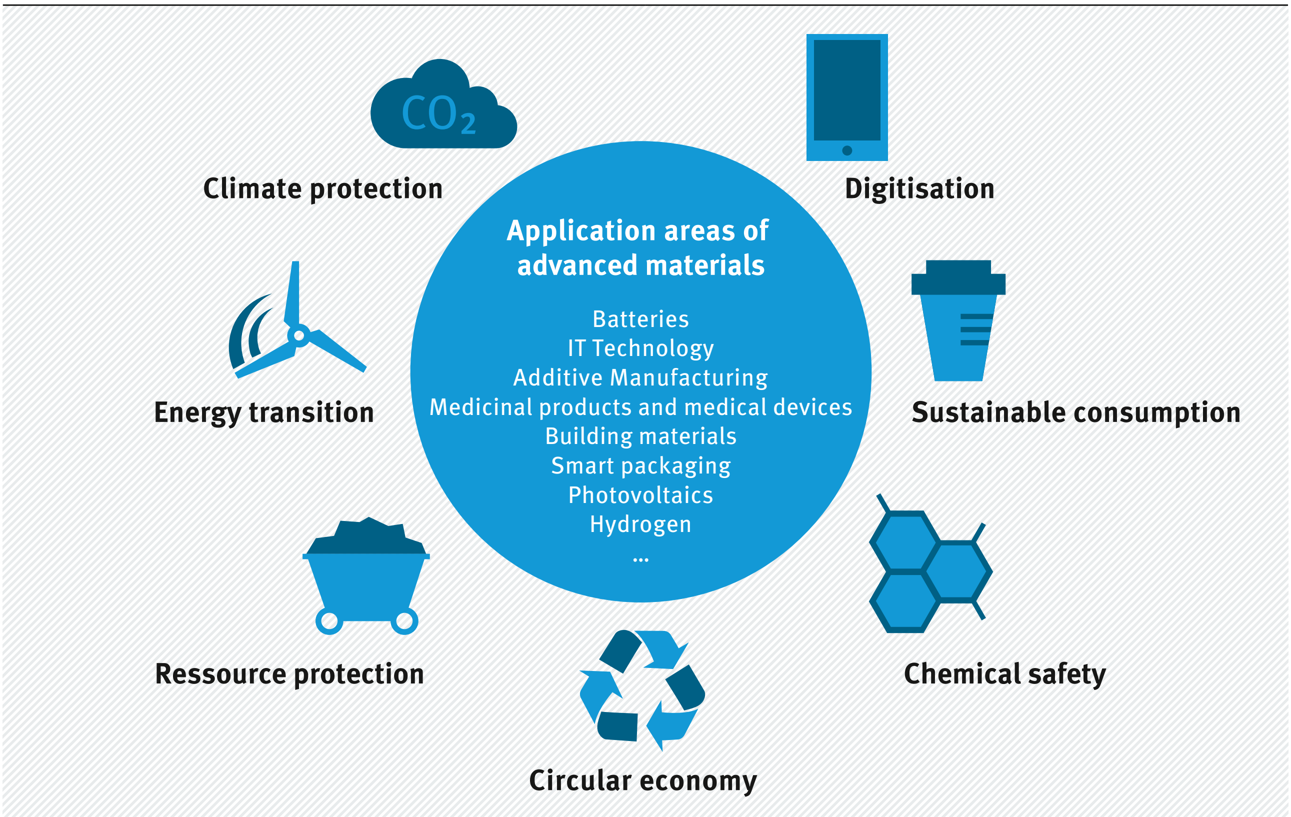
The sustainable transformation of society pursues the goal of not only reducing CO_2 emissions, but also meeting the challenges of climate change, the loss of diversity and resources, and the increasing burden of chemical substances, averting them and mitigating their negative consequences. The measures taken to achieve this goal must meet all mentioned challenges. These are closely interlinked and mutually dependent, so that it is not expedient to try to solve only one task and thereby lose sight of the others or to regard them as subordinate. Meeting these challenges can lead to conflicting goals. Nevertheless, these conflicting goals do not exist between the global challenges themselves, but can arise between the individual measures for solution.

In order to address the above challenges, ways must be found to change societal systems in such a way that they are compatible with the protection of the environment, health and climate[12]. Not only techniques and production processes have to be reconsidered, but also patterns of consumption and lifestyles. This requires an immediate and concerted approach, involving different policy areas and actors from society as a whole, in order to enable systemic change.

Advanced materials play an important role in a sustainable transformation. In a wide variety of fields of application (Figure 2), their use can help, for example, to use energy more efficiently, to save resources, and to reduce or even replace the use of problematic or less sustainable chemicals. However, their use is connected to questions about chemical safety and sustainability of their application over the life cycle.

Figure 2

Fields of application of advanced materials relevant to the various topics of the German Environment Agency



own illustration, German Environment Agency

Chapter 2 shows the possible benefits as well as the expected challenges of the use of advanced materials in important environmentally relevant fields of action and describes areas of tension using selected examples. The references used for the paper describe advanced materials and their potential applications that are already on the market, but also those for which it has not been conclusively clarified whether they can actually be successfully marketed in the future. It is also not always possible to describe the actual advantages of the materials and their applications or the actual extent of a potential risk based on the current information situation.

2.1 Advanced materials in the context of environment and health

The combination of existing or new (active) substances and/or materials makes it possible to produce advanced materials with improved or previously unattained functionalities or properties. This makes new forms of application and therapy as well as technical solutions possible. Also, depending on the material, desired effects can be caused by the structure of the materials, instead of or in addition to a chemical effect. Thus, advanced materials offer a number of possible opportunities for environmental protection and human health. These include, but are not limited to:

- The reduction of the use of chemicals and thus the entry of substances into the environment through more targeted use, lower dose and higher efficiency and thereby in turn fewer undesirable effects on humans and the environment.

- Improved environmental and health protection through the provision of new or improved techniques and processes using advanced materials, such as separation, absorption or catalysis for (drinking) water treatment[13], for the removal of pollutants[14] and for environmental analysis and diagnostics[15]; development of so-called *Smart Textiles*[16] for e. g. health management.

- The replacement of substances that are of concern from an environmental and health point of view or otherwise unsustainable in their use (e. g. those with high resource requirements, high global warming potential, high long-distance transport potential, poor recyclability), but also the realisation of new technical processes or changed value chains (e. g. chemical-free alternatives, more sustainable consumer behaviour), which can be made possible by advanced materials.

However, the use of advanced materials can also lead to unknown or increased risks for the environment and health. Conceivable in this context are:

- The environmental exposure of new substances or new forms of a substance (e. g. as so-called building blocks of advanced materials) with unknown properties or an increased or changed environmental exposure of known problematic substances (problematic e. g. with regard to persistence, mobility, bioaccumulation potential or toxicity).

- New formulations and combinations that make the use of (eco)toxic (active) substances possible in the first place.

- Increasing the ecological footprint and/or deteriorating of other sustainability criteria, for example if the production of an advanced material has a higher global warming potential or requires a higher use of raw materials than that of the conventionally used material or substance[17].

- Missing or inappropriate bases for assessment (e. g. OECD test guidelines, exposure scenarios or models).

- Gaps or exceptions in the requirements of existing regulatory concepts that in consequence lead to the situation that hazards and risks cannot be identified, adequately described or addressed.

EXAMPLE – Advanced carrier systems for active ingredient formulations

Advanced carrier systems are used for the controlled transport and protection of a substance (cargo), e. g. an active ingredient. Different types of materials or combinations of them can act as carriers. So far, micelles, liposomes, (bio-)polymers, dendrimers, hydrogels, porous silicon dioxide, metal organic frameworks (MOF), DNA origami, electrospun fibers or carbon-based carriers have been described[18]. These possibilities result in numerous (potential) areas of application in medicine, but also in cosmetics, pesticides and biocides. In medicine, a wide variety of applications are possible, such as for cancer or anti-inflammatory drugs. Hormones, enzymes or nucleic acids (e. g. mRNA, siRNA) can also be packaged, protected and transported to the destination in this way. Carrier systems gained greater awareness through the use of lipid nanoparticles as vehicles for COVID-19 mRNA vaccines.

By means of the carrier system, various advantages can be obtained, such as improved bioavailability of the cargo, protection of the cargo from premature metabolism / degradation or control over the release of the cargo at a certain time at a certain location. The latter can be done via a stimulus, such as changing environmental conditions (e. g. pH, temperature, radiation). In this way, a targeted and more effective transport of, for example, active ingredients to the site of the desired effect can take place. In addition, previously inaccessible novel mechanisms of action (e. g. small-scale mechanical mechanisms of action) of the cargo can be made usable. Other possible advantages that benefit human health and the environment include the treatment and prevention of diseases that have so far been difficult to treat, an overall lower use of active ingredients and thus a reduction in the potential exposure of humans and the environment or the reduction of undesirable (environmental) side effects.

Research and development on carrier systems have been increasing continuously for years. Already developed products increasingly enter the market[19]. However, there is a lack of a sufficient overview of which of the diverse carrier systems will actually be used (in the future) and which areas of application will be affected. In view of the known and presumed areas of application such as pharmaceuticals and medical devices, plant protection products and cosmetics, possibly also biocides and food and feed, this is of particular relevance in order to be able to properly derive the need for adaptation of environmental risk assessment for the regulatory areas concerned. In this regard, questions arise to what extent the various carrier systems influence environmental behaviour and effects of the actual cargo and whether existing test methods are suitable for determining the environmental behaviour and effects of the overall system and the “building blocks” from which they are built. Relevant knowledge needs to be gained and fed into an appropriate environmental assessment, as current environmental assessment methods for advanced materials and material-active ingredient combinations have significant gaps or are non-existent[20].

2.2 Advanced Materials – Resource conservation and circular economy

The use of advanced materials in various products opens up a wide range of opportunities for resource conservation, reuse and recycling of products:

- Efficiency enhancement through new and improved production processes with lower resource consumption or reduced generation of industrial waste, e. g. through novel catalysts[21] or the more targeted use of chemicals/active ingredients.
- Realisation of new processes (e. g. additive manufacturing such as 3D printing or electrospinning[22], production of printed electronics[23]), which allow new forms of added value and decentralised production, as well as repair or traceability of products.
- Increased durability of products by improving the weather and abrasion resistance, for example of coatings, or by protecting against corrosion, moisture and infestation[24].

EXAMPLE – Additive manufacturing in the context of material flows, resource use, waste and environmental and health protection

Additive manufacturing, colloquially often referred to as 3D printing, describes manufacturing processes in which components are built up layer by layer from one (or more) starting material(s). This opens up a wide range of possibilities for the production of complex composite materials or new designs, such as the design of geometrically complex structures that are not feasible with conventional subtractive manufacturing processes. Additive manufacturing includes a wide variety of processes that are becoming increasingly important. They are used in a wide variety of industries, but are also increasingly used by professional users, consumers and in the education sector[25]. Depending on the method used, typical starting materials for additive manufacturing are liquid, powdery and solid metals, ceramics, polymers and synthetic resins, but also concrete, cement or wood. Additive manufacturing is used for the production of models, samples and prototypes but also for components, tools and tailor-made end products for a wide range of applications[26]. These range from medical devices to solar cells and buildings. A further development of 3D printing is 4D printing, which enables the production of shape memory materials, self-healing materials or so-called metamaterials[27]. The fourth dimension refers to time, because these materials have the ability to change their properties through an external stimulus.

The possibilities of decentralised operation promise reduced transport and storage costs. Additive manufacturing offers the opportunity to make components or spare parts available more easily, which extends the repairability and thus service life of products and provides incentives for product-service business models. Other advantages associated with additive manufacturing are the production of products with less waste and energy requirements or the use for lightweight construction. Due to the increased product lifetime, resources and energy can be saved[28].

Nevertheless, additive manufacturing poses a challenge to chemical safety and sustainability[29] as the starting materials may contain hazardous substances and the exact composition may not be specified[30]. During the printing process, volatile organic compounds, (nanoscale) solid compounds, plasticizers, flame retardants and monomers may be released[31]. Emissions to the air or wastewater are also conceivable during post-treatment processes such as polishing, sanding and cleaning of the printed product. There are open questions regarding the durability of the printed products, such as mechanical stability during the use phase or the release of components into the environment.

Due to the diversity of printed products and their areas of application, but also due to the complexity in the structure and composition of the printed products, and the lack of transparency about them, it is currently not clear how waste collection, processing and recycling of printed products can be realised. Additive manufacturing has a high energy requirement which varies between the individual processes and also depending on the field of application; compared to conventional production methods, the energy requirement can be lower. With the advantages of additive manufacturing, the likelihood of rebound effects also increases if the possibilities of use encourage unnecessary consumption.

However, the use of advanced materials can also lead to increased use of resources in complex compositions. This poses the following challenges:

- The production of advanced materials may be accompanied by the use of new raw materials or an increased consumption of raw materials[32] whose extraction is not sustainable or which leads to new dependencies on raw materials.
- The increasing complexity and variety of advanced materials, but also the diffuse use of raw materials for their production, further complicates traceability, risk assessment and circular economy (reuse, recycling); this can also lead to recycling processes becoming more chemical-heavier and energy-intensive. This is an undesirable consequence, especially if fossil fuels are used for it. In addition, advanced materials can physically disturb the recycling process or lead to the accumulation of problematic substances.

- Working with and on waste is risky due to its unpredictability and the fluctuating composition of waste: As previously shown for carbon fibre reinforced plastics[33], the waste treatment of advanced materials can lead to risks for workers and the environment, e. g. through the release of problematic components during recovery.

- The occurrence of rebound effects: Due to the efficiency enhancements described above, it is conceivable that supply and demand of certain applications will increase, which leads to a situation that savings achieved by the use (e. g. environmental input of chemicals, greenhouse gases, resources) are partially cancelled. In this context, the use of advanced materials is also conceivable, which does not bring any technical advantage, but serves above all to launch new products on the market in an effective advertising manner.

2.3 Advanced materials for climate protection and the energy transition

For the energy transition and climate protection, resource-efficient materials are just as important as material innovations that enable technical solutions for renewable energy generation and energy storage. The use of advanced materials is intended to increase efficiency, contribute to longevity and energy savings. The following areas of application are intended to support climate protection and the energy transition:

- Advanced materials are in research and development for use in techniques to generate renewable energy (e. g. for the production of solar panels[34] and wind turbines[35]) or for green hydrogen production[36], as well as for energy storage[37] and to make these techniques more efficient.

- Advanced materials contribute to making procedures and processes (e. g. catalysts[38], lightweight construction) more energy-efficient. This design extends to the development of so-called *Smart Textiles* for energy generation[39].

- In the construction sector, advanced materials are used to reduce energy consumption in buildings (e. g. as insulation material[40] or in window panes to regulate light and heat radiation[41]).

However, the use of advanced materials in techniques to promote climate protection and the energy transition also leads to challenges, risks and open questions. These include:

- The production of advanced materials for energy transition technologies often includes the use of problematic substances that can lead to exposure of workers and the environment, especially during production and at the end of the product's life or during waste treatment.

- There is often a lack of suitable methods and collection concepts for recycling to recover the materials used from technical applications.

- The use of advanced materials for the technologies of the energy transition leads to a changed demand for raw materials, which entails new or changed environmental impacts (e. g. input of problematic substances into the environment, land consumption) and dependencies.

EXAMPLE – Electrochemical energy storage for the energy transition

The demand for electrochemical energy storage systems (colloquially: batteries) is increasing worldwide. They are used for stationary and mobile storage of energy for smartphones, laptops, e-bikes, e-cars or as intermediate storage of solar power. With the increasing digitisation and electrification of everyday life, new applications are constantly being added. Electrochemical energy storage systems play an important role in the energy transition, as they can store energy from non-storable renewable sources (solar, wind) and make it available at a later date. Novel electrochemical energy storage devices are diverse and complex systems using a variety of materials. The focus of the further development of electrochemical energy storage systems is above all to increase their performance and service life, to reduce production costs and to avoid incidents. Advanced materials play an important role in the provision of electrode material, membranes for separation or charge transfer or electrolyte materials[42].

Potential environmental effects of electrochemical energy storage systems cannot be described in general. They depend on the respective battery system, the life cycle considered and the possibilities of recycling[43]. A particular challenge for global environmental protection is the enormous increase in demand for critical metals due to the market development of batteries, especially if their extraction is associated with a lack of environmental and social standards[44]. The recycling of energy storage systems is very complex, but ecologically more advantageous than the use of primary raw materials. The cost-effectiveness of recycling depends on the volume of used batteries and recyclable material prices. The desirable long usage phase, however, makes it difficult to establish recycling strategies. The secondary use of lithium-ion batteries (LIB), e. g. via the stationary storage of solar power by discarded car batteries, leads to a better utilisation of their storage capacity, but can make recycling even more difficult, as the use phase is further extended and thus recyclable materials are available with further delay[45]. The rapid development of electrode materials also makes it difficult to establish a state of the art for recycling. For example, there is still a considerable need for research into the recycling of electrochemical energy storage systems and their components. For a large number of techniques or subsystems, there are currently no recycling and reuse concepts that are sufficiently satisfactory from an ecological point of view.

The substances and materials used for electrochemical energy storage pose a challenge for chemical and plant safety, especially during production and recycling, but also in the context of improper use and disposal or due to malfunctions and accidents. Electrode materials contain (eco-)toxic metals such as cobalt, chromium, copper, nickel, thallium and silver[46]. With respect to LIB, cathode production is based on the use of fluorine-containing polymers such as polyvinylidene difluoride and the toxic and mutagenic solvent N-methyl-2-pyrrolidone. Research on water-soluble and fluorine-free binders is promising, but a field that has so far been little studied[47]. Studies show that the aging of LIB leads to a decomposition of the electrolyte, which in the further course leads to the formation of toxic organofluorophosphates[48]. The formation of hydrogen fluoride and phosphoric acid is also possible when an aged battery is opened (e. g. due to an accident or during recycling). LIB are characterised by a high energy density. In the event of mechanical damage, thermal impacts or improper storage, the energy stored in the cell can be released explosively.

3 Cornerstones for safe and sustainable material innovations

Advanced materials can contribute in many ways to societal well-being and to the solutions needed to tackle global challenges such as the energy transition, sustainable mobility concepts or health protection. However, the way advanced materials are manufactured, used and disposed, as well as the potential negative impacts of their inherent properties, can also contribute to the aggravation of the major environmental crises of climate change, resource loss, biodiversity loss, and pollution. In addition, not every advanced material or its application may have a societal benefit. A holistic approach must therefore be pursued, which on the one hand enables the use of these materials in applications to promote a sustainable future, but on the other hand also ensures the safety and sustainability of these materials and their applications over their life cycle.

It is to be expected that conflicting goals will arise, for example in the case of the inevitable use of potentially harmful advanced materials for (new) technologies with high social benefits (e. g. when used for renewable energies). Therefore, it is important to develop approaches that allow balancing between the use of advanced materials to combat the major crises of our time and their possibly limited chemical safety or sustainability over the life cycle. This also includes to identify conflicting goals at an early stage, and to derive and implement measures in a timely manner.

At the beginning of 2022, UBA, together with the Federal Institute for Risk Assessment (BfR) and the Federal Institute for Occupational Safety and Health (BAuA), published initial recommendations on the risk governance of advanced materials from the perspective of chemical safety[49]:

Risk governance of advanced materials

In order to facilitate an exchange of perspectives and information between the various stakeholders concerned, UBA held a series of international thematic conferences on the safety and sustainability of advanced materials and their applications from 2019 to 2021[50]. On this basis, the three higher federal authorities UBA, BAuA, and BfR developed a joint perspective on the risk governance of advanced materials. This comprises five important fields of action:

- Early warning systems to identify materials and applications of concern
- Review and adaptation of chemicals regulation and risk assessment tools
- Promotion of Safe-&-Sustainable-by-Design for advanced materials
- Communication and networking
- Interdisciplinary research (preparatory and regulatory research)

In addition, BAuA, BfR, and UBA provide recommendations for action on advanced polymers, additive manufacturing, fibres, intelligent packaging, and nanocarrier. Since then, the discussion on advanced materials in the context of these fields of action has continued at national and international level. Among others, since 2020 there has been an interagency working group on advanced materials in Germany. Since 2021, a steering group within the OECD Working Party on Manufactured Nanomaterials is addressing advanced materials and questions of their safety, sustainability, and appropriate assessment.

The fields of action mentioned in the interagency perspective on risk governance are relevant across all protection targets and are therefore also important for the consideration of necessary measures for the safety and sustainability of advanced materials from an environmental point of view (for details on the fields mentioned, please refer to the paper).

In addition, there are further key points to support the safe and sustainable use of advanced materials, which are set out below:

Links in the EU Chemicals Strategy for Sustainability

Although advanced materials do not represent a a particular focus of the European Commission's Chemicals Strategy for Sustainability, the initiatives announced within that strategy are suitable for promoting measures for the safety and sustainability of advanced materials. With a reform of substance-related regulations, the EU Commission aims to further develop the legal framework and create an improved information base. This concerns, for example, the introduction of further obligations for the registration of certain polymers within the framework of the REACH Regulation.

As part of the EU Chemicals Strategy for Sustainability, technical criteria and indicators for the concept "Safe and Sustainable by Design" (SSbD) are being developed[51]. SSbD refers to the guiding instruments of green and sustainable chemistry and aims to steer innovation towards a more sustainable industrial transformation. In this respect, the aim is to replace or at least minimise the production and use of substances and materials of concern, as well as to reduce the impact on climate and the environment throughout the life cycle of chemicals and materials. The EU Commission also plans to take up SSbD more strongly in research and innovation funding. In addition, the EU Commission is considering taking up corresponding aspects in regulation. Partial aspects of SSbD are already being discussed in the legislative processes for the planned EU Battery Regulation and EU Ecodesign Regulation. It is still unclear whether corresponding aspects will also be taken up in the further development of EU chemicals legislation. In principle, these legislative procedures offer the opportunity to anchor such aspects in law.

The improved cooperation between EU agencies within the framework of the "one substance, one assessment" approach[52] aimed at in the EU Chemicals Strategy for Sustainability, and the desired better interaction of substance-related regulations can also help to identify risks earlier. This also applies to the planned creation of a general early warning system for chemicals. The EU Commission would like to start activities in this regard in 2023. So far, a concept study is available, but the concrete design is still open[53].

In order to ensure pollutant-free circular flows, problematic chemicals and materials in products should generally be avoided. Since advanced materials often also contain valuable metals and critical raw materials that are lost during conventional waste treatment, treatment processes for recycling for the various waste pathways must be made possible. To make this optimisation possible, it must be known which materials are to be expected in which wastes, also beyond the innovation and development phase. In addition, it must be economically worthwhile to recover materials with small quantities or that are difficult to detach from composite materials. Digital product passports with appropriate information standards could support the necessary transparency for process optimisation for the waste treatment of advanced materials. The European Commission has proposed a legal framework for the design of digital product passports under the Sustainable Products Initiative[54]. Furthermore, the OECD has presented digital product passports, which contain information for repair, reuse and recycling[55]. In addition to various information on production, maintenance, dismantling and recycling, these passports could also contain information about valuable substances and pollutants.

Basically, these initiatives are a step in the right direction. However, this does not automatically ensure that the special features of advanced materials are sufficiently taken into account. This is especially the case when the chosen approaches primarily consider only known challenges. For example, the identification and appropriate assessment of possible deviating risks due to different forms of a substance but also of completely new risks by material innovations must be ensured.

It also remains open whether the transformation of society and companies towards sustainability can be achieved with the initiatives taken and announced by the EU Commission. Presumably, it will be necessary to create further incentives and specifications to achieve such a comprehensive but necessary transformation.

Strengthening approaches to green and sustainable chemistry

The second edition of the Global Chemicals Outlook GCO-II (UNEP, 2019[56]) impressively shows that production capacity and sales in the chemical industry are doubling every 15 years. At the same time, the number of new chemicals is increasing. The diversity and spread of chemical uses and combinations is also increasing, which is also reflected in developments in the field of advanced materials. Against this background, it is necessary to develop sustainability-oriented solutions for advanced materials. On the one hand, these must serve human needs and contribute to a sufficient level of prosperity and sustainable development worldwide. On the other hand, they must not burden or exceed planetary boundaries.

The global community has missed the ambitious goal of a sound management of chemicals[57] set for 2020[58]. Still, the critical analyses also indicate that there are numerous suitable instruments, tools and solutions. However, these urgently need to be implemented even more intensively than before and expanded through more ambitious global action by all stakeholders ("business as usual is not an option"[59]).

Sustainable development in chemistry, and of chemicals and advanced materials requires an overall policy approach and coherent technical criteria. In addition to SSbD, there are already numerous approaches to how chemicals and advanced materials must be produced, consumed and used more sustainably:

- In 1998, Anastas and Warner described the Twelve Principles of Green Chemistry[60]. These are not only important for the synthesis of chemicals, but have also given new urgency to responsible chemistry.

- In an international workshop on sustainable chemistry in 2004, UBA and the OECD developed detailed criteria for sustainable chemistry that combine ecological, social, and economic aspects of sustainability in chemistry[61].

- In 2020, the UNEP Initiative for Green and Sustainable Chemistry postulated ten goals and guiding principles for green and sustainable chemistry as part of the UNEP Green and Sustainable Framework Manual[62]. They range from molecular design to ensuring that the use of chemicals to meet societal needs is free of pollution or other negative impacts. In this regard, UNEP provides a blueprint for aligning innovations in chemistry with sustainability.

- In addition to UNEP efforts, the International Sustainable Chemistry Collaborative Centre (ISC_3)[63] developed the Ten Key Characteristics of Sustainable Chemistry[64] in a stakeholder process in 2020. These extend the UNEP perspective to include general sustainability principles such as sufficiency, consistency, efficiency and resilience. Precaution and compliance with planetary boundaries are core principles. Chemistry is seen as a scientific and economic asset that encompasses supply chains and the entire life cycle. Consequently, the Ten Key Characteristics of Sustainable Chemistry aim to create new economic opportunities that are not purely profit and growth-oriented.

- Furthermore, there are various practice-oriented instruments to accelerate and implement more sustainability. The assessment schemes collected in the OECD's Substitution and Alternatives Assessment Toolbox[65] are mainly concerned with the prevention and management of hazardous properties. Some instruments include a broader view of sustainability, such as the UBA Guide on Sustainable Chemicals[66] and the associated IT tool SubSelect[67]. Innovative and sustainability-oriented business models such as chemical leasing complement these instruments in practice.

- As part of its work on the concept to promote safe and sustainable innovation of nanomaterials and other advanced materials, the OECD WPMN has published its working descriptions of the terms sustainability and safe and sustainable by design[68].

As a further contribution to stimulate the dynamic discussion, UBA organised its second international conference on sustainability transformation in November 2021 entitled "Socio-ecological Transformation: Production, Use and Management of Chemicals to serve People without Polluting the Planet". At the end of the conference, UBA summarised six main objectives, all of which relate to the sustainable production and use of chemicals[69]:

1. Preference for substances that cause no harm to health and the environment.

2. Hazardous substances may only be used if absolutely in the interest of society and sustainable development and there are no alternatives.

3. The circular economy requires pollutant-free material flows.

4. A sustainable measure for society's demand for chemicals including sustainable energy and resource consumption.

5. Chemicals must achieve climate neutrality throughout their life cycle.

6. Clear sustainability criteria and indicators in order to make balancing processes transparent, and for achieving the goals of the 2030 Agenda for Sustainable Development.

These goals represent a summary of green and sustainable chemistry and address all stakeholders and chemical-using sectors. Despite these successful efforts, it is important to further develop these approaches to strengthen the sustainable development and transformation in chemistry, and of chemicals, and advanced materials, and to apply them more than before, as well as to establish and disseminate further solutions for sustainable transformation.

Raising awareness and building knowledge

Transformation towards greater chemical safety and sustainability is often not sufficiently considered in the innovation phase of materials research. This is due, among others, to the fact that materials research is primarily aimed at achieving improved or new functionalities in order to solve a technical task. Nevertheless, there are also increasing efforts to integrate individual sustainability aspects into the development of advanced materials and their applications, provided that the achievability of a functionality is generally clarified and there is awareness about problematic properties of a material or substance used. To improve this situation, there is a need for inherent promotion of research and innovation of safe and sustainable materials. For this, all areas of safety and sustainability must be considered over the entire life cycle and not just partial aspects. In this context, there is a need to impart knowledge to current and future material developers about the impact of substances and materials of concern on humans and the environment as well as on their sustainability. In addition, it is important to build up expertise on the regulatory approaches and requirements among these actors. But also funding institutions should have the technical expertise to be able to evaluate funding proposals for material innovations with regard to the expedient consideration of safety and sustainability aspects. Initial offers for knowledge building on the safety of nanomaterials are e. g. provided by various completed and ongoing projects of the NanoSafety-Cluster[70] or by the EU H2020 project Nanomet[71], which amongst others set themselves the task of providing information, teaching and training material. These initiatives must be taken up and further expanded. The EU Horizon Europe project PARC[72] can contribute to this, which, amongst others, will also set up a knowledge and information platform as well as educational materials on the safety and sustainability of chemicals and materials. ISC_3 also promotes knowledge transfer on sustainable chemistry, including an international knowledge platform, a global start-up service, a summer school for sustainable chemistry and an international network. In this way, ISC_3 promotes the transition to sustainable chemistry through collaboration, innovation, education, research, and information exchange.

Integrating safety and sustainability into the innovation process

As mentioned above, the JRC has developed an SSbD concept that integrates aspects of the safety, recyclability, and functionality of chemicals and materials with consideration of sustainability throughout their life cycle and minimisation of their environmental footprint. This means that solutions, for example for avoiding the use of problematic chemicals and materials, waste prevention, safe disposal of waste, and optimal recovery of recyclable materials, must already be considered in the development and innovation phase of materials, and their products.

In order to be able to assess the ecological footprint or possible material risks, in particular of new or little-studied materials and chemicals, a suitable data basis based on the FAIR data principle[73] must be created. In turn, the collection of data requires generally accepted methods that are suitable for properly assessing advanced materials with regard to their impact on human health, the environment, their recyclability or their ecological footprint. This is necessary both to enable material developers to check whether SSbD criteria are met for an innovation, and to ensure regulatory acceptance when entering the market at a later date. Generally accepted assessment methods are therefore an important building block to make innovation successful, also from an economic point of view. On the one hand, they provide legal certainty for the fulfilment of data requirements. On the other hand, as in the case of the OECD Test Guidelines, and on the basis of the mutual acceptance of data, it can be avoided to have to repeat tests unnecessarily when entering the market in other OECD member countries. However, a comprehensive data basis is also necessary for decision-makers and authorities in order to identify existing knowledge gaps, concerns or conflicting goals, and to be able to derive and implement suitable measures as a consequence.

Identify materials of concern at an early stage and close identified knowledge and assessment gaps

In accordance with the precautionary principle, there is a need for early identification of those advanced materials that give rise to concern, whether from the perspective of a possible health or environmental risk, sustainability or insufficient regulatory coverage. Within the framework of early warning systems, advanced materials and new applications giving rise for concern can be identified, concerns can be formulated, knowledge gaps can be recognised, and needs for action can be described. Recommended actions may include, on the one hand, the collection of data to proof or disproof the expressed concern, but also the development of methods for the appropriate evaluation of the materials. The result of an early warning system can also provide recommendations for a re-design of the material or its application in the sense of the SSbD concept. A proposal for an early warning system addressing the concerns of advanced (nano)materials is available (Early4AdMa[74]), but other systems are also conceivable for application (The EU Foresight System – FORENV[75]). However, the consideration of advanced materials in early warning systems always remains a case-by-case consideration. The selection of the materials considered, the application of the system, results, and the resulting conclusions will thus depend on the capacity, expertise, and interest of the persons involved.

Closing assessment gaps should also take into account the impact of environmental risks on human health. The idea of the One Health approach[76] can form the basis for an improved integrative assessment, e. g. of pharmaceuticals, and should also be taken into account for the risk assessment of pharmaceuticals based on advanced materials.

Developing a new understanding of innovation

Achieving a more sustainable society requires more than looking at the safety and sustainability of materials and chemicals on a case-by-case basis. It requires a broader understanding of innovation that, in addition to technical progress and economic feasibility, also considers and counteracts possible disadvantages for the environment and society from the onset. For this purpose, a holistic approach is necessary, e. g. to reduce the consumption of chemicals and materials as well as the associated resource consumption, and production of climate-damaging gases through more sustainable business models and changes in the general consumption behavior. An overall societal dialogue is necessary in order to be able to grasp an understanding of the complex interests, to enable knowledge transfer, to identify alternatives and measures, and thus to steer innovation towards greater sustainability.

Current UBA activities on advanced materials

Dialogue: In order to bring together stakeholders concerned and stimulate a comprehensive discussion on advanced materials and their challenges for chemical safety, UBA held international thematic conferences from 2019 to 2021 on the need for action on advanced materials in the context of chemical safety. UBA brings the environmental perspective on advanced materials into the expert dialogues of the German Government's Nanodialogue[77].

Networking: UBA exchanges information on the topic nationally and at European level with partner authorities and institutes, but also with academia, NGOs and industry. This takes place, among others, at the national level within the framework of the interagency working group of higher federal authorities, in which different perspectives and expertise on advanced materials come together and challenges and need for action towards advanced materials are identified from an authority perspective. Within the framework of the OECD Working Party on Manufactured Nanomaterials (WPMN), UBA chairs the steering group on advanced materials, which deals with safety and sustainability issues in the context of advanced materials, and their applications[78].

Strategic preview and early warning systems: As part of the strategic preview, UBA identifies new topics with environmental relevance. In this context, UBA has assessed the environmental impacts of 3D printing in a trend study[79], which forms the basis for further research on the subject at UBA. Together with colleagues from the Dutch RIVM, the BfR and BAuA, UBA employees developed the early warning system EARLY4AdMa[80] for the identification of advanced (nano)materials that are expected to require action on the basis of safety or sustainability concerns.

Assessment tools: Due to its expertise in regulatory environmental risk assessment, UBA is involved in various committees and initiatives to develop assessment tools for nanomaterials for chemical safety. For example, UBA is represented on the board of the Malta Initiative, which aims to promote the development of OECD test methods. These bodies and initiatives are currently expanding their field of work to advanced (nano-)materials. UBA remains committed to make its contribution here.

Research: In addition to UBA's involvement in third-party funded projects as a partner or in advisory bodies at national or European level, UBA supervises a number of research projects from the BMUV's ReFoPlan. This research currently includes both so-called preparatory research, which serves to identify and deal with new relevant topics and fields of action, but also concrete research questions. Among others, UBA is currently conducting a project that deals with the challenges of novel carrier systems for environmental risk assessment.

4 Summary

Advanced materials include both new and existing materials that have improved or new properties over conventional materials. Thus, they include a large number of material types of different structures and complexities, which create different properties and functionalities, and could therefore be used in very different areas of application. Chemicals and materials are essential for the provision of low-CO_2, pollution-free, energy- and resource-efficient techniques, materials, and products. They are indispensable for the transformation of society and the economy towards greater sustainability. A discussion of the challenges posed by the use of advanced materials in terms of chemical safety and sustainability is therefore complex and the question of appropriate actions to meet the challenges cannot be answered uniformly for all advanced materials. However, based on the chemical composition, functionalities, and complexity of an advanced material, and its intended areas of application, it is possible to formulate questions that may require closer examination. This concerns questions about environmental or health risks as well as ecological footprints along the life cycle or recycling.

UBA is committed to identifying and averting negative impacts to environmental protection, health protection and sustainability. It develops approaches for dealing with these challenges with the aim of helping to shape the urgently needed transformation towards sustainability in Germany, Europe and worldwide. In this context, UBA wants to identify environmentally relevant challenges of advanced materials at an early stage and derive suitable measures to support the best possible use of the advantages of these materials for a transformation towards a more sustainable economy and society. Advanced materials promise technical solutions for the energy and transport transition, resource conservation, digitisation or health care, among others. In order to support the development towards a more sustainable economy and society, it is a basic prerequisite that advanced materials themselves are safe and sustainable over their entire life cycle. To ensure this, UBA has identified a number of key points. These include pre-regulatory approaches such as knowledge transfer, dialogue, early identification, and research up to regulatory approaches, such as the provision of suitable assessment tools. These approaches should be taken up by political and regulatory parties as well as by research, industry and society.

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