

FKZ 3719 66 402 0

# **ADVANCED MATERIALS – OVERVIEW OF THE FIELD**

## FACTSHEETS ON SELECTED CLASSES OF ADVANCED MATERIALS

ANNEXES TO THE FINAL REPORT

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## **Abstract: Factsheets on advanced materials - Annexes to the final report**

The factsheets on advanced materials are structured into several sections: general information with a characterization of the described advanced material type, used synonyms, information on its composition and structure, potentially existing sub-classes and the main functionalities as well as indications on the regulatory status. Other sections concern the fields of application, information on hazards, exposures and risks as well as on the lifecycle and circular economy.

The factsheets are an input to the second thematic conference, which is organized as two online conferences due to the Corona pandemic. Hence, the factsheets should be understood as initial discussion basis. They are neither complete nor comprehensive but intended to propose a structuring of the field of advanced materials as well as to compile easily accessible information.

## **Kurzzusammenfassung: Datenblätter zu Advanced Materials – Anhänge zum Abschlussbericht**

Die Datenblätter über Advanced Materials sind in verschiedene Abschnitte unterteilt: Allgemeine Informationen, einschließlich einer Charakterisierung der Klasse von Advanced materials, Synonymen, Informationen zur Zusammensetzung und Struktur, ggf. existierende Unterklassen und der wichtigsten Funktionalitäten sowie Hinweise auf ihren regulatorischen Status. Weitere Abschnitte behandeln die Anwendungsfelder, mögliche Gefahren, Expositionen und Risiken sowie Aspekte im Lebenszyklus und bezüglich der Kreislauffähigkeit.

Die Datenblätter sollen für die zweite thematische Konferenz dienen, die aufgrund der Corona Pandemie in Form von zwei Online-Konferenzen durchgeführt werden. Daher sollten diese Datenblätter als erster Input für die Diskussion angesehen werden. Sie sind weder vollständig noch vollumfassend sondern sind ein Vorschlag zur Strukturierung des Feldes der Advanced Materials sowie eine Zusammenstellung verhältnismäßig einfach verfügbarer Informationen zu den einzelnen Aspekten.

Abbr.	Explanation
<b>AdMa</b>	Advanced material
<b>As</b>	Arsenic
<b>BAS</b>	Bovine serum albumin
<b>Cd</b>	Cadmium
<b>CMR</b>	Carcinogenic, mutagenic, reprotoxic
<b>CNT</b>	Carbon nano tube
<b>CNT MMC</b>	Carbon nano tube in metal matrix
<b>CO<sub>2</sub></b>	Carbondioxide
<b>Cr</b>	Chromium
<b>DNA</b>	Deoxyribonucleic acid
<b>ED</b>	Endocrine disruption
<b>EU</b>	European Union
<b>Ga</b>	Gallium
<b>H<sub>2</sub></b>	Hydrogen
<b>HEA</b>	High entropy alloy
<b>IMA</b>	Intermetallic alloy
<b>In</b>	Indium
<b>MnO</b>	Manganese oxide
<b>µm</b>	Micrometer
<b>nm</b>	Nanometer
<b>Pb</b>	Lead
<b>PBS</b>	Phosphate buffered saline
<b>PET</b>	Polyethylene terephthalate
<b>PIM</b>	Polymer of intrinsic microporosity
<b>PLA</b>	Polylactic acid
<b>REACH</b>	Regulation on the registration, evaluation, authorisation and restriction of chemicals
<b>RNA</b>	Ribonucleic acid
<b>S</b>	Sulphur
<b>SBNP</b>	Sugar-based nano particle
<b>Se</b>	Selenium
<b>Si</b>	Silicon
<b>SiO<sub>2</sub></b>	Silicon dioxide
<b>SMA</b>	Shape memory alloy
<b>Te</b>	Tellurium
<b>THF</b>	Tetrahydrofurane
<b>TiO<sub>2</sub></b>	Titanium dioxide
<b>TRL</b>	Technology readiness level
<b>WHO</b>	World Health Organisation
<b>Zr</b>	Zirconium

# 1 INTRODUCTION

This document is an Annex to the report “Advanced materials – Overview of the field and screening criteria for relevance assessment”. The report and the factsheets were developed in the frame of the research project “Advanced materials - Thematic conferences. Assessments of needs to act on chemical safety”, which was commissioned by the German Environment Agency (UBA) and financed by the German Ministry of the Environment, Nature Protection and Nuclear Safety (BMU).

This report is a collection of information on several clusters of advanced materials in the form of structured factsheets.

The aim of the factsheets is to structure the field of advanced materials and provide accessible information on the various types of advanced materials. It proved impossible to unambiguously structure advanced materials. Regardless of the criteria chosen for categorising them, overlaps existed. The project's approach to form clusters and classes of advanced materials was limited by and had to deal with:

- a) A lack of accessible information to form and differentiate types of advanced materials;
- b) The high number of possible criteria to categorise advanced materials;
- c) The need to define a manageable number of advanced material types at a sufficient level of detail to differentiate the material types;
- d) The need to integrate partly established “definitions” of advanced materials and
- e) The limited resources to elaborate the core characteristics of the various clusters of advanced materials.

Despite the above limitations, the approach of elaborating factsheets to describe distinct types of advanced materials was chosen to give all stakeholders some (debatable) structure for their work and fix the starting point for further discussions, in particular at the second conference organised in the frame of this project.

In this regard, the factsheets should be regarded as living documents.

## 1.1 Use of the factsheets in the project

The factsheets support certain aims and tasks in the project, including to:

- Derive specific questions on advanced materials and/or specific clusters of advanced materials for the online survey, i.e. aiming at filling the “major gaps” and/or verifying initial conclusions on commonalities or applications in the group;
- Provide structured and understandable information to the general public and the authorities on advanced materials in form of annexes to the main report;

- Initiate a discussion on the types of discrete clusters of advanced materials that the (national/EU) authorities agree to focus on in their monitoring and relevance assessment;
- Provide an information basis for a first relevance assessment of selected clusters of advanced materials as documented in the main report;
- Highlight areas of information gaps and lack of knowledge and hence provide a basis for priority setting regarding information collection and/or selection of clusters of advanced materials for regulatory scrutiny and further work.

## **1.2 Extent of elaboration**

The factsheets are only a starting point for describing different types of advanced materials and do neither claim to be complete nor final with a view to the selection of the described material clusters. Furthermore, some factsheets list sub-classes of advanced materials but no factsheets exist for these.

The information sources used to compile the factsheets are:

1. A literature research on the topic “advanced materials”;
2. Expert interviews;
3. Presentations and discussions at the first thematic conference;
4. Additional targeted information collection from literature and an online survey conducted during February 2020.

## **1.3 Structure of the factsheets**

The factsheets are separated into several chapters. Information for the different types of materials are inserted as far as accessible to the authors. Lack of information indicates a potential need for data gathering and generation.

### **1.3.1 General information**

This Section includes: a working definition, common synonyms, a description of the main building blocks and the main structural characteristics, list of obvious and potentially confusing overlaps with other types of advanced materials and specific functionalities are described.

### **1.3.2 Applications**

The section contains a table listing application areas and indicating the development stage. This information is anecdotal due to the large number of (potential) applications.

### **1.3.3 Regulatory information**

This section only includes information on which regulatory definition an advanced material fulfils or which definitions it might fulfil, in case this cannot be clearly decided. A discussion of the implications of the regulatory status and potentially applicable legislation is included in the main report.

### **1.3.4 Information on potential risks**

Information on the hazard and exposure potential that, in combination with information on their uses, support the risk assessment of the advanced material is provided. The hazards and exposures are differentiated into effects on either humans or the environment.

### **1.3.5 Information on environmental impacts and material circularity**

A general evaluation of the respective issues is reflected in this section based on either information from literature or derived by the authors from the information presented in the respective factsheet.

## **1.4 List of advanced materials covered by individual factsheets**

- Biopolymers (Materials based on naturally occurring polymers, which are designed for a specific functionality)
  - DNA-based Biopolymers
  - RNA-based Biopolymers
  - Protein-based Biopolymers
  - Sugar-based Biopolymers
  - Lipid-based Biopolymers
- Composites (combination of two or more materials)
  - Macroscopic Composites
  - Hybrid Materials (Materials that are a combination of organic and inorganic materials)
  - Fibre-reinforced Composites
  - Particle-reinforced Composites
- Porous materials (Materials which show a porous structure, differentiated by pore size)
  - Microporous Materials
  - Mesoporous Materials
  - Macroporous Materials
- Metamaterials (Materials with properties that go beyond the naturally occurring properties of their components)
  - Electromagnetic Metamaterials
  - Acoustic Metamaterials
- Particle systems (properties of the materials are related to their particles' structure)
  - Quantum Dots

- Supraparticle
- Nanoflowers
- Graphene
- Advanced Fibres (fibres several  $\mu\text{m}$  or smaller in diameter with an intended functionality)
  - Organic Fibres
  - Carbon-based Fibres (incl. CNTs)
  - Inorganic Fibres (e.g. silica)
- Advanced Polymers (Polymers with an intended functionality)
  - Electro-active Polymers
  - Self-repairing Polymers
  - Co-polymers
- Advanced Alloys (Alloys, which comprise more than two components; at least two components have a large share in the final material)
  - Advanced Alloys

## 2 FACTSHEET: DNA-BASED BIOPOLYMERS

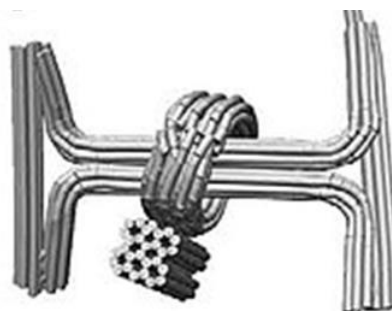


Figure 1: DNA origami rotaxane (ring on an axis). From List et al (2016).<sup>1</sup>

### 2.1 General information

**Synonyms:** Bionanomaterials or nanobio-materials are synonyms for the main group biopolymers, of which DNA-based polymers are a subgroup.

**Working definition:** DNA-molecules, which are designed to fulfil a specific active functionality. They develop complex 2D or 3D structures, mostly at nanoscale.

**Sub-groups:** No further differentiation is regarded necessary or meaningful.

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<sup>1</sup> List, J., Falgenhauer, E., Kopperger, E. et al. Long-range movement of large mechanically interlocked DNA nanostructures. Nat Commun 7, 12414 (2016). <https://doi.org/10.1038/ncomms12414>. License CC BY 4.0.

**Main building blocks, composition:** A long DNA-strand to which shorter DNA-strands are attached at pre-determined sites forming the desired structure (typically 25-150 nm). Nucleotides serve as monomers.

**Structural characteristics:** DNA-origami, meaning a folded 2D or 3D structure at nanoscale.

**Intended change of materials during use / intended transformation during application:** Often intended to change during use, e.g. opening of a “lid” to release drugs (see Figure 1). The DNA-based biopolymers respond to other matter by changing their structure or modifying their surface properties. They may also act passively as carriers or only change the properties of the matter they interact with, e.g. thin films of DNA change the optical properties of the organic surfaces they cover<sup>2</sup>.

**(Combinations of) properties and related (intended) functionalities:** DNA-based biopolymers interact with their environment. They are mostly constructed to interact with other matter, e.g. as a carrier to deliver drugs they “open” when in contact with the targeted matter or as cleaning substances to an organic environment they “close” when in contact with the pollutant. Self-assembly is a further intended functionality.

**Other characteristics:** No further characteristics identified as relevant.

**Regulatory information:** It is not entirely clear, which definition DNA-based biopolymers<sup>3</sup> fulfil. The most likely applicable definitions are: substance (in nanoform) or mixture.

## 2.2 Application(s)

Table 1: Applications of DNA-based biopolymers – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Medicine	Tailored encapsulation, e.g. cancer medication		Close to market		
Medicine	Sensors		x		
Agriculture	Tailored encapsulation for plant protection products and fertilizers		x		
Agriculture	Agent to change electro-optic interface applied on plants to have a broader transmission interface	x			

<sup>2</sup> Anton, Adina-Mirela, Ileana Rau, Francois Kajzar, Alina-Marieta Simion, und Cristian Simion. „Third Order Nonlinear Optical Properties of DNA-Based Biopolymers Thin Films Doped with Selected Natural Chromophores“. *Optical Materials* 88 (February 2019): 181–86. <https://doi.org/10.1016/j.optmat.2018.11.037>.

<sup>3</sup> The term biopolymers may be confusing as it suggests these materials being polymers in the sense of the REACH definition. However, the use of the term “polymer” in the field of advanced materials does not necessarily correspond to that definition.

Sector	Use	Basic scientific research	Research on specific applications	"Recent" market introduction	Use is "common"
Material manufacturing	Molecular tools and nano reactors for processing materials		x		

## 2.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 2: Compilation of hazard and exposure information of DNA-based biopolymers

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>4</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>	Significant cytotoxicity is unlikely <sup>4F5</sup> , need for pharmacokinetic and pharmacodynamic studies as well as long term assessment of cytotoxicity	In vitro and in vivo studies available
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>		
Exposure (Human)		
Exposure during use and service life of products	Invasive use as drug delivery system	

<sup>4</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

<sup>5</sup> Udomprasert A, Kangsamaksin T. DNA origami applications in cancer therapy. *Cancer Sci.* 2017;108(8):1535–1543. doi:10.1111/cas.13290

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>4</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Uptake and metabolism, kinetic behaviour in humans	Distribution and degradation time within a living organism is uncertain, DNA-Origami is only comparable to the behaviour of natural DNA to a limited extent	Little information available
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	In principle degradable, but time course is unclear due to non- natural structural motives that are possible with synthetic biopolymers	Information on biodegradation and persistence of DNA-based biopolymers as such is not available
Transport within and between environmental compartments		

## 2.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Among the main benefits of DNA-based biopolymers are the controlled delivery of active substances to their target location in the human or animal body, for plant protection etc. DNA-based biopolymers could also be used for “cleaning the environment”, e.g. cleaning lakes from pesticides.

**Information on possible circularity deficits:** DNA-based biopolymers are in theory fully degradable and thus expected to have a rather short lifetime. However, the time course is unclear due to non-natural structural motives that are possible with synthetic biopolymers. Moreover, they will most probably be produced in small amounts for specific purposes. Since there is currently no indication for a high-volume product application and thereby a replacement of non-degradable materials, no general improvement regarding circular economy can be expected from DNA-based biopolymers.

## 2.5 Uncertainties, lack of information

Information on the stability of DNA-based biopolymers, their behaviour in the environment and the human body as well as the potential adverse effects of the building blocks (DNA fragments) is currently insufficient for risk assessment. There is a suspicion of risks due to the fact that interactions with DNA in living cells are generally possible.

How DNA-based biopolymers are covered by the present legislation and its definitions and whether the existing guidelines for information generation and risk assessment already consider the character of the new material is not clear.

Hazards cannot be deduced based on information from the building blocks/constituents and nucleotides as monomers unless synthetic derivatives are used. Appropriate test methods to identify hazards are missing.

Information on uses and related emissions of DNA-based polymers as well as information on the stability/persistence (during use and disposal and/or in the environment) is scarce.

### 3 FACTSHEET: RNA-BASED BIOPOLYMERS

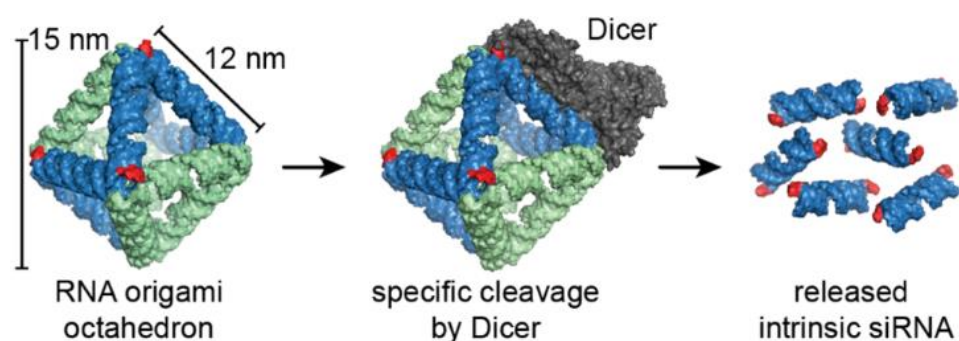


Figure 2: A 3D scaffolded RNA origami octahedron with intrinsic siRNAs (blue and red). The enzyme Dicer binds the structure at specific recognition sites and cleaves the structure, which releases the siRNAs. The octahedron was demonstrated to efficiently silence a target reporter gene when transfected into cells. From: Høiberg et al, 2019.<sup>6</sup>

#### 3.1 General information

**Synonyms:** Bionanomaterials or nanobio-materials are synonyms for the main group biopolymers, of which RNA-based polymers are a subgroup.

**Working definition:** RNA-molecules, which are designed to fulfil a specific functionality. They develop complex 2D or 3D structures, mostly at nanoscale.

**Sub-groups:** Further differentiation is not regarded necessary or meaningful.

**Main building blocks, composition:** RNA-strand to which shorter RNA-strands or other substances are attached at pre-determined sites. Nucleotides serve as monomers.

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<sup>6</sup> Aarhus University, Interdisciplinary Nanoscience Center, News: New methods for building 3D RNA nanostructure ready to knock down target genes. <https://inano.au.dk/about/news-events/news/show/artikel/new-unique-method-for-building-3d-rna-nanostructure-ready-to-knock-down-target-genes/>

**Structural characteristics:** RNA-origami, which is a 2D or 3D folded structure on nanoscale.

**Intended change of materials during use / intended transformation during application:** RNA nano-scaffolds are created to self-assemble and may change their structure as a response to certain stimuli.

**(Combinations of) properties and related (intended) functionalities:**

Intended functionalities include passive, structure-related interaction on nanoscale and active interaction (like an enzymatic function). Also, combinations of RNA-based functionalities (riboswitches, ribozymes, interaction sites, and aptamers) may be intended.

**Other characteristics:** No further characteristics identified as relevant.

**Regulatory information:** It is not clear, which definition RNA-based biopolymers<sup>7</sup> fulfil. The most likely applicable definitions are: substance (in nanoform) or mixture.

## 3.2 Application(s)

RNA-based biopolymer research seems to lag behind the research on DNA-based biopolymers since no applications at or close to the market stage could be found. Instead, a lot of promising research activities exist.

Table 3: Applications of RNA-based biopolymers – overview

Sector	Use	Basic scientific research	Research on specific applications	"Recent" market introduction	Use is "common"
Medicine	Cell recognition and binding for diagnosis, sensors, programmable packaging and cargo delivery systems for biomedical applications	x			
Synthetic biology	Knock down of target genes	x			
Synthetic biology	Active nano devices used to construct biological systems	x			

## 3.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last

<sup>7</sup> The term biopolymers may be confusing as it suggests these materials being polymers in the sense of the REACH definition. However, the use of the term "polymer" in the field of advanced materials does not necessarily correspond to that definition.

column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 4: Compilation of hazard and exposure information of RNA-based biopolymers

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>8</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	Possible response of an organism, e.g. immune system to foreign RNA	High uncertainty – no literature available
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?	Possible response of an organism, e.g. immune system to foreign RNA	High uncertainty – no literature available
Exposure (Human)		
Exposure during use and service life of products	Invasive use as drug delivery system	
Uptake and metabolism, kinetic behaviour in humans	Distribution and degradation time within a living organism is uncertain, RNA-Origami is only comparable to the behaviour of natural RNA to a limited extent	Little information available
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	Fully degradable, but persistence and environmental interaction until degradation unclear.	Information on persistence and biodegradation of RNA-based biopolymers as such is not available.
Transport within and between environmental compartments		

<sup>8</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

### **3.4 Information on environmental impacts and material circularity**

**Information on environmental „value“/possible benefits and adverse impacts:** The main benefits of RNA-based polymers are likely to consist of improved diagnostics and treatment of disease. No application targeting relief of environmental burdens are currently identified.

**Information on possible circularity deficits:** RNA-based biopolymers are biodegradable, they are expected to have a rather short lifetime. Moreover, they will most probably be produced in small amounts for specific purposes at present. The application in medicines and synthetic biology suggest no relevant wastes for potential recycling. Hence, no impacts on circularity are expected.

### **3.5 Uncertainties, lack of information**

Information on the stability of RNA-based biopolymers, their behaviour in the environment and the human body as well as the potential adverse effects of the building blocks (fragments) is currently insufficient for risk assessment. There is a suspicion of risks due to the fact that interactions with living cells are generally possible.

How RNA-based biopolymers are covered by the present legislation and its definitions and whether the existing guidelines for information generation and risk assessment already consider the character of the new material is not clear.

So far it is unclear in which amount RNA-based biopolymers will be used in the future. Thus, their exposure potential for emerging applications is still unknown. Nevertheless, manifold activities in research suggest a variety of products and therefore most probably also exposure to RNA-based biopolymers in many application contexts.

Hazards cannot be deduced based on information from the building blocks/constituents and nucleotides as monomers unless synthetic derivatives are used. Appropriate test methods to identify hazards are missing.

## **4 FACTSHEET: PROTEIN-BASED BIOPOLYMERS**

### **4.1 General information**

**Synonyms:** Bionanomaterials or nanobio-materials are synonyms for the main group biopolymers, of which protein-based polymers are a subgroup.

**Working definition:** Proteins that are used to design and develop complex structures at nanoscale for a specific functionality.

**Sub-groups:** Further differentiation is not regarded necessary or meaningful.

**Main building blocks**, composition: Combinations of amino-acids (natural and non-natural/non-canonical) forming proteins, potentially with not naturally occurring sequences, which are used as structural elements and structural motifs forming larger 3D-structures.

**Structural characteristics**: Protein-Origami, folded 2D or 3D structure.

Intended change of materials during use / intended transformation during application: Protein-based biopolymers are intended to change their structure and composition over lifetime. Some are targeted to transform during their application (medical application), some are targeted to change or degrade after their use (packing).

**(Combinations of) properties and related (intended) functionalities**:

Protein-based biopolymers show outstanding mechanical properties, further they are degradable. A variety of other properties can be designed like super-hydrophobicity.

**Other characteristics**: No further characteristics identified as relevant.

**Regulatory information**: It is not clear, which definition protein-based biopolymers<sup>9</sup> fulfil. The most likely applicable definitions are: substance (in nanoform) or mixture.

## 4.2 Application(s)

Table 5: Applications of Protein-based biopolymers – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Medicine	Artificial silk for biomedical applications		x		
Packing industry	Bio-“Plastics”, food-packing,		x		
Medicine	Elastin self-assembled matrix for implantation		x		
Medicine	Drug delivery		X		
Medicine	Tissue engineering (e.g. with Resilin <sup>10</sup> , collagen and gelatine or plant-derived globular proteins such as zein (maize protein) and soy proteins for the fabrication of tissue-engineering constructs)		X	X	X <sup>11</sup>

<sup>9</sup> The term biopolymers may be confusing as it suggests these materials being polymers in the sense of the REACH definition. However, the use of the term “polymer” in the field of advanced materials does not necessarily correspond to that definition.

<sup>10</sup> Renay S.-C. Su, Yeji Kim, Julie C. Liu (2014) Resilin: Protein-based elastomeric biomaterials. Acta Biomaterialia, Vol 10, Issue 4, 1601-1611, ISSN 1742-7061.

<sup>11</sup> Lee, Singla, and Lee, 'Biomedical Applications of Collagen'. International Journal of Pharmaceutics, Volume 221, Issues 1–2, 19 June 2001, Pages 1-22.

Sector	Use	Basic scientific research	Research on specific applications	"Recent" market introduction	Use is "common"
Textiles	Artificial silk for e.g. bulletproof vests		x		
Electronics	Protein-based bioelectronics (using elastin, silk, keratin, reflectin, collagen)		X		

### 4.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 6: Compilation of hazard and exposure information of Protein-based biopolymers

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>12</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>	Suspected immunogenicity	Little literature available
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>	Suspected immunogenicity	Little literature available
Exposure (Human)		
Exposure during use and service life of products	Invasive use as drug delivery system	
Uptake and metabolism, kinetic behaviour in humans	Distribution and degradation time of artificial proteins within a living organism may be prolonged	Little information available

<sup>12</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>12</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	Degradability, persistence and environmental interaction until degradation unclear, prolonged persistence for synthetic sequences cannot be excluded	
Transport within and between environmental compartments		

#### 4.4 Information on environmental impacts and material circularity

##### Information on environmental „value“/possible benefits and adverse impacts:

The main benefits of protein-based biopolymers in medical applications are improved materials that are better performing in and on the human body (medicinal products).

When it comes to applications with high production volumes (comparable to bulk chemicals) it is unclear how to produce sufficient organic matter as source to provide protein-based polymers without being in competition with the production of other needs based on organic/ living matter, like food/feed.

**Information on possible circularity deficits:** Protein-based biopolymers may replace existing plastic materials for some specific applications, e.g. in the packaging sector. This would reduce the use of non-biodegradable plastics (and related micro-plastics pollution).

If collection systems are in place, packaging materials could be composted.

#### 4.5 Uncertainties, lack of information

Information on the stability of protein-based biopolymers, their behaviour in the environment and the human body as well as the potential adverse effects of the building blocks (fragments) is currently insufficient for risk assessment. There is a suspicion of risks due to the fact that interactions with living cells is generally possible.

How protein-based biopolymers are covered by the present legislation and its definitions is not fully clear.

## 5 FACTSHEET: SUGAR-BASED BIOPOLYMERS

### 5.1 General information

**Synonyms:** Bionanomaterials or nanobio-materials are synonyms for the main group biopolymers, of which sugar -based polymers are a subgroup. The general term “Biomaterials” is often used considering sugar-based biopolymers, but also for entirely different materials.

**Working definition:** Sugar molecules that are designed for a specific functionality.

**Sub-groups:** Biocompatible sugar-based nanoparticles (SBNPs).

**Main building blocks, composition:** Naturally occurring monomers (sugars), usually synthetically produced.

**Structural characteristics:** Controlled polymerized sugars, some represent nanoparticles (SBNPs).

**Intended change of materials during use / intended transformation during application:** Sugar-based biopolymers are intended to change over their lifetime. Some are targeted to transform during their application (medical application), some are targeted to change (degrade) after their use (packing).

**(Combinations of) properties and related (intended) functionalities:** Sugar-based biopolymers can be very durable and they are biodegradable. They also show adhesive properties. The combination of stability and biodegradability leads to a range of applications.

**Other characteristics:** No further characteristics identified as relevant.

**Regulatory information:** It is not clear, which definition sugar-based biopolymers<sup>13</sup> fulfil. The most likely applicable definitions are: substance (in nanoform) or mixture.

### 5.2 Application(s)

Table 7: Applications of sugar-based biopolymers – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Medicine	Cancer imaging therapy, drug delivery (Nanoparticles)	x			

<sup>13</sup> The term biopolymers may be confusing as it suggests these materials being polymers in the sense of the REACH definition. However, the use of the term “polymer” in the field of advanced materials does not necessarily correspond to that definition.

Sector	Use	Basic scientific research	Research on specific applications	"Recent" market introduction	Use is "common"
Coatings and adhesives	Replacement of BPA	x			
Packing industry	Bio-"Plastics", Food-packing				x

### 5.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 8: Compilation of hazard and exposure information of sugar-based biopolymers

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>14</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>	Suspected immunogenicity	Little literature available
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>	Suspected immunogenicity	Little literature available
Exposure (Human)		
Exposure during use and service life of products	Invasive use as drug delivery system	
Uptake and metabolism, kinetic behaviour in humans	Distribution and degradation time of artificial sugars within a living organism may be prolonged	Little information available
Exposure (Environment)		

<sup>14</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>14)</sup>	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	Presumably biodegradable in most cases but persistence and environmental Interaction until degradation unclear, prolonged persistence possible	
Transport within and between environmental compartments		

## 5.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Sugar-based biopolymers show potential to replace existing (fossil) materials. Thereby, larger production volumes for applications as e.g. packaging material might reduce the need for fossil-based plastics and eventually also some of their hazardous components and additives. Further, sugar-based biopolymers like Chitosan can be applied for environmental cleaning.<sup>15</sup>

When it comes to applications with high production volumes (comparable to bulk chemicals) it is unclear how to produce sufficient organic matter as source to provide protein-based polymers without being in competition with the production of other needs based on organic/ living matter, like food/feed.

**Information on possible circularity deficits:** Replacing plastics would improve circularity, if sugar-based polymer materials were collected and separately treated/composted.

A fast degradability of sugar-based polymers, which would facilitate waste treatment and recycling, can also lead to deficits: A short life-time of products can lead to higher production rates due to higher replacement rates of materials/products.

<sup>15</sup> Hui, Ma, Pu Shengyan, Hou Yaqi, Zhu Rongxin, Zinchenko Anatoly, and Chu Wei. "A Highly Efficient Magnetic Chitosan 'Fluid' Adsorbent with a High Capacity and Fast Adsorption Kinetics for Dyeing Wastewater Purification." Chemical Engineering Journal 345 (August 2018): 556–65. <https://doi.org/10.1016/j.cej.2018.03.115>.

## 5.5 Uncertainties, lack of information

Regarding hazardous properties, the main information gap exists regarding potential effects of the materials on the immune system.

How sugar-based biopolymers are covered by the present legislation and its definitions and whether the existing guidelines for information generation and risk assessment already consider the character of the new material is not clear.

# 6 FACTSHEET: LIPID-BASED BIOPOLYMERS

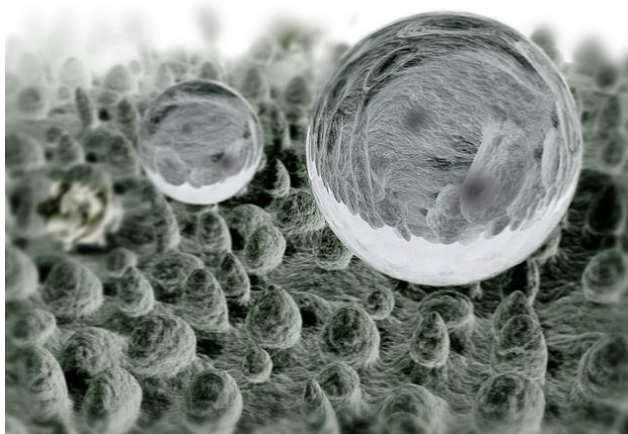


Figure 3: Effect caused by a lipid-polymer: Microscopic image of a Lotus leaf with some drops of water. From William Thielicke 2007.<sup>16</sup>

## 6.1 General information

**Synonyms:** Bionanomaterials or nanobio-materials are synonyms for the main group biopolymers, of which lipid-based biopolymers are a subgroup.

**Working definition:** Esters of fatty acids (polyester, triacylglycerides, phospholipids, cholesteryl esters).

**Sub-groups:** Further differentiation is not regarded necessary or meaningful.

**Main building blocks, composition:** Unsaturated and saturated fatty acids, glycerols, phosphate groups, cholesterol.

**Structural characteristics:** Lipid-based biopolymers are rather small with the exception of polyesters.

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<sup>16</sup> William Thielicke (2007): More pictures and bionics. Own work, Hamburg, Germany., CC BY-SA 3.0.  
<https://commons.wikimedia.org/w/index.php?curid=788207>

**Intended change of materials during use / intended transformation during application:** Except degradation no change of the polymer structure is intended in the use cases obtained so far.

**(Combinations of) properties and related (intended) functionalities:** Lipid-based biopolymers can be designed to be biocompatible and biodegradable. For medical purposes they can be designed to (passively) interact with their environment, e.g. for drug delivery and tissue engineering.

**Regulatory information:** It is not clear, which definition lipid-based polymers<sup>17</sup> fulfil. Potentially applicable definitions are: substance (in nanoform) and/or polymer, mixture or article.

**Other characteristics:** No further characteristics identified as relevant.

## 6.2 Application(s)

Table 9: Applications of lipid-based biopolymers – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Medicine	Tissue engineering by using chitosan and phospholipids				X
Medicine	<ul style="list-style-type: none"> <li>• Drug delivery by lipid-polymer hybrid nanoparticles</li> <li>• Permeable cell membranes for drug delivery using alginate and phospholipids</li> </ul>				X
Construction	Heat storage by using saturated fatty acid eutectics				X
Packaging	Food packaging using bioplastic (polyester polymer) made of cutin monomers		X		

## 6.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last

<sup>17</sup> The term biopolymers may be confusing as it suggests these materials being polymers in the sense of the REACH definition. However, the use of the term “polymer” in the field of advanced materials does not necessarily correspond to that definition.

column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 10: Compilation of hazard and exposure information of DNA-based biopolymers

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>18</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	Possible response of an organism, e.g. immune system to foreign lipids	High uncertainty – no literature available
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?	Possible response of an organism, e.g. immune system to foreign lipids  May accumulate if degradation is low	High uncertainty – no literature available
Exposure (Human)		
Exposure during use and service life of products	Food contact, invasive use as drug delivery system	
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Potentially high release rate for lipids that are used for food packaging	
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	In principle degradable, but time course is unclear due to non-natural structural motives that are possible with synthetic biopolymers. Cutin is fully degraded (hydrolysed) by soil microorganisms in $t < 1$ year. <sup>19</sup>	Information on biodegradation and persistence of lipid-based biopolymers as such is not available.
Transport within and between environmental compartments		

<sup>18</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

<sup>19</sup> De Vries H, Bredemeijer G, Heinen W. 1967. The decay of cutin and cuticular components by soil microorganisms in their natural environment. *Acta Botanica Neerlandica* 16, 102–110.

## **6.4 Information on environmental impacts and material circularity**

Information on environmental „value“/possible benefits and adverse impacts: A major benefit of lipid-based biopolymers is their biocompatibility and degradability which enables applications as drug carries and for food preservation.

Information on possible circularity deficits: Lipid-based biopolymers are in theory fully degradable and thus expected to have a rather short lifetime. However, the time course is unclear due to non-natural structural motives that are possible with synthetic biopolymers. Moreover, they will most probably be produced in small amounts for specific purposes except for packaging. If the latter are successful and substitute non-degradable materials, an improvement regarding circular economy can be expected from lipid-based biopolymers.

## **6.5 Uncertainties, lack of information**

Information on the stability of lipid-based biopolymers, their behaviour in the environment and the human body as well as the potential adverse effects of synthetic derivatives of lipids are currently insufficient for risk assessment. For natural variants biocompatibility as well as degradability can be assumed.

So far it is unclear, whether lipid-based biopolymers are covered by the present legislation (incl. their definition as polymers) and whether the existing guidelines already consider the character of the new material.

Hazards cannot be deduced based on information from the building blocks/constituents. Appropriate test methods to identify hazards are missing.

Information on uses and related emissions of lipid-based polymers as well as information on the stability/persistence (during use and disposal and/or in the environment) is scarce.

## 7 FACTSHEET: MACROSCOPIC COMPOSITES

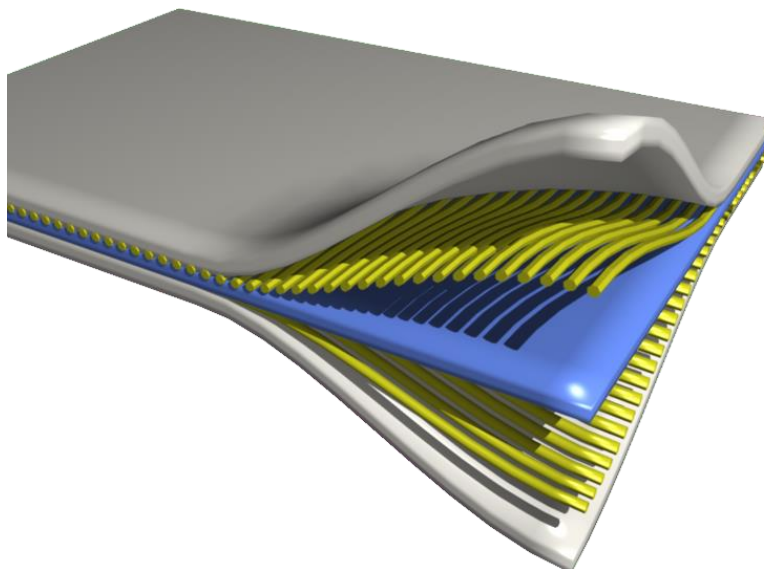


Figure 4: Schematic drawing of a macroscopic composite material. From PerOX 2009<sup>20</sup>

### 7.1 General information

**Synonyms:** None.

**Working definition:** Two or more materials combined together in macroscopic layers to form an overall structure with properties that differ from that of the individual components.

**Sub-groups:** No differentiation regarded as useful.

**Main building blocks, composition:** Various, often a combination of metallic layers, polymers, or carbon fibre mats, often including layers of adhesive material.

**Structural characteristics:** Layers of different materials are connected using adhesives, resins, welding or adhesive force.

**Intended change of materials during use / intended transformation during application:** None.

**(Combinations of) properties achieved by targeted design and related (intended) functionalities in the application:** Macroscopic composites show a huge spectrum of possible properties and related functionalities. Often, they are multifunctional or feature a new combination of functionalities. Common properties are increased elasticity, conductivity or thermal/electrical isolation.

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<sup>20</sup> Released to the public domain. Wikimedia Commons. URL: [https://commons.wikimedia.org/wiki/File:Composite\\_3d.png](https://commons.wikimedia.org/wiki/File:Composite_3d.png)

**Other characteristics:** Not identified.

**Regulatory information:** The production process could be regarded as formulation as the individual components do not react with each other. Hence the material would fulfil the definition of a mixture.

## 7.2 Application(s)

Use of macroscopic composites is widespread, thus only a few examples are included in the following table.

Table 11: Applications of macroscopic composites – examples

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Transport	Lightweight bodys for aircraft, cars etc				X
Energy	Wind turbine blades				X
Food	Food packaging				X
Medicine	Sterile packaging				

## 7.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 12: Compilation of hazard and exposure information of macroscopic composites

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>21</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		

<sup>21</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>21</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	Degradation products of filaments yield pathogenic fibres	
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?		
Exposure (Human)		
Exposure during use and service life of products	Release of fibres as either degradation products or due to mechanical stress depends on the type of application and handling (e.g. abrasive techniques)	
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)		
Transport within and between environmental compartments		

## 7.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Material savings enables large wind turbines, lightweight vehicles save on fuel.

**Information on possible circularity deficits:** Recycling is generally limited, as targeted delamination is often not possible. Shredding and use as filler materials is a frequent solution.

## 8 FACTSHEET: HYBRIDS

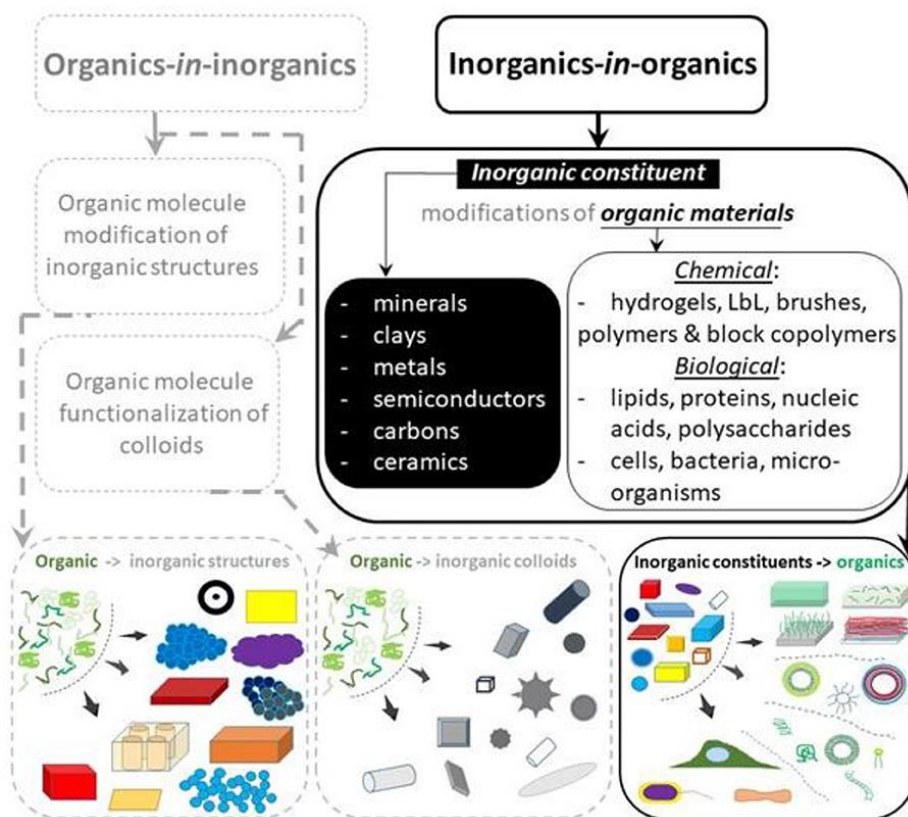


Figure 5: Classification of selected major classes of inorganic (left) and organic (right) components of hybrid materials.  
From Saveleva 2019.<sup>22</sup>

### 8.1 General information

**Synonyms:** Hybrid materials. In some definitions (cf. Figure 6) “hybrids” are only seen as a part of “hybrid materials”, when distinguished by scale (0.1 – 100 nm)<sup>23</sup>, in other studies the terms are used with a similar meaning.

**Working definition:** Hybrids are composite materials of inorganic and organic constituents, where the inorganic components are included in an organic matrix or vice-versa with predefined geometry, assembled to get new functionalities for a specific purpose. Hybrids are a subgroup of composite materials. Some definitions characterize hybrids as “sub-micron level mixture of different kinds of material” from 0.1 nm to 100 nm, e.g. Makishima 2004 cited in Nanko, 2009, p123.

<sup>22</sup> Saveleva, Mariia S., Karaneh Eftekhari, Anatolii Abalymov, Timothy E. L. Douglas, Dmitry Volodkin, Bogdan V. Parakhonskiy, und Andre G. Skirtach. „Hierarchy of Hybrid Materials—The Place of Inorganics-in-Organics in it, Their Composition and Applications”. *Frontiers in Chemistry* 7 (4. April 2019): 179.  
<https://doi.org/10.3389/fchem.2019.00179>. Licensed under CC BY.

<sup>23</sup> Nanko, Makoto. „Definitions and Categories of Hybrid Materials”. *Adv. in Tech. of Mat. and Mat. Proc. J.* 11, Nr. 1 (2009): 1–8.

**Sub-groups:** Based on the combinations of building blocks, several sub-groups could be formed; e.g. ceramic composite materials. This is not further differentiated here, because of the large number of materials. However, differentiation may be necessary to identify sub-groups of hybrids, which may require more (regulatory) attention than others (e.g. those containing heavy metals as building blocks).

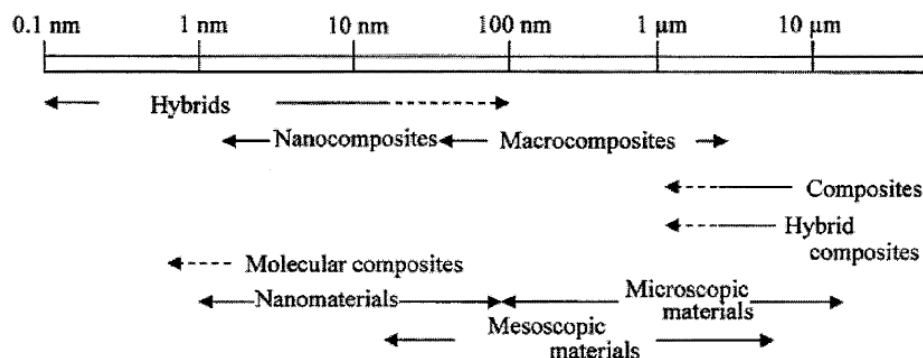


Figure 6: Classification of materials at their scale by Material Science Society, Japan, 1993<sup>24</sup>

**Main building blocks, composition:** Both, the organic and the inorganic compounds, show high diversities of substances (cf. Figure 5).

**Structural characteristics:** Compounds are connected on molecular scale, often nanoscale. The structure is chosen according to the intended functionality, e.g. segmented structures, lattice structures or sandwich construction.

**Intended change of materials during use / intended transformation during application:** In most applications hybrids do not change during use. Some applications e.g. switchable glazing intend transformation in appearance/structure, but not in the material itself.

**(Combinations of) properties achieved by targeted design and related (intended) functionalities in the application:** Hybrids show a huge spectrum of possible properties and related functionalities. Often, they are multifunctional and may feature a new property in comparison with its components. The targeted design aims to combine advantages of inorganic and organic elements.

**Other characteristics:** New types of processing, especially additive manufacturing, e.g. multi material 3D printing, is used for manufacturing of hybrids.

**Regulatory information:** The definition applicable to a hybrid material depends on how the building blocks are interlinked. If production is a synthesis (chemical reaction forming a covalent bond), the hybrid would be regarded a substance (potentially in nanoform). If one building block is rather dissolved in the matrix of the other, the definition of a mixture would apply.

<sup>24</sup> Materials Science Society of Japan, Molecular Hybridization and Hybrid Materials, Composite System in Materials, Shokabo Publishing Co., Tokyo, Japan (1993) 336-343.

## 8.2 Application(s)

Table 13: Applications of hybrids – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Medicine	Resins for dental fillings				x
Electronics	Displays		x		
Energy	Batteries, solar cells		x		
Automobile	Coatings for corrosion protection, scratch resistance			x	
Environment	Hybrid lipid membranes		x		
Consumer products	Textiles, packing		x		
Construction	Switchable glazing, isolation			x	
Optics	Antireflective, sensors			x	

## 8.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 14: Compilation of hazard and exposure information of hybrids

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>25</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		No information for hybrids as such, since different hybrids show totally different physical-chemical properties

<sup>25</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>25</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?		
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?		
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Release of building blocks depends on the type of application and handling (e.g. abrasive techniques)	Information on stability of hybrids as such not available
Release of compounds at End of Life (during disposal, combustion, recycling)	Separation and release of building blocks may happen during disposal	
Persistence (info on degradability, solubility)	Fate of nanosized building blocks will resemble the behaviour of comparable engineered nanomaterials	
Transport within and between environmental compartments	Fate of nanosized building blocks will resemble the behaviour of comparable engineered nanomaterials	

## 8.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Some applications for environmental protection are intended, e.g. membranes to clean environment.

**Information on possible circularity deficits:** Recycling might become problematic, since different materials are connected on molecular/nanoscale. This would require chemical recycling (breaking up the constituents) which is unlikely to be economic because the value of the materials is constituted by the structure rather than the contained materials. To which extent the content of hybrids in other materials and products would hinder the recycling of these materials is unclear.

## 8.5 Uncertainties, lack of information

Most materials are not yet proven to be cost efficient. The way of processing is unclear, often additive manufacturing is mentioned. Thereby, it is unclear how important the use of these materials will be in future.

Especially for construction materials, long time stability is not proven yet. Research is needed on environment, health and safety issues. Whereby the use of (eco-) toxic building blocks and circularity might be a problem.

The coverage of different regulatory definitions is unclear, i.e. whether hybrids should be considered substances or mixtures.

# 9 FACTSHEET: FIBRE-REINFORCED COMPOSITES

## 9.1 General information

**Synonyms:** No synonyms identified.

**Working definition:** Fibre-reinforced composites are composite materials, which are reinforced with fibres, often at nanoscale, i.e. objects in a size range between 1 and 100 nm in two dimensions.

**Sub-groups:** The reinforced material can be distinguished into polymer-, ceramic- and metal-matrices. Depending on the used materials, some fibre-reinforced composites also fall under the definition of hybrids.

**Main building blocks, composition:** Matrix consists of polymers, metals or ceramics. Nanoscale fibres could be carbon based (CNTs) or consist of other materials, such as silica.

**Structural characteristics:** Fibre-reinforced nanocomposites are bulk materials of a macro-size structure, which is reinforced (no implicit chemical bond, but can be) with nanofibres. Nanofibres show a high surface to volume ratio, which leads to new properties.

**Intended change of materials during use / intended transformation during application:** In general, nanocomposites are not designed to change during use. Most applications intend a high stability and long life-time.

**(Combinations of) properties and related (intended) functionalities:** (Nano)fibre-reinforced composites combine the advantages of (nano-size) fibrous material and composite materials to achieve improved physical properties, like flexibility, catalytic activity, changing reflective index, mechanical strength.

**Other characteristics:** None.

**Regulatory information:** Fibre-reinforced composites may fulfil the definition of a substance, where the matrix chemically bonds with the fibres or that of a mixture, where the fibres are dissolved in the matrix only.

## 9.2 Application(s)

Selected applications are focused on nanocomposites, since macroscopic composites have been in widespread use for decades, use is thus common and little new areas of interest are likely.

Table 15: Applications of fibre-reinforced composites – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Construction	Carbon nanotubes in metal matrix (CNT-MMC) for structural material intended high specific strength or specific thermal or electrical characteristics		x		
Military	CNT-MMC for exoskeleton protection system		x		
Military	CNT-MMC and nano-ceramics for military vehicles and armour		x		
Textiles	Natural textiles reinforced with CNT to improve mechanical properties		x		
Textiles, sporting goods	Surface-modified natural fibres to increase interfacial adhesion and enhance mechanical properties, e.g. hemp and sisal surfaces with bacterial cellulose		x		
Renewable energy (wind turbines, solar cells)	Glass fibre-reinforced composites, e.g. with CNT or graphene oxides		x		
Aerospace	Components to prevent lightning strikes			x	

## 9.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last

column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 16: Compilation of hazard and exposure information of fibre-reinforced composites

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>26</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	Fibres fulfilling the WHO definition may cause cancer or inflammation of the lung	Information on fibre-toxicology available, but as fibre risks generally appear to be insufficiently addressed by the REACH testing regime, risks of fibre-reinforced composites cannot be fully identified
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?		As fibre risks generally appear to be insufficiently addressed by the REACH testing regime, risks of fibre-reinforced composites cannot be fully identified
Exposure (Human)		
Exposure during use and service life of products	Potentially hazardous fibres may be released; mechanical stress/abrasion/weathering may further this process	
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Polymer based composites decompose under weathering; potentially hazardous fibres may be released; solubility of fibres may change under UV irradiation	Differ significantly, available for some materials
Release of compounds at End of Life (during disposal, combustion, recycling)	If there is a potential for the bulk material to decompose, potentially hazardous fibres may be released, especially during waste treatment (WHO fibres)	
Persistence (info on degradability, solubility)		
Transport within and between environmental compartments		Lack of information on dispersion

<sup>26</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

## 9.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Fibre-reinforced composites are designed to make products more durable. Thereby, they can contribute to a longer lifetime of products. In addition, they may lead to resource savings as less materials are needed, e.g. in construction, which may also lead to energy saving (light-weight construction). Whether or not these savings are balanced by the resource consumption for manufacturing fibre-reinforced composites is unclear.

**Information on possible circularity deficits:** Composite materials can hardly be separated in general. Therefore, rather the reuse of materials could be of relevance than the recycling. Even though, for some fibre-reinforced composites research focusses on possibilities for disassembly of the materials after use.

## 9.5 Uncertainties, lack of information

The durability of fibre-reinforced composites is decisive for potential risks (release of hazardous components/fibres) and the benefits from their use (longevity of products). Here, information is not available to a sufficient extent.

Regulatory uncertainty exists as fibre-reinforced composites could be considered as either mixture or substance depending on the interaction of fibre and matrix.

# 10 FACTSHEET: PARTICLE-REINFORCED COMPOSITES

## 10.1 General information

**Synonyms:** No synonyms identified.

**Working definition:** Particle-reinforced composites are composite materials, which are reinforced with nanoparticles. Nanoparticles are particles between 1 and 100 nm in all three dimensions. Many materials also contain fibres in addition.

**Sub-groups:** Magneto-active polymers.

**Main building blocks, composition:** Bulk structures/matrices (usually ceramic or polymers) reinforced with nanoparticles.

**Structural characteristics:** A main (macro-size) matrix into which nanoparticles are included. No chemical bond provided, but may be.

**Intended change of materials during use / intended transformation during application:** In general, composites are not designed to change during use. Most applications intend a high stability and long life-time.

**(Combinations of) properties and related (intended) functionalities:**

Particle-reinforced composites combine the properties of the compounds to improve e.g. their interlaminar shear strength, fracture toughness or fracture energy. Reaction to external magnetic fields can be achieved.

Their intended functionalities are often related to reduced delamination and fatigue resistance.

**Other characteristics:** mainly used in combination with fibre-reinforcement.

**Regulatory information:** According to REACH, particle-reinforced composites are most likely defined as chemical mixtures (particles are dissolved in the matrix) but may also be substances (chemical bonding between matrix and particles).

**Regulations exist for particle reinforced food packaging:** Carbon black and synthetic amorphous silicon dioxide (among several others as e.g. iron oxide or zinc oxide) are authorized as additives in their nanoform in EU Regulation No 10/2011 on plastic materials and articles intended to come into contact with food.

## 10.2 Application(s)

Applications of particles-reinforced composites are a hot topic in research but most still show a low TRL (technology readiness level).

Table 17: Applications of particle-reinforced composites – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Construction	Nanoparticles such as SiO <sub>2</sub> for enhancement of the tribological performance of polymer composites reinforced with carbon fibres or short glass fibres	x			
Construction	Nanoclay enhances thermal and flexural properties	x			
Textiles	Surface modification of empty fruit bunch fibres of oil palm with Cu nanoparticles	x			
Textiles	Flax fibre yarn with nanosized TiO <sub>2</sub> for higher shear strength or Zr=2 to reduce water uptake	x			
Hygiene	Using plant extract as reducing agent for the functionalization of microcrystalline cellulose with silver nanoparticles and	x			

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
	their reinforcement into PLA for antimicrobial activity against <i>Bacillus stearothermophilus</i>				
Food	Food contact materials (e.g. polymers with nanosilver additives, clay minerals in PET)				X
Electronics	Sensors	X			
Electronics	Actuators	X	X	X	
Microfluidics	Valves, pumps	X	X	X	
Automotive	Tires (reinforcement of elastomer matrix)				X

### 10.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 18: Compilation of hazard and exposure information of particle-reinforced composites

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>27</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity	Particles may form new nanoparticles under suitable conditions	Several studies for food contact materials <sup>28</sup>
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>		
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> </ul>		

<sup>27</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

<sup>28</sup> E.g. review study: Störmer, Bott, Kemmer, Franz: Critical review of the migration potential of nanoparticles in food contact plastics, Trends in Food Science & Technology 2017, URL: <https://doi.org/10.1016/j.tifs.2017.01.011>.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>27</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
<ul style="list-style-type: none"> <li>Bioaccumulative potential?</li> <li>ED properties?</li> </ul>		
Exposure (Human)		
Exposure during use and service life of products	Use in food and textiles may lead to ingestion/inhalation of migrated particles Mechanical stress/ abrasion/ weathering may further the release of particles	Migration outside human body is a frequent topic, human uptake is less well studied
Uptake and metabolism, kinetic behaviour in humans		Migration outside human body is a frequent topic, human uptake is less well studied
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Particles might migrate from composite to environment, especially due to mechanic stress (e.g. cutting), abrasion, or degradation of the bulk material (UV)	Several studies for food contact materials
Release of compounds at End of Life (during disposal, combustion, recycling)	Similarities to fibres in disposal likely (release during combustion or shredding)	
Persistence (info on degradability, solubility)	Depending on individual particles. Most have low solubility, some are modified to increase it	
Transport within and between environmental compartments		

## 10.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** (Nano)Particle-reinforced composites are designed to make products more durable. Thereby, they can contribute to a longer lifetime of products. They may also lead to reduced resource and energy consumption by reducing the overall volumes of materials used.

**Information on possible circularity deficits:** Composite materials can hardly be separated. Therefore, reuse of materials or components are more likely to be relevant than any recycling processes, although no viable concepts exist. Composites inadvertently introduced in recycling processes may be detrimental to the process or resulting product.

## 10.5 Uncertainties, lack of information

The durability of (nano)particle-reinforced composites is decisive for potential risks (release of hazardous components) and the benefits from their use (longevity of products). Here, information is not available to a sufficient extent.

# 11 FACTSHEET: MICROPOROUS MATERIALS

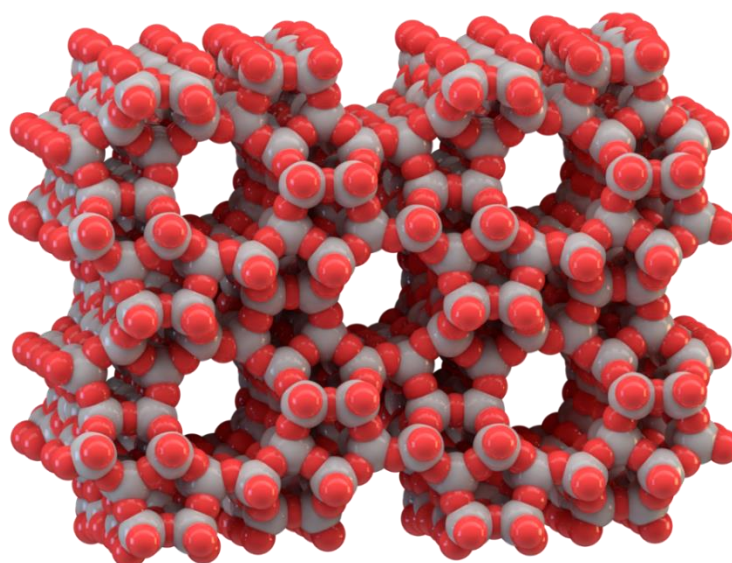


Figure 7: The microporous molecular structure of a zeolite, ZSM-5. From Splettstoesser 2015.<sup>29</sup>

## 11.1 General information

**Synonyms:** No synonyms identified.

**Working definition:** Microporous materials are bulk materials with a pore size of less than 2nm.

**Sub-groups:** Following Usman et al (2019)<sup>30</sup>, microporous polymers may be classified as follows:

- Amorphous Polymer
  - Inorganic Amorphous Polymer
    - Silica
  - Organic Amorphous Polymer

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<sup>29</sup> Wikimedia commons, <https://commons.wikimedia.org/wiki/File:Zeolite-ZSM-5-vdW.png>, own work by Thomas Splettstoesser (www.scistyle.com), Licensed under CC BY-SA 4.0

<sup>30</sup> Usman, Muhammad, Adeel Ahmed, Bing Yu, Qiaohong Peng, Youqing Shen, und Hailin Cong. „A Review of Different Synthetic Approaches of Amorphous Intrinsic Microporous Polymers and Their Potential Applications in Membrane-Based Gases Separation". European Polymer Journal 120 (November 2019): 109262. URL: <https://doi.org/10.1016/j.eurpolymj.2019.109262>.

- Hyper crosslinked polymers
- Conjugated microporous polymers
- polymers of intrinsic micro porosity
- Crystalline Polymer
  - Inorganic Crystalline Polymer
    - Zeolite
  - Organic Crystalline Polymer
    - Metal-organic Frameworks
    - Covalent-organic Frameworks

**Main building blocks, composition:** Cross-coupled solid (sometimes foam)  
3D building blocks, mostly polymers.

**Structural characteristics:** The material consists of a skeleton/structured solid and sometimes is a foam. The pores can be filled with liquids or gases (mostly air).

**Intended change of materials during use / intended transformation during application:** No change intended

**(Combinations of) properties and related (intended) functionalities:**  
Specific conductivity for and/or absorption/isolation of heat or matter, gas transport and partition due to high free volume.

**Other characteristics:** No further relevant characteristics identified.

**Regulatory information:** The materials are may be considered substances or articles under REACH.

## 11.2 Application(s)

Table 19: Applications of microporous materials – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Construction	Aerogels for heat/sound isolation				x
Energy	Metal-organic-frameworks for H <sub>2</sub> storage		x		
Laboratories / gas facilities	Polymers of intrinsic micro porosity (PIMs) gas separation				x
Medicine	Skin protection				x

## 11.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into

effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 20: Compilation of hazard and exposure information of microporous materials

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>31</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity	High surface-to-volume-ratio	
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>		Building blocks that are polymers are currently exempted from REACH registration; therefore a lack of hazard information is likely
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>		Building blocks that are polymers are currently exempted from REACH registration; therefore a lack of hazard information is likely
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)		
Transport within and between environmental compartments		

<sup>31</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

## 11.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Some are used as adsorbent for environmental protection.

**Information on possible circularity deficits:** Recyclability heavily depending on building blocks.

## 11.5 Uncertainties, lack of information

To the knowledge of the authors, information on possible hazards is currently not available. Especially for biomedical applications a lack clinical trials and in vivo screening in general is present.

# 12 FACTSHEET: MESOPOROUS MATERIALS

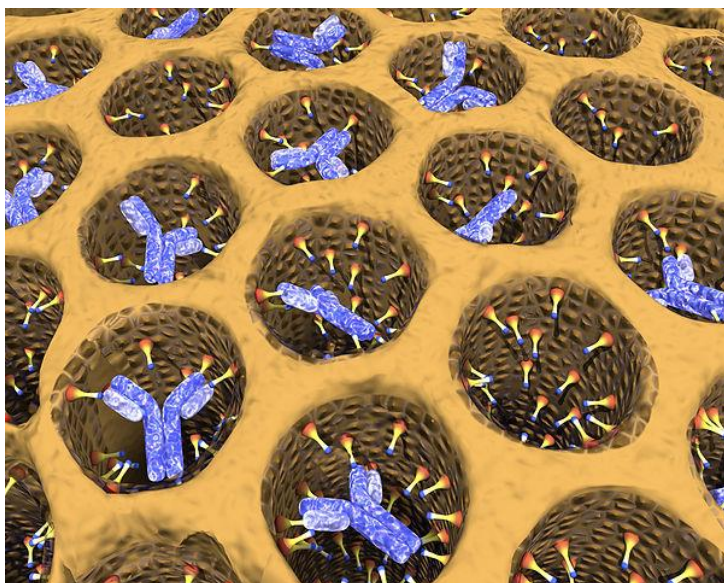


Figure 8: Mesoporous silica (orange) loaded with antibodies for medical application. From ENERGY.GOV 2014.<sup>32</sup>

## 12.1 General information

**Synonyms:** No synonyms identified.

**Working definition:** Mesoporous materials are bulk materials with a pore size of 2 nm to 50 nm.

<sup>32</sup> ENERGY.GOV (2014): Wikimedia Commons. URL: <https://commons.wikimedia.org/w/index.php?curid=34550762>

**Sub-groups:** Not defined.

**Main building blocks, composition:** Cross-coupled solid (sometimes foam)  
3D building blocks, from a variety of substances (metal-oxides, silica, alumina, carbon).

**Structural characteristics:** The material consists of a skeleton/structured solid and sometimes is a foam; pore size between 2nm and 50 nm.

**Intended change of materials during use / intended transformation during application:** No change intended.

**(Combinations of) properties and related (intended) functionalities:**  
Electronic conductivity, large surface area, chemical and electrochemical stability, high life-time and coulombic efficiency.

**Other characteristics:** No further relevant characteristics identified.

**Regulatory information:** A decision of which REACH definition applies requires a specific assessment of the composition which was not possible in the context of the project. Possibly applicable definitions are substance or article.

## 12.2 Application(s)

Table 21: Applications of mesoporous materials – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Electronics	Mesoporous carbons for supercapacitors in energy storage, hybrid vehicles and flexible electronics			x	
Medicine, food industry, buildings	Activated Carbon for absorption and filtering				x
Medicine	Mesoporous silica for catalysis, drug delivery and imaging for biosensors		x		

## 12.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 22: Compilation of hazard and exposure information of mesoporous materials

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>33</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	Mesoporous silica (nanoparticles) can pass through cell walls	Building blocks that are polymers are currently exempted from REACH registration; therefore a lack of hazard information is likely
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?		Building blocks that are polymers are currently exempted from REACH registration; therefore a lack of hazard information is likely
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	For some mesoporous materials high stability can be expected	
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	Some compounds may have low degradability	
Transport within and between environmental compartments		

## 12.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** May be used in environmental protection measures (adsorbant, filtration, removal of specific pollutants through functionalization).

<sup>33</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

**Information on possible circularity deficits:** Recyclability unclear and heavily depending on building blocks.

## 12.5 Uncertainties, lack of information

To the knowledge of the authors, information on possible hazards is currently not available. Especially for biomedical applications a lack clinical trials and in vivo screening in general is present.

# 13 FACTSHEET: MACROPOROUS MATERIALS

## 13.1 General information

**Synonyms:** No synonyms identified.

**Working definition:** Macroporous Materials are bulk materials with a pore size of over 50nm.

**Sub-groups:** Not defined.

**Main building blocks, composition:** Cross-coupled mostly solid (mineral based, glasses)<sup>34</sup>, sometimes foam, 3D building blocks.

**Structural characteristics:** The material consists of a skeleton/structured solid (sometimes a foam); pore size over 50 nm.

**Intended change of materials during use / intended transformation during application:** No change intended.

**(Combinations of) properties and related (intended) functionalities:** Network strength, create anisotropy and directionality within the networks.

**Other characteristics:** No further relevant characteristics identified.

**Regulatory information:** A decision of which REACH definition applies requires a specific assessment of the composition which was not possible in the context of the project. Possibly applicable definitions are substance or article.

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<sup>34</sup> Soler-Illia, Galo J. de A. A., Clément Sanchez, Bénédicte Lebeau, and Joël Patarin. "Chemical Strategies To Design Textured Materials: From Microporous and Mesoporous Oxides to Nanonetworks and Hierarchical Structures." *Chemical Reviews* 102, no. 11 (November 2002): 4093–4138. <https://doi.org/10.1021/cr0200062>.

## 13.2 Application(s)

Table 23: Applications of macroporous materials – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Medicine	Tissue engineering and drug delivery		X		
Environmental protection	Filtration and sorption of environmental pollutants		X		
Medicine	Macroporous scaffolds for bone repair		X		

## 13.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 24: Compilation of hazard and exposure information of macroporous materials

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>35</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>		Lack of clinical trials and in vivo screening for biomedical applications
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>		

<sup>35</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>35</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties)
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	For some macroporous materials high stability expected	
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	Many used compounds have low degradability	
Transport within and between environmental compartments		

### 13.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** May be used in environmental protection measures such as water treatment.

**Information on possible circularity deficits:** Recyclability unclear and heavily depending on building blocks.

### 13.5 Uncertainties, lack of information

Market size is unclear, because of challenges in scale- up and reproducibility of various production methods.

For biomedical applications a lack of clinical trials and in vivo screening in general is present.

## 14 FACTSHEET: ELECTROMAGNETIC METAMATERIALS

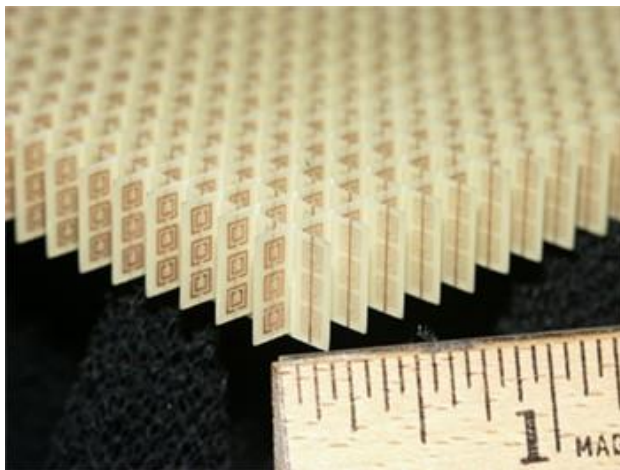


Figure 9: A metamaterial split ring resonator array for microwave radiation. From NASA Glenn Research 2006.<sup>36</sup>

### 14.1 General information

**Synonyms:** Dielectric metamaterials (as a subgroup), photonic metamaterials (as a subgroup).

**Working definition:** Electromagnetic Metamaterials are materials, which respond to electric and magnetic fields. Their electromagnetic properties go beyond naturally occurring materials. They are able to modify the phase and amplitude of incoming radiation in a fraction of a wavelength.

**Sub-groups:** Dielectric metamaterials (radio and microwave frequencies), photonic metamaterials (for wavelength between 400 nm and 700 nm), one-dimensional (layers), two-dimensional (production via photolithography or drilling) or three-dimensional (drilling from different angles, tacking of 2-D layers, self-assembly).

**Main building blocks, composition:** Small units of structured composite materials of several compositions, e.g. semi-conductors, glasses, polymers, silver or gold.

**Structural characteristics:** Made from assemblies of multiple elements fashioned from composite materials in repeating patterns at scales that are smaller than the wavelengths of the electromagnetic waves they influence.

**Intended change of materials during use / intended transformation during application:** Change is not intended.

**(Combinations of) properties and related (intended) functionalities:** Possible targeted properties are negative or non-linear refractive indices to

<sup>36</sup> Released to the public domain, Wikimedia Commons. URL: [https://commons.wikimedia.org/wiki/File:Split-ring\\_resonator\\_array\\_10K\\_sq\\_nm.jpg](https://commons.wikimedia.org/wiki/File:Split-ring_resonator_array_10K_sq_nm.jpg).

create new electro-magnetic functionalities like negative permittivity and very high or negative magnetic permeability.

**Other characteristics:** No further characteristics identified as relevant.

**Regulatory information:** Electromagnetic metamaterials could fall under the definition of a mixture or article. As the building blocks are composites, the definition of a substance is most likely not applicable.

## 14.2 Application(s)

There is an existing metamaterials market from a financial view reaching \$448.0 million in 2018 at a compound annual growth rate of 32.0% from 2018 to 2023 (McWilliams, 2018<sup>37</sup>). Nevertheless, there is an existing lack of knowledge when it comes to actual sales of metamaterials. The share of electromagnetic materials in these sales is not known.

The theoretical and experimental study of electromagnetic metamaterials gained impetus in the last 20 years.

Table 25: Applications of electromagnetic metamaterials – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Electronics	Antennas			X	
Electronics	Electromagnetic absorber		X		
Optics	Superlenses		X		
Electronics	Sensors for non-destructive material analyses		X		
Optics	Superlenses		X		
Military	Cloaking			Working prototype	

## 14.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

<sup>37</sup> McWilliams, Andrew (2018): Metamaterials: Technologies and Global Markets. BCC Research Report Overview.

Table 26: Compilation of hazard and exposure information of electromagnetic metamaterials

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>38</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity	Reactivity is not intended, activity is possible	
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	If building blocks are nanomaterials: Toxicity or particle effects of the constituting nanomaterials; information may be available to a lesser extent than for macroscale substances	Unclear whether or not the building blocks are hazardous or not
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?	If building blocks are nanomaterials: Ecotoxicity or particle effects of the constituting nanomaterials; information may be available to a lesser extent than for macroscale substances	Unclear whether or not the building blocks are hazardous or not
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Finely structured surfaces may be subject to abrasion, which may lead to unintended release	
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)		
Transport within and between environmental compartments		

<sup>38</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

## 14.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** The currently identified potential uses of electromagnetic metamaterials are not directly related to improving the environmental performance of a product or material and hence do not immediately reduce any environmental loads. However, electromagnetic metamaterials may improve the performance of existing products/materials or enable novel products and functionalities, which may indirectly also lead to environmental benefits. Semiconductor building blocks may require the use of critical raw materials, like rare earth materials.

The production of electromagnetic metamaterials may require high energy inputs, which are unlikely to be recoverable. It is unclear, whether or not the metamaterials are stable enough to survive the disposal. A separation into building blocks and their recovery from waste appears not to merit the effort.

**Information on possible circularity deficits:** Recycling/Reuse of metamaterials is generally unlikely, because their properties are derived from high level of structuring, which is most likely destroyed upon removal of the metamaterial from its “host application”.

## 14.5 Uncertainties, lack of information

There are information gaps and uncertainties regarding the stability of the materials, which are both important to identify hazard potentials and potential exposure levels as well as environmental benefits and possibilities to recover intact structures from wastes.

The use of nanomaterials as building blocks suggests that hazard assessment should be derived from the respective nanomaterials, where generally the information availability on their potential specific fate and effects is lower. This may give rise to concern. It is unclear which regulatory definition electromagnetic metamaterials fulfil.

## 15 FACTSHEET: ACOUSTIC METAMATERIALS

### 15.1 General information

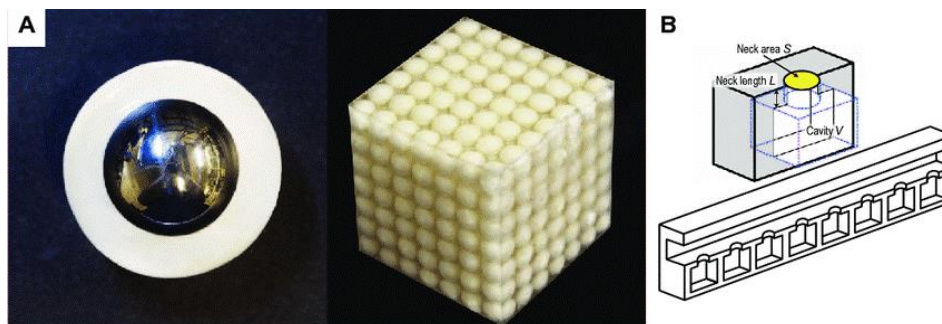


Figure 10: Acoustic metamaterial exhibiting a local resonance-induced anomalous mass effect. Left: unit cell consisting of a small metallic sphere coated by a thin uniform layer of silicone rubber (diameter: 1.55 cm). Right: complete sample. From Ma and Sheng 2016<sup>39</sup>

**Synonyms:** No synonyms identified.

**Working definition:** Acoustic metamaterials are artificial materials which are designed to achieve novel physical properties, which go beyond properties observed in nature. The assemblies of multiple elements fashioned from composite materials affect sound waves as occurring in gaseous, liquid or solid phases.

**Sub-groups:** No sub-groups identified as relevant.

**Main building blocks, composition:** Small units of structured composite materials from various composition, including metals and organic materials.

**Structural characteristics:** Assemblies of multiple elements in repeating patterns at scales that are smaller than the wavelengths of the sound waves they should influence. They can be one, two or three dimensional. The basic unit of an acoustic metamaterial usually is a mass-in-mass unit cell.

**Intended change of materials during use / intended transformation during application:** Change is not intended.

**(Combinations of) properties and related (intended) functionalities:** Intended functionalities are vibration mitigation and isolation, impact absorption and wave guides.

**Other characteristics:** No further characteristics identified as relevant.

**Regulatory information:** Acoustic metamaterials could fall under the definition of a mixture or article. As the building blocks are composites, the definition of a substance is most likely not applicable.

<sup>39</sup> Ma, Guancong & Sheng, Ping. (2016): "Acoustic metamaterials: From local resonances to broad horizons". Science Advances. 2. e1501595. 10.1126/sciadv.1501595. published under CC BY-NC.

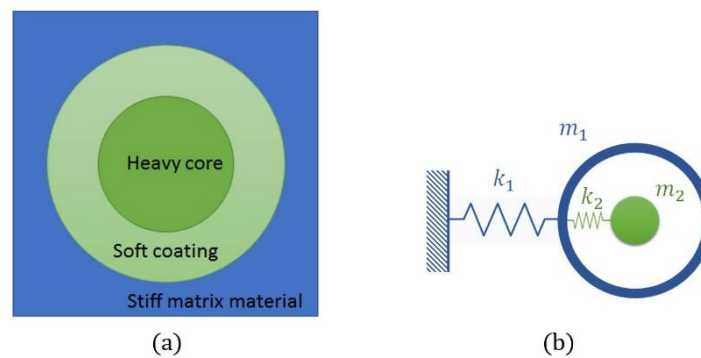


Figure 11: Schematic of a 1D acoustic material, with  $m$  = mass and  $k$  = coupling constant (Comi and Driemeier, 2018)<sup>40</sup>

## 15.2 Application(s)

There is an existing metamaterials market from a financial view reaching \$448.0 million in 2018 at a compound annual growth rate of 32.0% from 2018 to 2023 (McWilliams, 2018 ). Nevertheless, there is a lack of knowledge when it comes to actual sales of metamaterials. Due to no available information, it is assumed that the volume comprises not only sales, but especially research volume.

There is currently no known market of an acoustic metamaterial.

Table 27: Applications of Acoustic Metamaterials – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Construction	Seismic protection		X		
	Sound filtering		X		
Construction	Vibration control technologies		X		
Military	Sound cloaking			Working prototype	
Construction	Thermal insulation		X		

## 15.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the

<sup>40</sup> Comi, Claudia, & Driemeier, Larissa. (2018). Wave propagation in cellular locally resonant metamaterials. Latin American Journal of Solids and Structures, 15(4), e38. Epub June 04, 2018. <https://doi.org/10.1590/1679-78254327>, published under CC BY

reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 28: Compilation of hazard and exposure information of acoustic metamaterials

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>41</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>		
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>		
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)		
Transport within and between environmental compartments		

## 15.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** The currently identified potential uses of acoustic materials are not directly related to improving the environmental performance of a product or material and hence do not immediately reduce any environmental loads.

<sup>41</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

However, acoustic metamaterials may improve the performance of existing products/materials or enable novel functionalities, which may indirectly also lead to environmental benefits.

The production of acoustic metamaterials may require high energy inputs, which are unlikely to be recoverable.

**Information on possible circularity deficits:** Recycling/reuse of acoustic metamaterials would require maintaining the complex metastructure during waste collection and recovery. It is unclear, whether or not they are stable enough to survive the disposal. A separation into building blocks and their recovery from waste appears not to merit the effort.

### 15.5 Uncertainties, lack of information

There are information gaps and uncertainties regarding the stability of the materials, which are both important to identify hazard potentials and potential exposure levels as well as environmental benefits and possibilities to recover intact structures from wastes.

It is unclear how acoustic metamaterials are regulated, as the applicability of (REACH) definitions is ambiguous.

## 16 FACTSHEET: QUANTUM DOTS

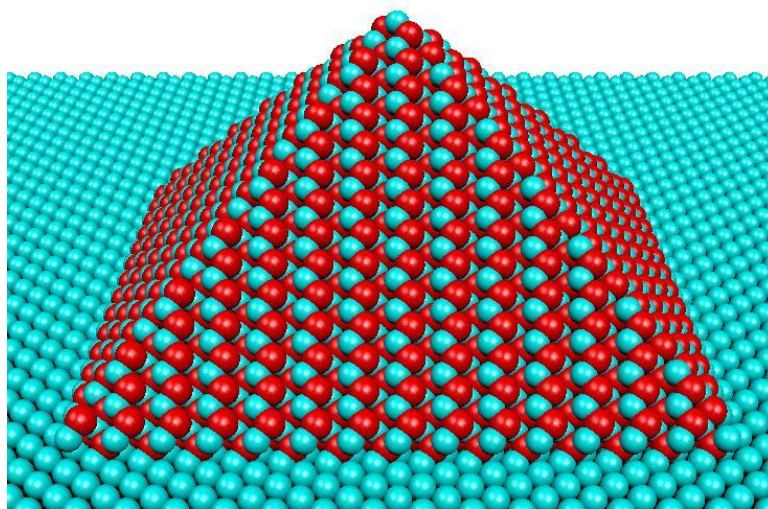


Figure 12: Idealized pyramidal In/As quantum dot. From Alexander Kleinsorge (2008)<sup>42</sup>

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<sup>42</sup> Wikimedia commons, URL: <https://commons.wikimedia.org/wiki/File:QD-pyramide.JPG>, work by Alexander Kleinsorge, Licensed under GFDL

## 16.1 General information

**Synonyms:** Semiconductor nanocrystals.

**Working definition:** Semiconducting nanoparticles with optical and electronic properties differing from macroscopic systems (quantum confinement effects depend on the size of the particle).

**Sub-groups:** Differentiation into sub-groups not regarded necessary or meaningful.

**Main building blocks, composition:** Binary compounds (e.g. CdSe, PbS, CdS, CdTe), ternary compounds (e.g. CdSeS, InGaAs), silicon, germanium, carbon.

**Structural characteristics:** 5-50 nm sized particles arranged in a regular order on a substrate or kept in suspension, they may have core and shell.

**Intended change of materials during use / intended transformation during application:** Quantum dots can absorb and (re)emit light, change conductivity depending on external stimulus (e.g. electric field, light).

**(Combinations of) properties and related (intended) functionalities:**

Tuneable optical and electrical characteristics (particle size controls bandgap which defines e.g. the fluorescence spectrum) as opposed to 'classical' semiconductors with fixed bandgap

**Other characteristics:** Can be coated with a bioactive coating for use in biological environments

**Regulatory information:** Quantum dots fulfil the definition of a substance in nanoform under REACH. Currently, no registration of a quantum dot is known to the authors. This most likely due to the production process not being perceived as a substance manufacturing. In addition, it is possible that even if the production of the quantum dot is perceived as a manufacturing, the registration threshold<sup>43</sup> is not met. Hence, it seems that no hazard and exposure information is currently available in the REACH database of registered substances.

The constituent substances used to synthesise the quantum dots are partly regulated, e.g. Cd or Pb at EU level due to their very hazardous properties.

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<sup>43</sup> This may be the case if no manufacturing of the substance takes place in other contexts.

## 16.2 Application(s)

Table 29: Applications of quantum dots – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Chemistry	Photocatalysts	x	x		
Chemistry	Fluorescent markers				X
Electronics	LED, displays				x
Electronics	Photodetectors		x		
Electronics	Transistors, quantum computing	x			
Electronics	Spintronics (e.g. magnetic memory devices)	x			
Energy	Photovoltaic cells	x			
Medicine	Marker, drug transport	x			

## 16.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 30: Compilation of hazard and exposure information of quantum dots

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>44</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>Indications for toxicity and other health hazards?</li> </ul>	Depending on type, quantum dots may be cytotoxic. Some constituent substances are highly toxic.	

<sup>44</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>44</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
<ul style="list-style-type: none"> <li>CMR/ED properties?</li> </ul>	Quantum dots may affect cell growth and viability.	
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>Bioaccumulative potential?</li> <li>ED properties ?</li> </ul>	Depending on type, quantum dots may be cytotoxic.	
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans	Unintentional uptake is possible as aerosol, solution; medical administration is planned Little information about kinetic behaviour is available, depending on size and coatings high mobility is likely. Accumulation in organs is likely.	
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	While most quantum dot cores are chemically stable, coatings can be affected by photolysis and oxidation.	
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	Depending on type, quantum dots can be highly persistent in vivo (several years). Persistence in ecosystems is dependent on type and conditions. Depending on the synthesis process, quantum dots have high solubility (colloidal solutions), are easy to disperse (powder), or strongly bonded to a macroscopic substrate. Behaviour is dependent on coating (if present).	
Transport within and between environmental compartments		

## 16.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Use for improved photovoltaics is planned, possible visible light photocatalysts for CO<sub>2</sub> reduction. It is likely that energy production from photovoltaic applications will justify the high resource consumption for the production of quantum dots, especially if scarce resources can be replaced.

**Information on possible circularity deficits:** While widespread use of quantum dots in chemical analysis and electronics is to be expected, effective material amounts are comparatively small. Retrieval of quantum dots from applications is technically challenging (i.e. loss of materials and/or potential contamination of material streams with hazardous substances).

## 16.5 Uncertainties, lack of information

Information on the toxicity and behaviour of quantum dots is partly available suggesting that some of these potentially pose risks. Also, the uses of quantum dots are comparably well known. The very high variability in types and designs may create the need for further differentiation.

# 17 FACTSHEET: SUPRAPARTICLES

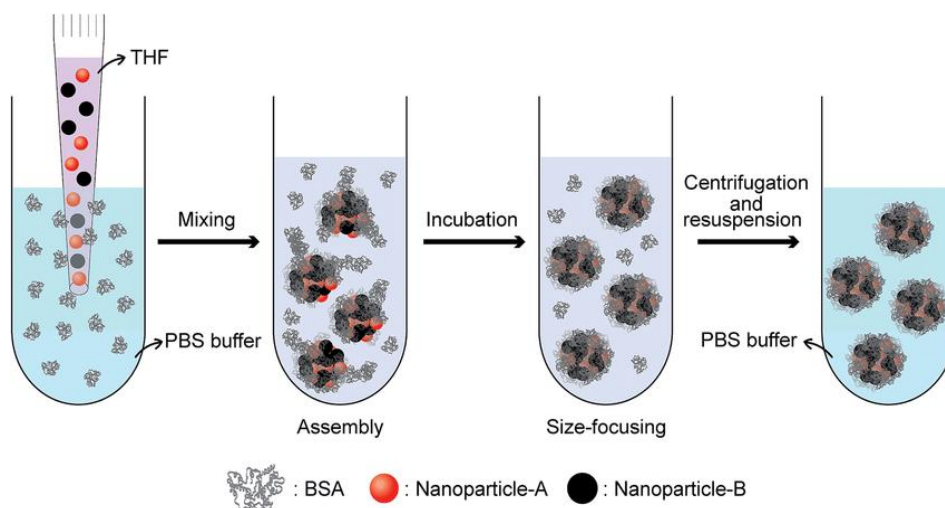


Figure 13: Schematic of the formation process of supraparticle co-assemblies suggested by experimental results. From Yu et al. 2019.<sup>45</sup>

BSA = Bovine serum albumin, THF = Tetrahydrofuran (solvent), PBS = Phosphate buffered saline

## 17.1 General information

**Synonyms:** Superparticular systems, superstructures, colloidal molecules, supercolloids, hierarchical organized matter, 3D-architected materials.

**Working definition:** Clusters of nanoparticles which form defined, self-assembled structures.

**Sub-groups:** Sub-groups could be formed based on the constituting materials.

<sup>45</sup> Yu, Xiaoya & Liu, Xiao & Ding, Wanchuan & Wang, Jun & Ruan, Gang. (2019). Spontaneous and instant formation of highly stable protein–nanoparticle supraparticle co-assemblies driven by hydrophobic interaction. *Nanoscale Advances*. 10.1039/C9NA00328B.

Main building blocks, composition: Dispersed nanoparticles.

**Structural characteristics:** Dispersed clusters of nanoparticles which form defined structures with a consistent structural motif amongst all particles between nano- and macroscale. The functionality is enabled through cooperative interplay of nanosized building blocks.

**Intended change of materials during use / intended transformation during application:** Triggered decomposition when used as drug carriers.

**(Combinations of) properties and related (intended) functionalities:** Magneto-responsivity, dynamically changing electrical properties.

**Other characteristics:** Extremely wide array of applications from simple (encapsulation of drugs as carriers) to highly complex (light driven in situ assembly of micro-lenses).

**Regulatory information:** A decision on which of the REACH definitions apply requires an assessment of the composition and structure, in particular the mechanism of self-assembly and resulting bonds. Different supraparticles may fulfil different definitions. Potentially applicable definitions are: substance, substance in nanoform or mixture.

## 17.2 Application(s)

Table 31: Applications of supraparticles – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Construction	Functional fillers		X		
Environmental	Cleaning agents		X		
Chemistry, Medicine	Tracers, Markers		X		
Electronics	Actuators		X		
Construction	Modifiers for surface effects		X		
Construction	Modifying agent for mechanical properties		X		
Chemistry	Catalysts	X			
Medicine	Drug carriers		X		
Electronics	Sensors		X		
	Combined uses	X			

### 17.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 32: Compilation of hazard and exposure information of supraparticle

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>46</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ ...)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity	Depending on intended use – e.g. catalysts may trigger unexpected reactions	
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	Accounting for their potential degradation, hazardous properties of the constituent nanoparticles should be considered here	
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?	Accounting for their potential degradation, hazardous properties of the constituent nanoparticles should be considered here	
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Destabilization of supraparticles expected. Effect of individual nanoparticles needs to be considered	
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	Persistence of supraparticle probably low, their nanoscale parts may have high persistence	

<sup>46</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>46</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ ...)
Transport within and between environmental compartments		

## 17.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Supraparticles can be used in applications for environmental protection, e.g. cleaning. High efficiency building materials can lead to less material use. There is no information on necessary energy input available yet.

**Information on possible circularity deficits:** Circularity benefits or deficits are strongly depending on the individual application. Deliberate destabilization or aggregation may be possible. Removal might be possible, though economically unattractive.

## 17.5 Uncertainties, lack of information

The durability of supraparticles is decisive for potential risks (release of hazardous components). Here, information is not available to a sufficient extent. (Eco)toxicological studies are not available.

## 18 FACTSHEET: NANOFLOWERS

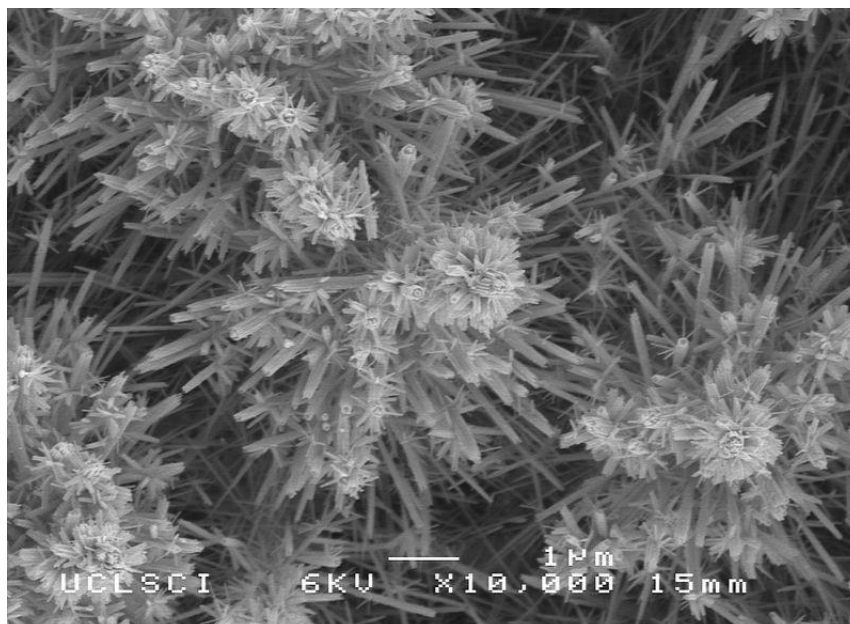


Figure 14: Scanning electron microscope picture of nanostructured tungsten oxide supported gold nanoparticle nanoflowers. From Anara Molkenova 2011.<sup>47</sup>

### 18.1 General information

**Synonyms:** Nanobouquets, nanotrees, nanomeadow, organic-inorganic hybrid nanoflowers (HNFs).

**Working definition:** Nanometer-sized structures which resemble flowers.

**Sub-groups:** No meaningful subgroups identified.

**Main building blocks, composition:** Mostly binary compounds (e.g. MnO, SiC, TiO<sub>2</sub>).

**Structural characteristics:** Extremely high surface area, highly porous.

**Intended change of materials during use / intended transformation during application:** Ion exchange – adsorption and release.

**(Combinations of) properties and related (intended) functionalities:** High surface to volume ratio.

**Other characteristics:** Structures are grown on various substrates (metal foil, PET foil, proteins).

**Regulatory information:** Nanoflowers most likely fulfil the definition of substances in nanoform.

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<sup>47</sup> Licensed under CC BY-SA 4.0, URL: <https://commons.wikimedia.org/wiki/File:Nanoflowers.jpg>

## 18.2 Application(s)

Table 33: Applications of nanoflowers – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Electronics	Supercapacitors	X	X		
Medicine	Enzyme carriers, biosensors	X	X		
Medicine	Catalyst (cancer treatment)	X			
Environment	Filters	X			

## 18.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 34: Compilation of hazard and exposure information of nanoflowers

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>48</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity	High surface may cause unintended interactions, e.g. catalytic effects	
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	Most, currently used substances indicate low toxicity. Preparation is sometimes done under extreme conditions were toxic by-products may form	
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties ?	Most, currently used substances indicate low toxicity. Depending on the used elements an application where ion release is possible increases the toxic potential; Preparation is sometimes done under extreme conditions were toxic by-products may form	

<sup>48</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>48</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans	Little information about kinetic behaviour is available, depending on size and form high mobility is likely	
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Nanoflowers are described as highly stable, depending on synthesis process Deliberate instabilities are created as part of some applications	
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	Some nanoflowers are designed for high solubility using coatings	
Transport within and between environmental compartments		

## 18.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Release of nanoflowers used in health treatment to the environment is likely due to their uses as „isolated particles“. Possible applications in the energy sector may reduce the resource footprint of energy storage devices.

**Information on possible circularity deficits:** Use of nanoflowers in pharmaceuticals does not result in wastes for circulation. Recuperation of the nanoflowers with intact surface structures is technically challenging and the practical realization appears unlikely, even for high value materials.

## 18.5 Uncertainties, lack of information

Structural stability in intended applications and the environment is currently unknown. High surface area may cause unintended effects such as catalytic change of substances or immune response.

## 19 FACTSHEET: GRAPHENE

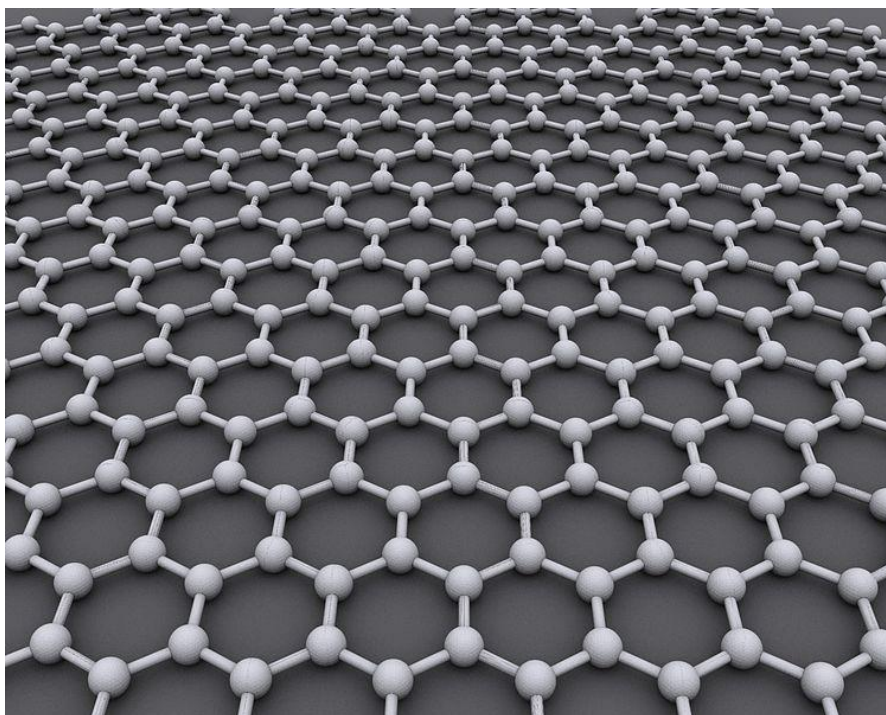


Figure 15: Idealized graphene structure. From AlexanderAIUS 2010,<sup>49</sup>

### 19.1 General information

**Synonyms:** Exfoliated graphite.

**Working definition:** Single layer of carbon atoms with each atom bound to three neighbours in a honeycomb structure<sup>50</sup>.

**Sub-groups:** Differentiation into sub-groups not regarded necessary or meaningful.

**Main building blocks, composition:** Carbon.

**Structural characteristics:** Single layer of carbon atoms in a two-dimensional hexagonal lattice in which one atom forms each vertex; two dimensional material.

**Intended change of materials during use / intended transformation during application:** Applications with energy transformation exist, e.g. graphene plasmons, organic semiconductors.

**(Combinations of) properties and related (intended) functionalities:** Low density, high strength, high conductivity, high transparency.

**Other characteristics:** Chemically stable, not biodegradable, hydrophobic.

<sup>49</sup> Wikimedia Commons. Licensed under CC BY-SA 3.0, URL: <https://commons.wikimedia.org/wiki/File:Graphen.jpg>

<sup>50</sup> ISO 80004-3

**Regulatory information:** Graphene is considered a substance according to REACH. It is registered in the tonnage band of 10 to 100 t/a. Consequently, some information on the toxicity is available, whereas the data on higher tier testing are lacking. The REACH registrants do not classify graphene as hazardous under the CLP regulation.

## 19.2 Application(s)

In 2013 the Graphene Flagship Consortium was launched with a €1 billion EU grant to explore and promote applications of graphene. This led to the identification of hundreds of possible applications. In the following table only several larger areas will be highlighted.

Table 35: Applications of graphene – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Electronics	Wearables	X	X		
Electronics	Supercapacitors	X			
Energy	Batteries	X			
Energy	Solar cells	X	X		
Energy	Heating/cooling	X	X		
	Composites	X	X		
Various	(Bio)sensors	X			
Medicine	Drug delivery	X			
Medicine	Contrast agents	X	X		
Medicine	Neural interfaces	X			

## 19.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 36: Compilation of hazard and exposure information of graphene

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>51</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity	The high surface area of graphene sheets facilitates adsorption of other substances, which may increase (unintended) interactions with the environment.	
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	Graphene sheets with sharp edges may induce direct physical damage to cells. Toxicity of graphene is dependent on the shape, size, purity, post-production processing steps, oxidative state, functional groups, dispersion state, synthesis methods; Initial starting materials and the methods used in the production as well as post-synthesis production steps could result in the presence of metallic impurities and oxidative debris in the final product, which could result in variable toxicity effects	
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties ?	Graphene is phytotoxic and significantly inhibits plant growth and biomass production. Toxicity of graphene is dependent on the shape, size, purity, post-production processing steps, oxidative state, functional groups, dispersion state, synthesis methods <sup>52</sup> ; Initial starting materials and the methods used in the production as well as post-synthesis production steps could result in the presence of metallic impurities and oxidative debris in the final product, which could result in variable toxicity effects Accumulation in organisms and along the food chain is likely <sup>53</sup>	
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans	The morphology, shape and size of graphene nanoparticles could influence their cellular uptake characteristics whereas presence of functional groups can alter their interactions with proteins, biomolecules and micronutrients. Regardless of exposure route, graphene sheets can be found in multiple organs with relatively large persistence.	

<sup>51</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

<sup>52</sup> Lalwani, Gaurav et al. "Toxicology of graphene-based nanomaterials." *Advanced drug delivery reviews* vol. 105,Pt B (2016): 109-144. doi:10.1016/j.addr.2016.04.028

<sup>53</sup> Shipeng Dong et al: Bioaccumulation of 14C-Labeled Graphene in an Aquatic Food Chain through Direct Uptake or Trophic Transfer. *Environmental Science & Technology* 2018 52 (2), 541-549 DOI: 10.1021/acs.est.7b04339

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>51</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	While graphene sheets are chemically highly stable, physical damage to the edges is possible and may result in changes of the shape or separation of parts of a sheet.	
Release of compounds at End of Life (during disposal, combustion, recycling)	Graphene burns at temperatures above 350°C but may form more stable compounds during heating. Graphene nanoparticles may be released during burning of products reinforced with said particles. Electrostatic removal is hindered due to graphene's high conductivity.	
Persistence (info on degradability, solubility)	Probably high degradation time in environmental compartments. Graphene is insoluble in water and organic solvents. Graphene oxide and other modifications are soluble in polar solvents.	
Transport within and between environmental compartments		

## 19.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Multiple applications in energy systems (PV, energy storage), possible organic substitute for hazardous inorganic compounds and allowing more limited resource use in electronics.

**Information on possible circularity deficits:** Recycling processes are under development, e.g. conditioning of electrodes as reinforcing filler.

## 19.5 Uncertainties, lack of information

Compared to other advanced materials, a relatively high amount of information is available.

Long term behaviour in biological systems is not known. High chemical stability, resulting in high persistence, as well as high potential for chemical interactions due to the large surface area make predictions of the behaviour difficult.

## 20 FACTSHEET: ORGANIC FIBRES

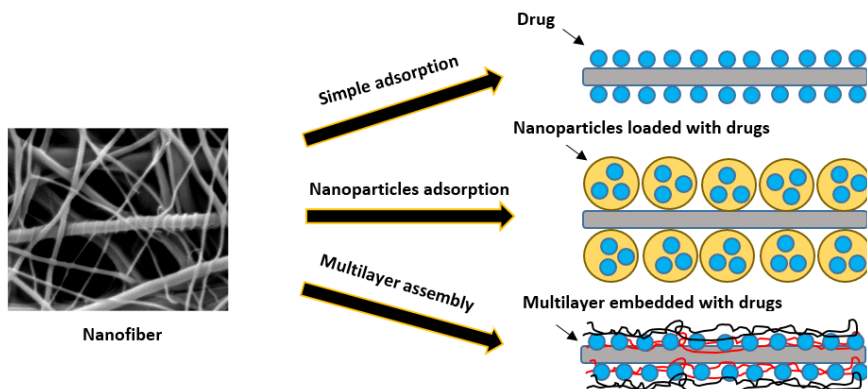


Figure 16: Different ways to load drugs on a nanofibre. From Parksoh17 2017. <sup>54</sup>

### 20.1 General information

**Synonyms:** Polymer (nano)fibres.

**Working definition:** Fibres several  $\mu\text{m}$  or smaller in diameter consisting of polymers.

**Sub-groups:** Natural polymer-based fibres, synthetic polymer based fibres.

**Main building blocks, composition:** Polymer chains connected via covalent bonds.

**Different polymers are used, some examples:** collagen, cellulose, polylactic acid, polyurethane.

**Structural characteristics:** Oriented or randomly-oriented fibres.

**Intended change of materials during use / intended transformation during application:** Biodegradation.

(Combinations of) properties and related (intended) functionalities: High stiffness and/or high tensile strength, biocompatibility.

Other characteristics: No further characteristics identified as relevant.

Regulatory information: Organic fibres most likely fulfil the definition of a substance.

<sup>54</sup> Wikimedia Commons. Licensed under CC BY-SA 4.0, URL:  
[https://commons.wikimedia.org/wiki/File:Drug\\_delivery\\_diagram.png](https://commons.wikimedia.org/wiki/File:Drug_delivery_diagram.png)

## 20.2 Application(s)

Table 37: Applications of organic fibres – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Energy	Electrodes for fuel cells/batteries				
Electronics	Optical sensors	X	X		
Clothing	Membrane textiles	x	x		
Environment	Air filtration, oil-water separation				X
Medicine	Cancer tests, tissue engineering, drug delivery	X	X		

## 20.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 38: Compilation of hazard and exposure information of organic fibres

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>55</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>	Fibres with asbestos-like dimensions (pathogenic fibres) are considered carcinogenic by inhalation. Short fibres (intentionally or due to abrasion) are respirable (see toxicity)	

<sup>55</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>55</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
	Cellular recognition of natural polymers can initiate an immune response	
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?		
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		Use in medical applications is planned – kinetic behaviour is so far unknown
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Fibres may break during use and hence thereby become pathogenic fibres Fibres may release toxic substances or degrade due to external factors, such as UV radiation, temperature changes etc.	
Release of compounds at End of Life (during disposal, combustion, recycling)	Fibres may break during disposal and hence thereby become pathogenic	
Persistence (info on degradability, solubility)		
Transport within and between environmental compartments		

## 20.4 Information on environmental impacts and material circularity

### Information on environmental „value“/possible benefits and adverse

**impacts:** Already used to produce high efficiency air filters. Many applications in the energy and environment sector, potentially reducing environmental burdens, e.g. by improving product durability, increasing resource efficiency and decreasing energy consumption.

**Information on possible circularity deficits:** Recycling is not possible because in most (currently known) applications, the fibres cannot be separated from e.g. the surrounding polymer. Shortening of fibres in the process reduces their strength and thus impede high quality recycling.

## 20.5 Uncertainties, lack of information

Increased use of nanofibres may result in large releases of fibres and dust in the environment. Possible effects are unknown.

# 21 FACTSHEET: CARBON-BASED FIBRES

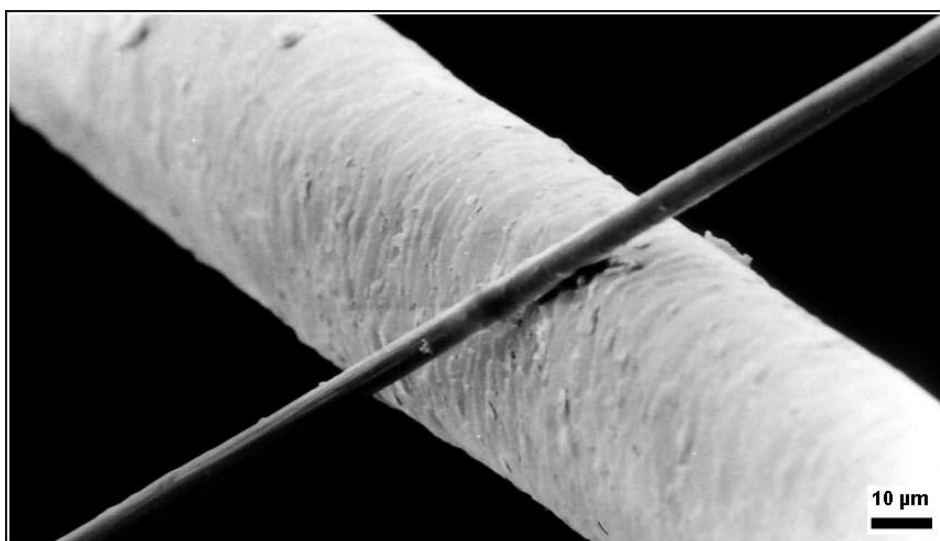


Figure 17: A 6 µm diameter carbon filament, compared to a 50 µm diameter human hair. From Anton 2005.<sup>56</sup>

## 21.1 General information

**Synonyms:** Carbon fibre, graphite fibre.

**Working definition:** Fibres several µm in diameter consisting mostly of carbon.

**Sub-groups:** Turbostratic carbon fibres, graphitic carbon fibres, carbon nanotubes.

**Main building blocks, composition:** Graphene sheets .

**Structural characteristics:** In graphitic carbon-based fibres, graphene sheets are regularly ordered (e.g. radially or in layers), in turbostratic carbon-based fibres they are randomly folded, carbon nanotubes resemble a single rolled up graphene sheet.

**Intended change of materials during use / intended transformation during application:** None.

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<sup>56</sup> Wikimedia Commons. Licensed under CC BY-SA 3.0, URL: [https://commons.wikimedia.org/wiki/File:Cfaser\\_haarrp.jpg](https://commons.wikimedia.org/wiki/File:Cfaser_haarrp.jpg)

**(Combinations of) properties and related (intended) functionalities:** High stiffness and/or high tensile strength.

**Other characteristics:** Electrically conductive, chemically inert, building blocks in fibre-reinforced composites, carbon nanotubes can adsorb gases.

**Regulatory information:** Carbon-based fibres most likely fulfil the definition of a substance.

## 21.2 Application(s)

Table 39: Applications of carbon-based fibres – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Construction, automotive	Reinforced polymers, carbon reinforced concrete				x
Energy	Electrodes for fuel cells/batteries				x
Electronics	Memory devices, templating (nano-structured copolymers), electrodes				x
Clothing	Wearable heating elements	x	x		x
Environment	Filters				x
Medicine	Cancer tests	X			

## 21.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 40: Compilation of hazard and exposure information of carbon-based fibres

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>57</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity	Good conductivity may lead to electrical problems from loose yarn or dust	
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/ED properties?	Fibres with asbestos-like dimensions (pathogenic fibres) are considered carcinogenic by inhalation. Carbon fibres are allergic to skin and mucous membrane Short fibres (intentionally or due to abrasion) are respirable (see toxicity)	
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?		
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		Use in medical applications is planned – kinetic behaviour is so far unknown
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Fibres may break during use and hence thereby become pathogenic fibres Large releases of short carbon fibres and CF dust from fires in CF reinforced structures (e.g. aircrafts) is possible	
Release of compounds at End of Life (during disposal, combustion, recycling)	Fibres may break during disposal and hence thereby become pathogenic. Electrostatic removal is hindered due to high conductivity of carbon based fibres.	
Persistence (info on degradability, solubility)	Carbon fibres are chemically inert and thus highly persistent	
Transport within and between environmental compartments		

<sup>57</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

## 21.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Many applications in the energy and environment sector, potentially reducing environmental burdens, e.g. by improving product durability, increasing resource efficiency and decreasing energy consumption. High persistence due to chemical inertness may be a hazard if large amounts of fibres are released in the environment

**Information on possible circularity deficits:** Recycling is not possible because in most (currently known) applications, the fibres cannot be separated from e.g. the surrounding polymer. Shortening of fibres in the process reduces their strength.

## 21.5 Uncertainties, lack of information

Increased use of carbon-based fibres may result in large releases of fibres and dust in the environment. Possible effects are unknown.

Carbon nanotubes may be used for applications beyond those of other carbon-based fibres, including environmental sensing techniques and medical applications. This would require additional assessments for these environments.

# 22 FACTSHEET: INORGANIC FIBRES

## 22.1 General information

**Synonyms:** Mineral fibres.

**Working definition:** Mineral fibres several  $\mu\text{m}$  or smaller in diameter.

**Sub-groups:** Fiberglass, basalt fiber, silica fiber, ceramic fibre.

**Main building blocks, composition:** Mineral fibre, e.g.  $\text{SiO}_2$ , sodium silicate.

**Structural characteristics:** Fibres with  $\mu\text{m}$  dimensions.

**Intended change of materials during use / intended transformation during application:** None.

**(Combinations of) properties and related (intended) functionalities:** High stiffness and/or high tensile strength, added conductivity.

**Other characteristics:** No further characteristics identified as relevant.

**Regulatory information:** Inorganic fibres most likely fulfil the definition of a substance.

## 22.2 Application(s)

Table 41: Applications of inorganic fibres – examples

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Construction	Thermal Insulation, reinforcement				x
Energy	Electrical insulation, possible use in lithium batteries filtration	x			x
Medicine	Joint replacement				x
Transport	Particulate filtration for fuel and air				X
Textiles	Antistatic textiles, EMI shielding				X

## 22.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 42: Compilation of hazard and exposure information of inorganic fibres

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>58</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>	Fibres with asbestos-like dimensions (pathogenic fibres) are considered carcinogenic by inhalation µm sized fibres are often sensitizers to skin and mucous membranes	

<sup>58</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>58</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>		
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans	Short fibres (intentionally or due to abrasion) are respirable (see toxicity)	
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)	Fibres may break during use and/or disposal and hence thereby become pathogenic fibres. Large releases of fibres and dust from fires or during (de)construction reinforced structures (e.g. building, wind turbines) is possible	
Persistence (info on degradability, solubility)	Chemically inert are usually highly persistent	
Transport within and between environmental compartments		

## 22.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Many applications in the energy and environment sector, which may lead to environmental benefits by replacing other materials and technologies.

**Information on possible circularity deficits:** Recycling is possible if the fibres can be separated from e.g. the surrounding polymer. In the frequent case of epoxy resin this is not possible.

## 22.5 Uncertainties, lack of information

Increased use may result in large releases of fibres and dust in the environment. Possible exposure and its effects are unknown. Especially biopersistence in different ecosystems is often unknown.

# 23 FACTSHEET: ELECTRO-ACTIVE POLYMERS

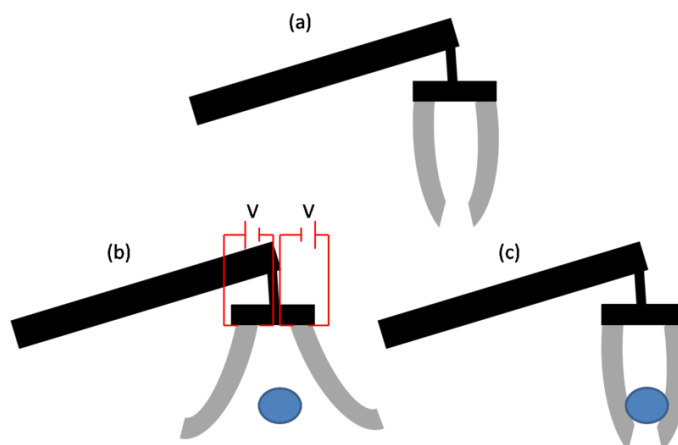


Figure 18: (a) Drawing of an EAP gripping device. (b) A voltage is applied and the EAP fingers deform in order to open the gripping device. (c) When the voltage is removed, the EAP fingers return to their original shape and hold the ball. From Chem538w10grp7 2010.<sup>59</sup>

## 23.1 General information

**Synonyms:** Artificial muscles.

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<sup>59</sup> Wikimedia Commons. Released to the public domain, URL: <https://commons.wikimedia.org/wiki/File:EAP-example2.png>

**Working definition:** Polymers that exhibit a change in size or shape when stimulated by an electric field.

**Sub-groups:** Dielectric elastomers, electrostrictive polymers, ionic polymer-metal composites, electro-active polymers, bucky-gel actuator.

**Main building blocks, composition:** Variety of polymers, depending on subgroup: Ionomers, ferro-electric polymers (e.g. polyvinylidene fluoride), ionic liquids/gels.

**Electrodes:** highly conductive metals, mostly silver and gold; carbon nanotube in ionic gels.

**Structural characteristics:** Depending on sub-group, electrodes may be part of the structure or external.

- Electrostrictive graft polymers: flexible backbone chains with side chains from polarized monomers
- Ferro-electric polymers: single polymer
- Liquid crystalline polymers: Main-chain liquid crystalline polymers have mesogenic groups linked to each other by a flexible spacer
- Ionic polymer-metal composites: ionic polymers (e.g. Nafion) with a plated or coated surface with conductors
- Bucky-gel-actuator: ionic liquid between electrode layers consisting of a carbon-nanotube infused ionic liquid

**Intended change of materials during use / intended transformation during application:** Reversible stretching or contraction of molecules through absorption of energy from an electric field / formation of an electrical field initiated by mechanical changes of the material.

**(Combinations of) properties and related (intended) functionalities:** Shape change under an electrical field and vice versa.

**Other characteristics:** No further characteristics identified as relevant.

**Regulatory information:** Electro-active polymers could generally fall under any of the REACH definitions. In particular as there are so many sub-types, it is not possible to make a general conclusion on this.

## 23.2 Application(s)

Table 43: Applications of electro-active polymers – overview

Sector	Use	Basic scientific research	Research on specific applications	"Recent" market introduction	Use is "common"
	Artificial muscles	x			
	Microfluidics	x			
	Sensors		x		

Sector	Use	Basic scientific research	Research on specific applications	"Recent" market introduction	Use is "common"
	Micro-actuators		x		

### 23.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 44: Compilation of hazard and exposure information of electro-active polymers

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>60</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>	Some used gels are toxic	
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>		
Exposure (Human)		
Exposure during use and service life of products	If used as artificial muscles in humans, unintended immune response is highly conceivable	
Uptake and metabolism, kinetic behaviour in humans	Medical applications planned, behaviour in living systems unclear	
Exposure (Environment)		

<sup>60</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>60</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Stability of the material during use; potential unintended release of compounds	Most polymers are highly stable, although interactions with biological environments need to be considered	
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)	Some used polymers indicate high persistence	
Transport within and between environmental compartments		

### 23.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Concrete benefits are not yet foreseeable.

**Information on possible circularity deficits:** Recycling of EAP-devices has similarities to the recycling of MEMS-devices. So far only targeted separation of devices from the surfaces they are connected to is possible, recycling does not exist yet.

### 23.5 Uncertainties, lack of information

Use of electro-active polymers in biological systems has hardly been assessed yet. The increased use of nano-structures in polymers in general and designs such as the bucky gel actuator, may introduce yet unknown risks in this material category.

## 24 FACTSHEET: SELF-REPAIRING POLYMERS

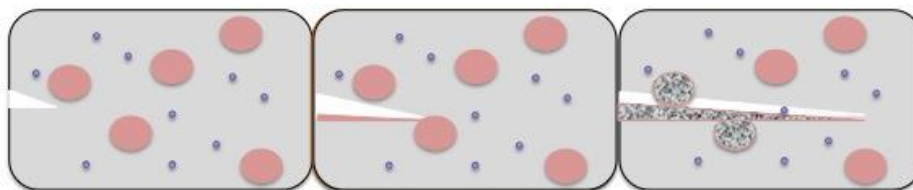


Figure 19: In Situ Polymerization of microcapsule-embedded composite materials. From Chem540f09grp11 2009.<sup>61</sup>

### 24.1 General information

**Synonyms:** Self-healing polymers.

**Working definition:** Polymers which can repair limited sustained physical damage.

**Sub-groups:** Extrinsic systems, intrinsic systems.

**Main building blocks, composition:** Polymers (often based on furan or maleimide), extrinsic systems with additional microcapsules (e.g. dicyclopentadiene and Grubb's catalyst as microparticles in an epoxy resin).

**Structural characteristics:** Depending on the type of healing system (see other characteristics). Intrinsic systems: single polymer with intrinsic healing abilities; Extrinsic systems: healing agents (monomer and catalyst) are separated from the surrounding polymer as capsules, tubes, networks etc.

**Intended change of materials during use / intended transformation during application:** Self-repairing of damage to the material with or without external stimulus

**(Combinations of) properties and related (intended) functionalities:** Self-repairing of damage to the material with or without external stimulus.

**Other characteristics:** Two different healing mechanisms:

**Intrinsic:** Cleaved bonds create species which reattach (radicals, cation anion pairs, reversible cycloaddition) or other bond-recreating reactions (metathesis reaction, bond exchange of crosslinked species) – additional stimuli such as heat may be necessary

**Extrinsic:** Reactants in a monomeric state are encapsulated in microstructures and dispersed throughout the polymer. A catalyst enabling the polymerization of the monomers at room temperatures is similarly encapsulated and dispersed. A microcrack needs to rupture both types of capsules to trigger the self-healing mechanism, which needs no additional energy.

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<sup>61</sup> Wikimedia Commons. Released by the author into the public domain, URL: [https://commons.wikimedia.org/wiki/File:Polymerization\\_in\\_situ.jpg](https://commons.wikimedia.org/wiki/File:Polymerization_in_situ.jpg)

**Regulatory information:** Self-repairing polymers appear to be mixtures under REACH. The constituents could fulfil various definitions, including that of a substance (monomer or polymer), as well as that of a mixture.

## 24.2 Application(s)

Table 45: Applications of self-healing polymers – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Construction	Coatings, structural applications	x			
Automotive	Coatings, structural applications	x			

## 24.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 46: Compilation of hazard and exposure information of self-healing polymers

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>62</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>	Furan is a classified carcinogen, maleimide is an acute toxic. Polymers based on these compounds may retain these properties Dicyclopentadiene as used in microcapsules is irritating to skin,	

<sup>62</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>62</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
	harmful if swallowed and causes respiratory irritation	
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>	Dicyclopentadiene is hazardous to the aquatic environment	
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds	Increased likeliness of thermal decomposition or release of reaction by-products during healing process (either exothermal reactions or necessary external heating) Loss of healing agents from microcapsules to environment due to abrasion is conceivable	
Release of compounds at End of Life (during disposal, combustion, recycling)	Loss of healing agents from microcapsules to environment during disposal is very likely	
Persistence (info on degradability, solubility)	Depending on individual compounds – some (dicyclopentadiene) are highly persistent and insoluble in water	
Transport within and between environmental compartments		

## 24.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Self-healing polymers could possibly increase the lifetime of manufactured goods, thus reducing their lifecycle impact.

**Information on possible circularity deficits:** Due to the added healing agents in extrinsic healing polymers recycling may be difficult.

## 24.5 Uncertainties, lack of information

Self-repairing polymers are still at a low technology readiness level, thus no information on applications and their possible interaction with their environment is available. Most used building blocks are well known and widely used, thus

further information is mostly needed on specific interactions in the final system and its use cases.

## 25 FACTSHEET: CO- POLYMERS



Figure 20: Different types of polymers: 1) homopolymer 2) alternating copolymer 3) random copolymer 4) block copolymer 5) graft copolymer. From V8rik 2008.<sup>63</sup>

### 25.1 General information

**Synonyms:** No synonyms identified.

**Working definition:** Polymer derived from more than one species of monomer.

**Sub-groups:** Linear copolymers, branched copolymers, graft copolymers, bipolymers, terpolymers, quaterpolymers.

**Main building blocks, composition:** Monomers usually with different characteristics (e.g. hydrophilic and hydrophobic).

**Structural characteristics:** Regular or irregular structure depending on type of copolymer.

**Intended change of materials during use / intended transformation during application:** None.

**(Combinations of) properties and related (intended) functionalities:** Different polymer structures depending on mixture – targeted design is comparatively limited.

**Other characteristics:** Microphase separation during copolymerization may form periodic nanostructures.

<sup>63</sup> Wikimedia Commons. Licensed under CC BY-SA 3.0, URL: <https://commons.wikimedia.org/wiki/File:Copolymers.svg>

**Regulatory information:** Advanced co-polymers fulfil the definition of a substance and are also polymers.

## 25.2 Application(s)

Copolymers are in wide use since at least 70 years, some commercial copolymers such as acrylonitrile butadiene styrene (ABS) or nitrile rubber being used in virtually every sector. Some special, emerging applications are mentioned in the following table.

Table 47: Applications of co-polymers – overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Medicine	Drug delivery (star-shaped polymers)	x	x		
Medicine	RNA adsorber	x			
Electronics	Memory devices, templating (nano-structured copolymers)	x			
Electronics	Organic LEDs	x	x		

## 25.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 48: Compilation of hazard and exposure information of co-polymers

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>64</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		

<sup>64</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>64</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Potential human toxicity, e.g. • Indications for toxicity and other health hazards? • CMR/EDC properties?	Varies largely between different copolymers. Some examples: reduction in cell proliferation for PLA-PGA materials toxic and carcinogenic decomposition products from ABS	Information on copolymers intended for use in medical products is usually better, though often insufficient; copolymers used in electronics are hardly screened for toxicity "Classic" copolymers (e.g. ABS, SAN, butyl rubber) are well assessed. Assessment is sometimes limited to used monomers.
Potential environmental toxicity, e.g. • Indications for aquatic toxicity (or toxicity in other compartments) • Bioaccumulative potential? • ED properties?		
Exposure (Human)		
Exposure during use and service life of products	Abrasion resistance varies, nanoparticles may form and be inhaled/ingested	
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)	Many copolymers emit toxic fumes upon decomposition	
Persistence (info on degradability, solubility)	High persistence in environmental compartments possible; biodegradation varies	
Transport within and between environmental compartments		

## 25.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Copolymers represent the majority of slowly decomposing plastic pollution.

**Information on possible circularity deficits:** Recycling is theoretically possible but due to the versatility of materials results in mixed/downgraded co-polymer fractions from waste processing.

## 25.5 Uncertainties, lack of information

Compared to other advanced materials, a very high amount of information is available.

# 26 FACTSHEET: ADVANCED ALLOYS

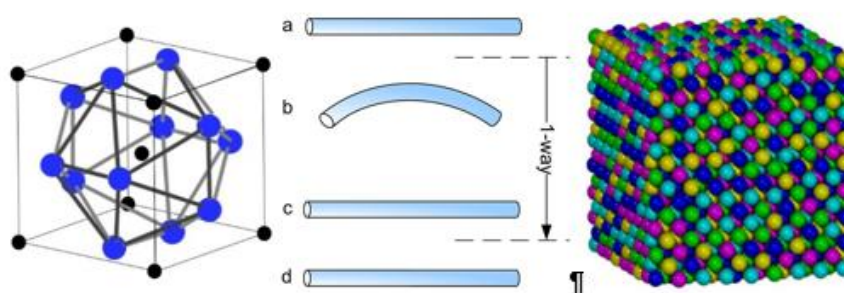


Figure 21: Left: Intermetallic alloy of the structure type A15 (blue: Cr, black Si), discovered 1933. From Eloic Ferdinand 2017.<sup>65</sup>

Middle: Schematic of the use of a one-way shape-memory-alloy: a) original state, b) external deformation, c) heating, d) after cooling. From Fongs 2006.<sup>66</sup>

Right: Atomic structure model of face-centered-cubic CoCrFeMnNi, a high entropy alloy. From Shaoqing Wang 2013<sup>67</sup>

## 26.1 General information

**Synonyms:** No synonyms identified.

**Working definition:** Alloys, which comprise more than two components. At least two components have a large share in the final material.

**Sub-groups:** Advanced intermetallic alloys (IMA): solid phases containing two or more metallic elements, with one or more non-metallic elements, whose crystal structure differs from that of the other constituents.

**Shape memory alloys (SMA):** When deformed at low temperature, returns to its pre-deformed shape when heated above transition point.

**High entropy alloys (HEA):** Consist of equal or relatively large proportions of four or more elements.

**Main building blocks, composition:** Metals and one or more other elements.

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<sup>66</sup> Wikimedia Commons. Licensed under CC BY-SA 2.5, URL: <https://commons.wikimedia.org/wiki/File:SMAoneway.jpg>

<sup>67</sup> Wikimedia Commons. Licensed under CC BY3.0, URL: [https://commons.wikimedia.org/wiki/File:Atomic\\_structure\\_model\\_of\\_fcc\\_CoCrFeMnNi.png](https://commons.wikimedia.org/wiki/File:Atomic_structure_model_of_fcc_CoCrFeMnNi.png)

**Structural characteristics:** HEA: solid solutions.

**Intended change of materials during use / intended transformation during application:** SMA: change from martensitic to austenitic phase with temperature change.

**(Combinations of) properties and related (intended) functionalities:**

IMA: various, mainly increased strength elastic modulus, inertness and temperature stability, metallic semi-conductors.

**SMA:** one or two specific shape configurations, which form depending on temperature.

**HEA:** exceptional mechanical characteristics (high strength at high temperatures, while brittle at low), low diffusion coefficients.

**Other characteristics:** No further characteristics identified as relevant.

**Regulatory information:** Advanced alloys are considered to fulfil the REACH definition of a mixtures and of alloys.

## 26.2 Application(s)

Table 49: Applications of advanced alloys– overview

Sector	Use	Basic scientific research	Research on specific applications	“Recent” market introduction	Use is “common”
Energy	HEA: Hydrogen storage, high temperature applications IMA: metallic semiconductors for photovoltaics	X			
Electronics	IMA: metallic semiconductors	X			
Unspecific	SMA: heat activated hydraulic switches HEA: cryogenic applications	X			
Medicine	SMA: high elasticity implants	X			

## 26.3 Information on potential risks

The following table lists information on the hazard and exposure potentials of the material. The risk factors hazard and exposure are differentiated into effects on either humans or the environment. Besides respective reasons for concern (as far as known to the authors, first column), information on the reliability or uncertainty of information in the first column is provided in the last

column if available in the time course and with the resources of this study. If cells are left blank, no information was available.

Table 50: Compilation of hazard and exposure information of advanced alloys

Risk factor	Reason for concern (as identified from screening some of the literature and databases <sup>68</sup> )	Reliability/Uncertainty (e.g. tests/ measurements/ information derived from comparable materials/ based on modelling/ morphology/ properties of components)
Hazard		
Physical-chemical properties indicating potential adverse effects, e.g. reactivity		
Potential human toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for toxicity and other health hazards?</li> <li>• CMR/ED properties?</li> </ul>		
Potential environmental toxicity, e.g. <ul style="list-style-type: none"> <li>• Indications for aquatic toxicity (or toxicity in other compartments)</li> <li>• Bioaccumulative potential?</li> <li>• ED properties?</li> </ul>		
Exposure (Human)		
Exposure during use and service life of products		
Uptake and metabolism, kinetic behaviour in humans		
Exposure (Environment)		
Stability of the material during use; potential unintended release of compounds		
Release of compounds at End of Life (during disposal, combustion, recycling)		
Persistence (info on degradability, solubility)		
Transport within and between environmental compartments		

## 26.4 Information on environmental impacts and material circularity

**Information on environmental „value“/possible benefits and adverse impacts:** Some alloys are candidates for rare earth substitution.

There is some potential for increased efficiency in machines due to exceptional mechanical properties. Said properties may also lead to material savings in general, which may be counteracted by the high energy demand and complexity of the production. High Entropy Alloys may be an option for low

<sup>68</sup> The table only lists clearly identified concerns. Empty cells do not indicate the absence of concerns. They are either due to a lack of resources to comprehensively screen the relevant literature and databases or due to the fact that no information is publicly available. As information will become available from safety research and regulatory requirements, this table presents a snapshot at the time of writing this report.

diffusion hydrogen storage. Metallic semiconductors may present new options for photovoltaics.

**Information on possible circularity deficits:** In many applications, recycling is unlikely due to the low material amounts and their use as coatings or within highly integrated systems. If mechanical separation is possible, recycling techniques could be developed.

## **26.5 Uncertainties, lack of information**

Dependent on individual alloy.