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Advanced Materials

Summary

Advanced materials are materials or material combinations with improved, novel or unique functionalities or properties. They are key technologies that are crucial for competitiveness and economic growth in the EU. The research framework programs of the EU, such as Horizon 2020 and Horizon Europe, reflect this importance. New developments range from innovative additives in food packaging and ultralight metal foams to transport systems for active ingredients in medicine or cosmetics. In many cases, these novel materials offer solutions to environmental problems, e.g. by saving energy and materials because of lighter weight. Consequently, they can contribute to a sustainable development of the environment, economy, and society. However, novel materials and/or new functionalities are also associated with uncertainties regarding human health and the environment. It is therefore important to highlight safety-relevant aspects at an early stage and identify potential risks in accordance with the precautionary principle. Because of the complexity of advanced materials, new approaches are required to gain all the necessary knowledge regarding their safety. The concepts of "safe by design" (SbD) and the more recent "safe and sustainable by design" (SSbD) are examples of such approaches. The aim is to integrate safety, recyclability, and functionality of products and processes throughout their whole life cycle to address potential risks to human health and the environment early in the innovation process of new materials. At present, it is still unclear whether all advanced materials are covered by existing chemical safety regulations. It is therefore necessary to review relevant regulations and corresponding risk assessment tools in this context to anticipate and fill any potential loopholes.

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Introduction

Materials with new or improved functionalities have always had great importance for humanity, evidenced by the fact that certain periods of time have been named after the available materials which shaped life (e.g. the Stone Age, Bronze Age, and Iron Age). Nowadays, rapid technological advances are resulting in material innovations at an even faster pace, i.e. the so-called advanced materials – a term that has been in use in the field of materials science for more than thirty years[1] – which bring about new functionalities and thus new possibilities, but also uncertainties in terms of their effects on humans and the environment. Because of their novel and advanced properties, it has often been pointed out that advanced materials can provide attractive solutions to global challenges, such as the need for continuous renewable energy, clean water, and transition to a low-carbon economy.

Advanced materials are promising in a number of ways: from new types of additives in food packaging and ultralight metal foams to transport systems for active ingredients in medicine or cosmetics (so-called "nanocarriers"), the applications cover various sectors and affect different industries. In many cases, these novel materials offer solutions to environmental problems, e.g. by saving energy and materials because of lighter weight, therefore contributing to the conservation of resources.[2]

Alongside such potentially positive aspects of novel materials, which have the potential to contribute to a more sustainable environment, there are, however, also uncertainties and challenges, for example with regard to occupational health and safety, waste disposal, and recyclability. Novel materials and their new functionalities are associated with uncertainties regarding risks to human health and the environment. It is therefore important to highlight safety-relevant aspects at an early stage and identify possible risks in accordance with the precautionary principle in advance. It is at this point where the many years of experience already gained in the field of nanotechnology will be useful and can be drawn upon.[3]

There are several different approaches to define the term advanced materials, which have the following features in common: they concern materials or combinations of materials with improved, novel or unique properties or functionalities that are superior to currently existing conventional materials. As a result, the content of the term advanced materials depends on different points of reference and can vary contextually. For this reason, not only the material under consideration plays a vital role, but also the application and the selection of conventional materials as a reference basis. Moreover, the aspect of improvement or better suitability also includes a time component.

Advanced materials can be designed and developed from scratch by assembling atoms in new ways. However, they can also be developed by modifying traditional materials such as metals, ceramics, gels, and polymers, giving them new properties.[4] These new properties, such as increased durability and elasticity, improve the performance of these materials which can therefore be superior to the conventional original materials. Materials used in hightechnology applications are sometimes also referred to as advanced materials. High technology refers to devices or products that operate or function according to complex principles, such as computers, aircraft, and spacecraft.[5] Advanced materials therefore represent a broad class of materials that include semiconductors, biomaterials, and nanomaterials.[5]

This dossier provides an overview of the different approaches to defining advanced materials, the materials' potentials and applications, and identifies areas where safety issues may arise.

Definitions

For nearly 20 years, many definitions of the term advanced materials have been created in various fields of research; however, there is currently no generally accepted or even legally binding definition. The first task is therefore to determine the extent to which such definition is needed at all. Experience with the regulation of nanomaterials has shown that a regulatory definition without scientific justification – in addition to the difficult process of reaching consensus – harbours additional potential risks, for example the fact that in the case of nanomaterials, regulatory definitions are based on properties that do not allow any statements about potential risks.[6] It therefore seems sensible to have uniform and generally acceptable working definitions that enable a common understanding of the currently still diffuse term of advanced materials and are not aimed at standardised regulation. Table 1 lists previous definitions of advanced materials that share certain common characteristics. Compilations of already existing definitions and categorisations can also be found in the meta-studies by Broomfield *et al.* (2016)[7] and Giese *et al.* (2020)[8].

Considering the definitions mentioned in Table 1, there is particular emphasis on the following properties of advanced materials:

- They are characterised by their novelty
- In one way or another they are more advanced than traditional materials (i.e. they have advanced properties)
- They are specifically tailored to fulfil a particular purpose or a particular functionality
- They have unique or exceptional properties and functionalities
- They are characterised by improved performance compared to their traditional form
- They are recognised as materials with high added value

Table 1: *Definitions of Advanced Materials.*

Source	Definition
Rensselaer Polytechnic Institute (2004)[9]	"[...] *advanced materials refer to all new materials and modifications to existing materials to obtain superior performance in one or more characteristics that are critical for the application under consideration.*" (p.1)
Maine und Garnsey (2006)[10]	"*Radical advanced materials technologies are here defined as product and process improvements that significantly enhance the cost-performance frontier of functional materials.*" (p.5)
Lukkassen and Meidell (2007)[11]	"*High-performance materials or advanced engineering materials, which are used in products that must have superior properties (extreme service environments, superior chemical resistance, wear resistance, and loading properties.*" (p.9
Technology Strategy Board, UK (2008)[12]	"*Advanced Materials, defined here as materials, and their associated process technologies, with the potential to be exploited in high value-added products, is both a multidisciplinary area within itself (including, for example, physics, chemistry, applied mathematics) and cross-cutting over both technology areas (e.g. electronics and photonics, biosciences) and market sectors (e.g. energy, transport, healthcare, packaging).*" (p.8)
National Institute of Standards and Technology (NIST) (2010)[13]	"[...] *we will define "materials advances" as: Materials that have been developed to the point that unique functionalities have been identified and these materials now need to be made available in quantities large enough for innovators and manufacturers to test and validate in order to develop new products.*" (p.5)
Romanow and Gustafsson (2012)[14]	"[...] *advanced materials are tailored to fulfil specific functions and/or have superior structural properties. We distinguish four conditions that define Value Added Materials:* ■ *a knowledge-intensive and complex production process,* ■ *new, superior, tailor-made properties for structural or functional applications,* ■ *potential to contribute to competitive advantage on the market,* ■ *potential to address Europe's Grand Challenges.*" (p.9)
EU Design and Advanced Materials As Driver of European Innovation (DAMADEI) (2013)[15]	"*An advanced material is any material that, through the precise control of its composition and internal structure, features a series of exceptional properties (mechanical, electric, optic, magnetic, etc) or functionalities (self-repairing, shape change, decontamination, transformation of energy, etc) that differentiates it from the rest of the universe of materials; or one that, when transformed through advanced manufacturing techniques, features these properties or functionalities.*" (p.25)
South Africa Department of Trade and Industry (DTI) (2018)[16]	"*Advanced materials can be defined in many ways. The broadest definition is to refer to all materials that represent advances over the traditional materials that have been used for hundreds or even thousands of years. From this perspective, advanced materials refer to all new materials and modifications to existing materials to obtain superior performance in one or more characteristics that are critical for the application under consideration.*"
Kennedy et al. (2019)[1]	"*Advanced Materials are materials that are specifically engineered to exhibit novel or enhanced properties that confer superior performance relative to conventional materials. As a result of their unique characteristics, advanced materials have a highly uncertain hazard profile and the potential to require special testing procedures and methods to assess potential for adverse environmental health and safety impacts.*" (p.1786)
Giese et al. (2020)[8]	"[...] *a delimitation of advanced material as materials that are rationally designed in order to fulfil the functional requirements of a certain application is suggested.*" (p.80)
German Environment Agency (UBA), German Federal Institute for Risk Assessment (BfR) & German Federal Institute for Occupational Safety and Health (BAuA) (2021)[17]	Draft working definition "[...] *AdMat (advanced materials) should be understood as 'materials that are rationally designed through the precise control of their composition and internal or external structure in order to fulfil the functional requirements'.*" (p.13)

Categorisations

A definition and systematisation of advanced materials into categories is useful and necessary to conduct safety assessments and prioritise environmental and health risks.[1] Fundamental to any risk screening, Kennedy *et al.* (2019)1 developed a categorisation system following several workshops and interviews, consisting of a series of questions about the properties of a material. Answering these questions allows users to distinguish whether a material is a conventional or an advanced material.

A classification into certain groups or categories was already proposed by Lukkassen and Meidell[11] in 2007 and by Baykara *et al.*[18] in 2015. They mention the areas of metals, ceramics, polymers, and composites. In a 2013 European Union report, advanced materials are categorised into active materials (materials that can change shape or colour, for example), advanced composites, novel manufacturing processes (e.g. 3D printing) as well as textiles and fibres, coatings, nanomaterials, gels and foams, high-performance polymers, and novel alloys.[15] The German Environment Agency (UBA) has looked at the topic of advanced materials in detail and proposes a classification into eight categories (see Table 2).[8] Their systematisation was based on literature research and several expert workshops. The UBA also publishes their own factsheets in which they provide a detailed overview of these materials, their areas of application, potential risks, and their current regulation.[19]

The complexity of the nature and application of advanced materials requires looking at them from different perspectives and dealing with different aspects. In this context, the UBA proposes considering four dimensions: science, economy, risk, and regulation. The following aspects should be considered: the novelty of the properties which these materials acquire, their market potential, possible risks to humans and the environment or a high exposure potential, and the inadequate regulatory coverage or lack of appropriate methods for risk assessment.[8]

Applications and risks

Advanced materials are primarily used in medicine, electronics, construction, the energy sector (including renewable energies), and also in the environmental sector:[19]

- **Medicine:** controlled drug delivery (transport systems, "nanocarriers"), artificial tissue engineering, imaging techniques, cancer therapy, artificial muscles, and highly elastic implants
- **Electronics:** protein-based bioelectronics, displays, sensors, organic light-emitting diodes (LEDs), wearables, and storage devices
- **Construction:** lightweight construction, sound filtering, thermal insulation, construction material with high strength or special thermal or electrical properties, and switchable glazing
- **Energy:** wind turbine blades, batteries, solar cells, metalorganic frameworks for H_2 storage
- **Environment:** filtration and sorption of environmental pollutants

Carbon-based fibres (also called carbon or graphite fibres) account for one important group of advanced materials that is considered relevant in terms of risk. They are not new materials in the strict sense, but offer notable new functionalities: because of their remarkable strength and load-bearing capacity, they can be used in novel applications in the construction and automotive industries, significantly reducing vehicle weight and thus improve energy efficiency.[22] In addition, they have been used in electronics, e.g. in storage media, in textiles as heating elements, in air filters, and also in medicine, e.g. in cancer tests.[19] Because of their large fibre diameter, carbon fibres do not normally pose a risk of respirable, carcinogenic fibre dusts. However, critical fracture behaviour with fibre dust release has only recently been observed in carbon fibres specifically developed with high mechanical strength.[23] Fires and thermal recycling processes of carbon fibrereinforced plastics can also lead to relevant changes in carbon fibres. As a result, a morphological characterisation of carbon fibre materials is imperative to reliably exclude health-critical fibre dust release in the life cycle, especially for wideranging applications such as in the construction industry. Morphological characterisation of materials is currently not yet enshrined in law, i.e. in the European chemicals legislation. From

Table 2: *Categorisation of advanced materials by the German Environment Agency (UBA)[8]*

Category	Characteristics
Biopolymers	Materials based on naturally occurring polymers, which are designed for a specific functionality
Composites	Materials that are a combination of two or more materials
Porous Materials	Materials which show a porous structure, differentiated by pore size
Metamaterials	Materials with properties that go beyond the naturally occurring properties of their components
Particle Systems	Materials with properties that are related to their particles' structure
Advanced Fibres	Fibres several µm or smaller in diameter with an intended functionality
Advanced Polymers	Polymers with an intended functionality
Advanced Alloys	Alloys which comprise more than two components; at least two components have a larger share in the final material

Case study on the categorisation of advanced materials in innovative solar cell technologies

In addition to questions regarding a definition, categorisation, and possible risks and adequacy of regulatory instruments, the question arises to what extent it is feasible in practice to categorise used materials as "advanced" when compared to conventional ones. Moreover, what is the added value of such categorisation when compared to existing definitions from a scientific point of view. The project SolarCircle[20] investigated areas of application and sustainability issues of novel photovoltaic technologies and the potentially novel materials they contain. In addition, a specific categorisation system (Kennedy *et al.*[1)]) was applied to materials in novel photovoltaic technologies to test the practicability of the approach. During a discussion with materials science experts, the system was applied experimentally to materials in actual research practice.

The starting point was a list of materials compiled by the Institute of Physical Chemistry and the Institute for Organic Solar Cells at the Johannes Keppler University in Linz, outlining frequently used materials in four selected emerging photovoltaic technologies (organic solar cells, dye-sensitised solar cells, perovskite solar cells, and quantum dot solar cells with different variations for each type). The list is based on a definition of "emerging photovoltaic technologies" (EPVs) by the National Renewable Energy Laboratory (NREL) Institute in Colorado[21]; however, the list is not exhaustive since many different materials are used in EPVs in practice. It does not include individual materials but rather families of materials, such as semiconducting polymers, perovskites or transparent contact layers, because a presentation by individual materials would be impossible to manage.

Based on this, the classification according to Kennedy *et al.*[1] revealed challenges that were routed in the respective materials' specific functionality. From a material development point of view, the proposed system offers only little added value where characterisation of materials found in EPVs is concerned. On the one hand, this is due to the complexity of the solar cell architectures, and on the other hand because of the diversity of the materials used. This means a lot of effort is required for the characterisation of individual materials, which is hardly feasible under real life circumstances. In practice, the term advanced materials itself was considered misleading and not very meaningful, if not problematic, by the experts because it suggested an implicit valuation between materials. To counteract this and to emphasise the importance of the functionality of such materials, it was advocated to not only codify functionality in the definition, but to also expand the term to "advanced functional materials".

a legal/regulatory point of view, it is also unclear when a material is a "substance" in the sense of the law regulating chemicals. With the help of a risk management option analysis (RMOA) to protect against harmful fibre dusts, the German higher federal authorities want to systematically search for comprehensive approaches to close these regulatory gaps.[24]

There are also still major uncertainties with DNA-based biopolymers regarding their risks to human health and the environment. They develop complex 2D or 3D structures mostly at nanoscale and have been designed to fulfil specific functionalities.[19]

DNA-based biopolymers are used, for example, for drug delivery in cancer treatment. They can also be used in the field of environmental monitoring because DNA molecules can detect a wide range of ions, molecules, and even cells with high specificity.[25] However, little is known about their persistence in the human body and in different ecosystems.[8] At present, there is insufficient information on the stability of these materials, their behaviour as well as their potentially harmful effects. Consequently, a long-term assessment of the materials' cytotoxicity is necessary.[19] Appropriate test methods for an adequate risk assessment are required; however, these are currently still lacking.[19]

Advanced materials in the context of sustainable development

Sustainable development policies for the continuous improvement of society, the environment, and the economy (three pillars of sustainability), covering new materials and products, should be guided by scientific analyses. However, as these dimensions are highly interconnected with complex interactions taking place, it is possible for an advantage in one area to lead to a deficit in another.[26]

The sustainable development of new materials can be conveyed through the following principles:[26]

- Efficient use of materials (reuse, recycling)
- Use of replacement materials (e.g. substitution of materials that are difficult to obtain)
- Development of materials to support alternative energy technologies, to replace fossil fuels and increase energy efficiency
- Mitigate undesirable environmental impacts

The European Commission hopes for advanced materials to not only bring economic benefits, it also considers them to be fundamental building blocks for the development of more sustainable technologies with more environmentally friendly properties and improved performance.[27] Under the EU's Horizon 2020 programme (2014-2020), advanced materials were therefore defined as one of six key enabling technologies (KET) and considered a priority. In the current successor programme Horizon Europe (2021-2027), advanced materials continue to be positioned amongst the category of most promising technologies.[28] The EU supports innovation in the areas of design, development, testing, and upscaling of advanced materials by focusing on the following areas: life cycle of materials, demonstration and prototyping activities in different sectors (e.g. energy, mobility, nanotechnologies, medical technology) and in different cross-sectoral fields of application (e.g. nanosafety). In addition, data-driven methods should be developed to design safe materials and to reduce costs, the number of materials used, and the time to market.[27]

In terms of a sustainable development of the environment, economy, and society, it is important to consider ecological and social factors as well as aspects of technological progress and economic feasibility whilst taking into account the precautionary principle and existing standards for environmental protection. Improvements, not only in terms of safety (safe by design, SbD) but also the sustainability of the design (safe and sustainable by design, SSbD), are essential to transition to a sustainable society.[17;36] The SSbD concept is a systemic approach to integrating the safety, recyclability, and functionality of products and processes throughout their entire life cycle.[29]

It is of utmost importance to undertake some form of technology evaluation at the early stages of development to address risks as early as possible. Life cycle assessment/analysis (LCA) is recognised as a suitable tool to assess the environmental impact of new technologies along the entire life cycle ("cradle to grave") and to facilitate decision-making in policy and research.[30;31] LCA is a method based on the approach of systems thinking that is considered essential for addressing major global challenges, such as the Sustainable Development Goals (SDGs).[32] Consequently, LCA has ingreasingly gained mportance at low Technology Readiness Levels ("TRL")[33] to enable the development of new technologies with improved environmental performance.[30] Moreover, it would be desirable to also have adequate representation of the risks to workers with the help of specific life cycle analysis approaches.

Advanced manufacturing – innovative production methods

Alongside new materials, the resulting new or enhanced manufacturing technologies, such as additive manufacturing, also require special attention in terms of potential risks, especially where the protection of workers is concerned. Such new manufacturing technologies accelerate the development of new materials and have significantly changed the traditional manufacturing model over the last 100 years.[34] It is therefore vital to address safety-related issues in terms of SSbD also in the field of advanced manufacturing as early as possible.

In additive manufacturing, very thin cross sections of a material are essentially layered (or "built-up") on top of each other until a 3D product is built.[34] Advanced materials in the form of a fine powder, liquid or solid strand are exposed to very high and focused energy sources (e.g. lasers or high temperatures) to bind the material into very thin layers which are then built up into a larger whole.[34] The potential applications of additive manufacturing range from medical implants to aircraft wings.[34]

Health and safety concerns do exist, for example, for powder bed fusion processes where workers can be exposed to the original materials (e.g. microscale metal and plastic powders)[35].

Risk assessment and the need for regulation

Because of the complexity of advanced materials in terms of their application and the science behind them, new approaches are required to gain all the necessary knowledge regarding their safety. The concept of SbD is an excellent example of such an approach. The aim of the SbD concept is to address safety issues regarding the potential risks to human health and the environment early in the innovation process of new materials.[36] Consequently, understanding and identifying risks is an essential step in the innovation process.

With regard to nanomaterials, SbD can include, for example, the avoidance of hazardous elements such as heavy metals, the development of nanomaterials with biodegradable components so that they are safer and more environmentally friendly, and the design of safer nanoscale manufacturing processes.[37] As mentioned above, an important aspect is the lowemission design of materials and products that prevents release throughout the entire life cycle.

The risk assessment also includes the evaluation of the technology readiness levels (TRLs). These can help with a decision whether a material can enter the next stage of development.[38] Many advanced materials are a combination of different substances with potential (environmental) toxicity, and it is unclear to what extent these can be a risk to health or the environment if released.[19] In addition, a specific critical morphology (respirable fibres, (ultra-)fine dusts) can also lead to hazards and risks, although the chemical composition of these substances is not initially considered relevant in terms of risk.[19] For example, the fracturing behaviour of carbon fibres (see above) and the resulting risks, especially for workers, demonstrate the importance of early and systematic risk identification. On the other hand, risk assessments of nanomaterials have shown that many concerns regarding possible health risks are not justified.[39] Nevertheless, new applications of advanced materials, for example in the medical field, still require a comprehensive risk assessment and hazard evaluation.

At present, it is still unclear whether all advanced materials are covered by existing chemical safety regulations. It is therefore necessary to review relevant regulations and corresponding risk assessment tools in this context to fill any potential loopholes. However, it seems that, for now, advanced materials are largely covered by existing regulations and that there is no need for risk management tailored to the entire group of materials, nor is there a need for independent legal regulation based on a comprehensive definition.[17]

Conclusion

The importance of advanced materials in the realisation of advanced technologies and the production of high-quality products is increasing; however, it is necessary to guarantee the safety of health and the environment when developing new materials. The entire life cycle should already be considered at the design stage of innovative materials and products in order to fully exploit any advantages – also in terms of sustainable development – and to be able to minimise potential risks in advance. Right now, existing instruments for risk management as well as regulations in the field of chemical safety appear to be largely sufficient where advanced materials are concerned; however, they need to be reviewed and may require adaptation for specific areas.

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