Smart materials and safe and sustainable-by-design - a feasibility and policy analysis

Hansen, Steffen Foss; Paulsen, Freja; Trier, Xenia

Published in:
Ensuring the environmental sustainability of emerging technologies

Link to article, DOI:
10.5075/epfl-irgc-298445

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Hansen, S. F., Paulsen, F., & Trier, X. (2023). Smart materials and safe and sustainable-by-design - a feasibility and policy analysis. In M-V. Florin (Ed.), *Ensuring the environmental sustainability of emerging technologies* (2 ed., pp. 73-89). Swiss Federal Institute of Technology Lausanne (EPFL). https://doi.org/10.5075/epfl-irgc-298445

Paper 3

Smart materials and safe and sustainable-by-design – a feasibility and policy analysis

Steffen Foss Hansen[1],
Freja Paulsen[1],
Xenia Trier[2]

Table of contents

---

[1] Department of Environmental and Resource Engineering, Technical University of Denmark, 2800 Kongens Lyngby, Denmark, sfha@dtu.dk.
[2] University of Copenhagen, Department of Plant and Environmental Sciences, 1871 Frederiksberg C, Denmark., xt@ku.plen.dk.

Introduction

Written in the context of EPFL International Risk Governance Center's (IRGC) project on ensuring the environmental sustainability of emerging technology outcomes, this paper considers how so-called "smart materials" are – or could be – assessed and managed to ensure that their applications do not threaten environmental sustainability. In the IRGC project to which this paper contributes, the concept of sustainability is broadly defined as the expectation that both current and future generations can meet their needs (IRGC, 2022). In this context, risks to environmental sustainability essentially cover the risk of damage to the environment that may manifest only in the long term as a result of (a) unknown effects at the time of deployment (examples in some advanced materials), and/or (b) the accumulation process, after a given material has accumulated and crossed some thresholds (examples with common pesticides) and/or (c) a long time gap between the introduction and subsequent manifestation of consequences (for example, with gene-editing techniques).

In the case of many emerging technologies, those whose task it is to anticipate, assess and manage risks do not have the information they need to do so properly. This particularly includes regulators that have a duty to avoid or mitigate risk while also being expected not to stifle innovation.

This paper presents how the EU's Chemicals Strategy for Sustainability aims to address this complex challenge, in particular through the concept of safe and sustainable-by-design (SSbD), and applies it to the case of smart materials.

Smart materials result from technologies that are relatively new, or even emerging. We examine if the currently developed SSbD assessment and reporting criteria are sufficient to address the specific challenges of emerging smart materials, in particular in relation to environmental sustainability.

After introducing the EU Chemicals Strategy for Sustainability (section 1), the paper describes the concept of and current approaches to SSbD (section 2), and then discusses specific features of smart materials (section 3). In conclusion, it reviews some of the challenges that smart materials might raise from a regulatory science perspective in relation to sustainability, life cycles and the protection of human health and the environment (section 4).

1.

EU Chemicals Strategy for Sustainability

In 2020, the European Commission adopted its new "Chemicals Strategy for Sustainability – towards a toxic-free environment" (CSS) (EC, 2020c). The CSS is part of the EU's zero pollution ambition – a key commitment of the European Green Deal – and aims to better protect citizens and the environment from harmful chemicals, as well as boost innovation by promoting the use of safer and more sustainable chemicals (EC, 2019). The CSS is also a key part of the European Green Deal and its associated strategies and policies to abate climate change (e.g., the Fit for 55 package), together with the Circular Economy Action Plan, the Farm to Fork Strategy, the Biodiversity Strategy and the Pharmaceutical Strategy. The CSS builds on previous ambitions to reduce the harm from chemical pollution to people and the planet, such as the European 7th Environment Action Programme (EAP), and a series of background studies supporting the call for a Non-toxic Environment Strategy (Milieu Ltd, Ökopol, Risk & Policy Analysts (RPA) and RIVM, 2017), including a list of potential policy responses (Camboni, 2017). While several of the ambitions of the CSS also relate to existing legislations such as REACH on industrial chemicals, the CSS applies more broadly to chemicals from all sources and to broader impacts, along with the life cycles of chemicals and associated products. The two supporting staff working documents (SWDs) on the combined exposure to mixtures of chemicals and on the per- and polyfluoroalkyl substances (known as PFAS) address chemicals across "vertical" product or environmental media policy silos and throughout their life cycles. The two overarching aims are to avoid harm to people and planet and to foster an industrial transition to safe and sustainable-by-design chemicals and materials, with the guiding principle of preventing pollution and harm, rather than cleaning up afterwards (prevention-mitigation-remediation-elimination).

To address chemicals across legislations, support innovation towards the development of safe and sustainable chemicals and to speed up their upstream regulation, the CSS introduces a number of new concepts, including safe and sustainable-by-design (SSbD), phasing out the most harmful chemicals for "non-essential uses" and the "mixture allocation factor" (MAF) (EC, 2020b). The CSS also calls for the Classification Labelling and Packaging Regulation (CLP) (EC, 2018) to include new hazard classes, with a focus on chronic effects such as developmental neurotoxicity and immunotoxicity, respiratory toxicants and chemicals with the intrinsic characteristics of being persistent and mobile (PMT, vPvM). Acute effects, such as physical hazards (e.g., explosions, corrosiveness, flammability linked to reactivity), and acute risks (e.g., suffocation, excessive nutrients) are not included. In addition, the CSS aims to achieve clean material cycles as well as several other objectives which are captured in the more than 60 actions in the Annex to the CSS (EC, 2020a). The SSbD concept is new in the sense that it brings together considerations on the health and safety of humans and the environment, as well as sustainability related to Earth systems (climate change, the ozone layer), biodiversity and the circular economy. As emphasised by the European Environment Agency (EEA), SSbD targets the upstream, pre-market design phase during technology development, aiming for fundamental changes in designs to deliver services in a tiered approach by (1) applying cut-off criteria to avoid the use of substances of concern and (2) a risk-based and multi-criteria decision approach to minimising impacts throughout chemical and product life cycles (EEA, 2021). This may involve other business models and eco-designs that allow for repair, reuse, upgrading, refurbishment, ease of maintaining and disassembling for recycling, which are energy and resource efficient, as captured in the Sustainable Products Initiative (EC, 2022a).

The CSS – and more specifically, the SSbD – is therefore highly relevant for emerging chemical technologies and smart materials, and it is thus important to analyse the challenges of ensuring their environmental sustainability.

2.

Safe and sustainable-by-design (SSbD)

The SSbD concept underlines that both safety and sustainability should be addressed in the design phase – and not considered as an afterthought, e.g., when a material or product has been developed and is about to be used in society. The scope of SSbD is currently a popular subject of discussion. The EEA (2021) published a briefing on SSbD, focusing on delivering services to minimise harm to the environment and people, which would require the consideration of chemicals, materials, processes and products. In contrast, the CSS only examines the molecular design of chemicals. Production process design and product design are to be addressed in a future sustainable products directive (EC, 2022b). This approach was taken in order to avoid double regulation on products.

The CSS called for the European Commission (EC) to set criteria and methodologies to support the SSbD in relation to chemicals and materials by early 2022, and several proposals have subsequently been made, albeit limited information is provided in the CSS about what these might be. Footnote 19 of the CSS (EC, 2020c), however, does state that the criteria should lay the foundation for a pre-market approach and could include considerations of whether the substance serves a function (or service), avoids volumes and chemical properties that may be harmful, avoids (eco)toxic, persistent, bio-accumulative or mobile substances and minimises the environmental footprint with regard to climate change, resource use, ecosystems and biodiversity from a life cycle perspective. As such, the CSS is clear in including only environmental sustainability aspects – and not societal or economic aspects.

2.1 Criteria and methodologies for SSbD: The JRC framework

The European Joint Research Centre (JRC), which is the EC's science and knowledge service, has been tasked with proposing a framework for the definition of criteria and evaluation procedures for chemicals and materials. In early 2022, a draft report was published and subsequently subjected to public consultation (Caldeira et al., 2022). The proposed methodology consists of a tiered approach, starting with applying cut-off criteria to avoid the use of the most harmful substances as well as substances of concern (SOC), followed by a life cycle (impact) assessment of the products' environmental footprint (PEF). SOCs are defined to some extent in the CSS as being those with chronic effects, although a specific definition of hazard classes is still being discussed internally in the EC. For chemicals and materials that do not meet the initial cut-off criteria, these are only to be allowed in uses proven essential for society. Just as we see with SSbD, how the term "essential use" is defined is subject to discussion, but it is generally understood as usage necessary for health, safety or the functioning of society, where there are no acceptable alternatives when considering the environment and health. Importantly, the Essential Use Concept (EUC) is only anticipated to be applied to known or suspected SOCs. The debate on EUC currently centres around the following: (1) if alternatives should be sought within the same technology group (drop-in substitution) or move to different (e.g., non-chemical) ways to provide the service and (2) if society should have the "right" to decide what is considered essential for the individual — a key example being if society has the right to decide if makeup with harmful substances should be allowed or not. The cut-off criteria follow the CSS's ambition to prevent the use of SOCs based on their intrinsic properties in order to avoid harm to people and the planet and to ensure clean material cycles. Continuing to wait for action until data is available for all chemical hazards and exposures to chemicals (mixtures), across all media and in multiple material cycles is simply unrealistic and has repeatedly proven to be ineffective in preventing the accumulation of pollution and harm (EEA, 2019b, 2019a). The cut-off criteria hence, arguably, represent a preventative and precautionary approach, which is combined with a traditional risk assessment for types of chemicals that currently are not known to be of concern.

Specifically, the JRC framework consists of two parts, namely the (re)design part and a safety and sustainability assessment. For the evaluations, the focus should fall on the functionality of the chemical/material, rather than its structure, which is supposed to make it easier to assess alternatives. Notably, the proposal also includes a consideration of social and economic aspects, which is not included in the original CSS ambition, so it is still unclear as to whether there will be policy support to include this in the final SSbD concept. While this is in line with the Sustainable Development Goals and what companies already do, the counter-argument is that finding agreement on all these complex matters, across technical and social dimensions, will slow down the implementation of the SSbD. A step-wise approach has therefore been proposed, starting with avoiding harmful chemicals and then adding the other dimensions as their frameworks become available (ChemSec, 2021).

To ensure that both safety and sustainability become part of the design process, the JRC framework proposes 13 design principles (Caldeira et al., 2022) (see table 1 below), drawing from the updated 12 principles of Green Chemistry (Anastas & Eghbali, 2009). Two of these are directly related to the development and safety of the chemical in question, namely No 2 "Design with less hazardous chemicals" and No 5 "Prevent and avoid hazardous emissions." Several of the other principles are also related to chemical substances, e.g., No 1 "Material efficiency," which includes all components in the production of the final product, in order to minimise waste, and No 8 "Consider the whole life cycle," which underlines the importance of taking into account every production, usage and end-of-life step. Principle No 4 "Use of renewable resources" is a contested point, since the current production/consumption of chemicals is at a scale whereby if it were moved to renewable feedstocks, it would compete with land set aside for nature as well as land, nutrients and energy used for food. Compared to fossil feedstocks, it also requires more energy and produces significant amounts of waste. Furthermore, it uses biomass, turns it into feedstock chemicals

Table 1 | SSbD principles for the design phase (reprinted from Caldeira et al., 2022)

1.	Material efficiency
2.	Design with less hazardous chemicals
3.	Design for energy efficiency
4.	Use renewable sources
5.	Prevent and avoid hazardous emissions
6.	Reduce exposure to hazardous substances
7.	Design for end-of-life
8.	Consider the whole life cycle

(e.g., ethanol or methane) and then starts the synthesis of chemicals. While principle No 4 “Use of renewable resources” might be a long-term aim, it would require a substantial reduction in global annual chemical production to avoid creating harm to, for instance, food supply ecosystems (Balan et al. 2022). Reducing the production and consumption of chemicals, on the other hand, is the one single action that would greatly reduce all risks across the board, from the extraction of resources through to life cycle emissions of chemicals.

2.2 Assessing safe SSbD

The sustainability assessment proposed by the JRC consists of five steps (see the first column of Table 2 below; columns 2 and 3 will be commented on in Section 2.3). In the first three steps, the safety of the chemical compounds is evaluated, whereas sustainability is examined in the final two steps.

Step four is the most encompassing step in the assessment, as it should include all aspects of environmental sustainability. The JRC suggests that a life cycle assessment (LCA) should be carried out and include toxicity, climate change, pollution and

Table 3 | Aspects to be included in the sustainability assessment (reprinted from Caldeira et al., 2022)

Impact category	
1.	Climate change
2.	Human toxicity, cancer
3.	Human toxicity, non-cancer
4.	Ecotoxicity
5.	Particulate matter
6.	Ionising radiation
7.	Ozone depletion
8.	Eutrophication, terrestrial
9.	Eutrophication, marine
10.	Eutrophication, freshwater)
11.	Ozone formation
12.	Acidification
13.	Mineral and metals resource depletion
14.	Fossil resource depletion
15.	Land use
16.	Water use

Table 2 | SSbD assessment steps and options, as presented by JRC, Cefic and Hauschild

JRC (Caldeira et al., 2022)	Cefic (2022)	Hauschild et al. (2022)
Step 1: Safety of chemical and material; hazard-based approach (cut-off criteria)	**Step 1**: Performance and functionality needs	**Option 1**: Develop an LCA and a risk assessment (RA), with two independent outcomes, without comparing their results
Step 2: Chemical or material processing safety; occupational safety and health approach (production focus)	**Step 2**: Identify scope through assessment dimensions (list of recommendations)	**Option 2**: Develop an LCA and an RA, and evaluate and compare the outcomes of using utility theory
Step 3: Human health and environmental impacts from the use phase; direct exposure (use focus)	**Step 3**: Select design principles along dimensions (list of recommendations)	**Option 3**: Develop an LCA and embed aspects of RA into it
Step 4: Environmental sustainability assessment (LCA)	**Step 4**: Perform comparative assessments	**Option 4**: Develop an LCA and embed RA to maximise the value of the LCA results
Step 5: Social and economic sustainability assessment (may be voluntary)	**Step 5**: Select solutions after having evaluated trade-offs	
Result: Either a class (poor, good, very good) or a numerical score (consider weighting)		

resources (a full list is provided in table 3). Life cycle assessment or analysis is employed to quantify the environmental impacts of a product, a material, a process or an activity. It is a cradle-to-grave approach that assesses all stages of a product's life cycle and estimates cumulative environmental impacts (IRGC, 2022). In order to use LCAs to fully evaluate environmental sustainability, further development of the method is required in order to include all other aspects (Packroff & Marx, 2022). It also needs to be noted that LCAs look at what is considered "normal" use and therefore fails to look at extreme cases, such as accidents (Hauschild et al. 2022). Moreover, in this regard, conventional LCAs apply to existing products and are thus not suitable for future applications of new technologies. For future products, methods for prospective LCAs are being developed, and data gap-filling tools are currently being researched in EU projects such as the Partnership for the Assessment of Risks of Chemicals (PARC). Such gap-filling will address the substantial data gaps in LCAs, i.e., a very data-heavy method where a lot of assumptions often have to be made. This means that more (and different) data is needed, and there is, therefore, a need for new data collection methods in order to generate accurate and useful results (Fantke et al., 2021).

2.3 Other suggestions for assessing SSbD: Cefic, Hauschild, ChemSec

Besides the JRC, other stakeholders have also presented alternative approaches to SSbD. For instance, Cefic (2022), which is the largest trade association for the chemicals industry in the EU, has proposed a framework that consists of five steps and focuses on the design phase in order to find the best alternative (see Table 2). Cefic defines SSbD as "chemicals, materials, products, processes and services that are safe, and deliver environmental, societal, and/or economic value through their applications". Furthermore, it interprets SSbD as a tool to facilitate innovation in which safety is evaluated based on a traditional risk approach, whilst the goal of the innovation in question is to improve environmental, societal and/or economic value, without negatively affecting any of the other aspects, thereby enabling the stepwise development of safer and more sustainable products. The definition and approach proposed by Cefic contrasts to the JRC framework in relation to two significant topics: risk-based safety evaluation and the fact that a "safe" chemical that delivers economic value is enough to be labelled SSbD under this definition. Since this is basically what industry is supposed to be doing now, the Cefic approach does not address how the approach would increase the prevention of repeated harm caused by pollution. Neither does it address how chemicals lacking in safety data can be risk assessed and therefore fed into the SSbD assessment. Avoiding the use of substances of very high concern is already a requirement and therefore does not advance the prevention called for by the CSS.

Another way of assessing SSbD has been proposed by Hauschild et al. (2022), who suggest that safety is evaluated via risk assessment, whereas sustainability is evaluated using an LCA (see Table 2). This would then lead to four options in relation to evaluating the results of each of these two assessments, namely (1) not safe/not sustainable; (2) not safe/sustainable; (3) safe/not sustainable and (4) safe/sustainable. After having weighed up the four options against a list of criteria, including feasibility, reliability, completeness, transparency and comparability with decision-making principles and the principles of "value of information", Hauschild et al. (2022) found that option 4, namely safe/sustainable, was the preferred option. The approach suggested by Hauschild et al. (2022) is in line with the JRC framework on using an LCA for evaluating sustainability and the suggestion made by Cefic (2022) to use a risk assessment to evaluate safety, albeit the latter would not prevent the use of SOCs, if data on hazard or exposure was missing.

Finally, the NGO ChemSec has published certain considerations that complement the other approaches. ChemSec interprets the idea of SSbD as a development guideline that can be used to determine what the EU should invest in (Lennquist, 2022). In line with the EEA approach and the JRC cut-off criteria, ChemSec underlines that hazardous chemicals can never be labelled "SSbD," as they are neither safe nor sustainable to use (ChemSec, 2021). Moreover, ChemSec argues that SSbD needs to have higher ambitions than current legislation that focuses on substances long established on the market being of very high concern; otherwise, the SSbD will not contribute with anything new (ChemSec, 2021). ChemSec also highlights the amount of data needed for evaluating SSbD and stresses that this must not result in "no data = no harm" whereby a lack of data results in positive assessments. To avoid this issue, ChemSec suggests a simple framework in the first years with a stepwise increase in the number of impact factors, in order to allow both academia and industries the time needed to produce methods and data (ChemSec, 2021).

2.4 Measuring, evaluating and reporting on SSbD

Besides questions about assessing SSbD, another question is how to measure, evaluate and report on the SSbD of chemicals. Evaluation, which is linked to the criteria setting, is a particular subject of interest in this regard. While consultations seem to indicate some agreement on communicating a relatively simple metric, there is also a desire to illustrate the performance of each protection goal outlined in the CSS. It has also been argued that it is essential to set minimum standards for each of the protection goals (EEA, 2021), to avoid burden shifting between risks, for example, to biodiversity, the climate or human health, and give credibility to the SSbD. Which level of harm is considered acceptable is linked to the carrying capacity and planetary boundaries of, for example, ecosystems and human health, which are still poorly understood in relation to chemicals (Persson et al., 2022). The final assessment uses a “multi-criteria decision-making” approach, which could allow for the weighting of different risks, potentially across different climatic and cultural regions. Ultimately, such evaluations involve societal value judgement and political decisions informed by science. To support the setting of criteria, funding has been given under the EU public-public research project PARC, involving scientists, national authorities and EU bodies. Other key points raised in the discussions on how to operationalise SSbD include the need to provide educational, financial and other incentives, such as having technical support centres (EEA, 2021), in addition to research funding going into the further development of the concept. In a global market, and to create a level playing field for products produced within or imported into the EU, it would also be key to develop analytical test methods, in order to demonstrate compliance with claims of SSbD.

3.

Smart materials

Before discussing how smart materials might compare with the ideals of SSbD, it is important to understand what they are and how they might be used in a variety of fields, such as construction, biomedical applications and food packaging. Often, references are made to smart nanomaterials — and here, it is important to note that smart nanomaterials are a subgroup of smart materials. In addition, nanomaterials are considered chemical substances in the EU and hence fall under the scope of existing legislation on, for example, industrial chemicals and biocidal and plant protection products. Sometimes, smart materials are labelled as “advanced materials” and here, it is important to understand that they are indeed a subgroup of advanced materials. Other examples of advanced materials subgroups include nanotechnology, advanced composites, light alloys and high-performance polymers (see Broomfield et al., 2016).

3.1 Definition of smart materials

The term “smart materials” is not new, and how to define such materials has been subject to discussion since the 1970s (Rogers, 1988). In the early days, they were often defined as man-made or natural materials that can respond in a timely manner to the surrounding environment (Ghosh, 2008; Rogers, 1988; Spillman et al., 1996). For instance, at a US Army Research Office consensus workshop in 1988, smart materials were defined as:

“A system or a material which has built-in or intrinsic sensor/s, actuator/s and control mechanism/s whereby it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short/appropriate time and reverting to its original state as soon as the stimulus is removed” (Rogers, 1988, p. 4).

Smart materials themselves are not necessarily new; for instance, magnetostrictive materials were first identified in 1842 by James Joule (Kumara & Arockiarajan, 2022), and the theory of thermoresponsive polymers originates from the 1940s (Thangudu, 2020). Nowadays, the term is more often associated with materials that obtain a new kind of functional property as a consequence of stimulation via external factors. These stimuli can be light, temperature, electromagnetic wave, electrical current, a magnetic field, stress, pressure, pH, etc. The new functional properties can vary in terms of shape, size, ductility, colour, etc. (Sharp & Clemen, 2004) (see figure 1).

In comparison to common materials, the response of smart materials is simple and immediate. Their versatility, aligned with the ability to control their properties via external stimuli, make them interesting for utilisation in a wide variety of applications such as aerospace, environment electronics, civil, electrical, medicine (controlled release of drugs, treatment of various diseases, biosensors), hospitality, agriculture, mechanical, sports, marine, defence, etc. (Mukherjee et al., 2021; Thangudu, 2020).

3.2 Types and classification of smart materials

Different types of smart materials exist, such as piezoelectric materials, magneto-rheostatic materials, electro-rheostatic materials and shape-memory alloys (see table 4). Each type has a different property that can be significantly altered.

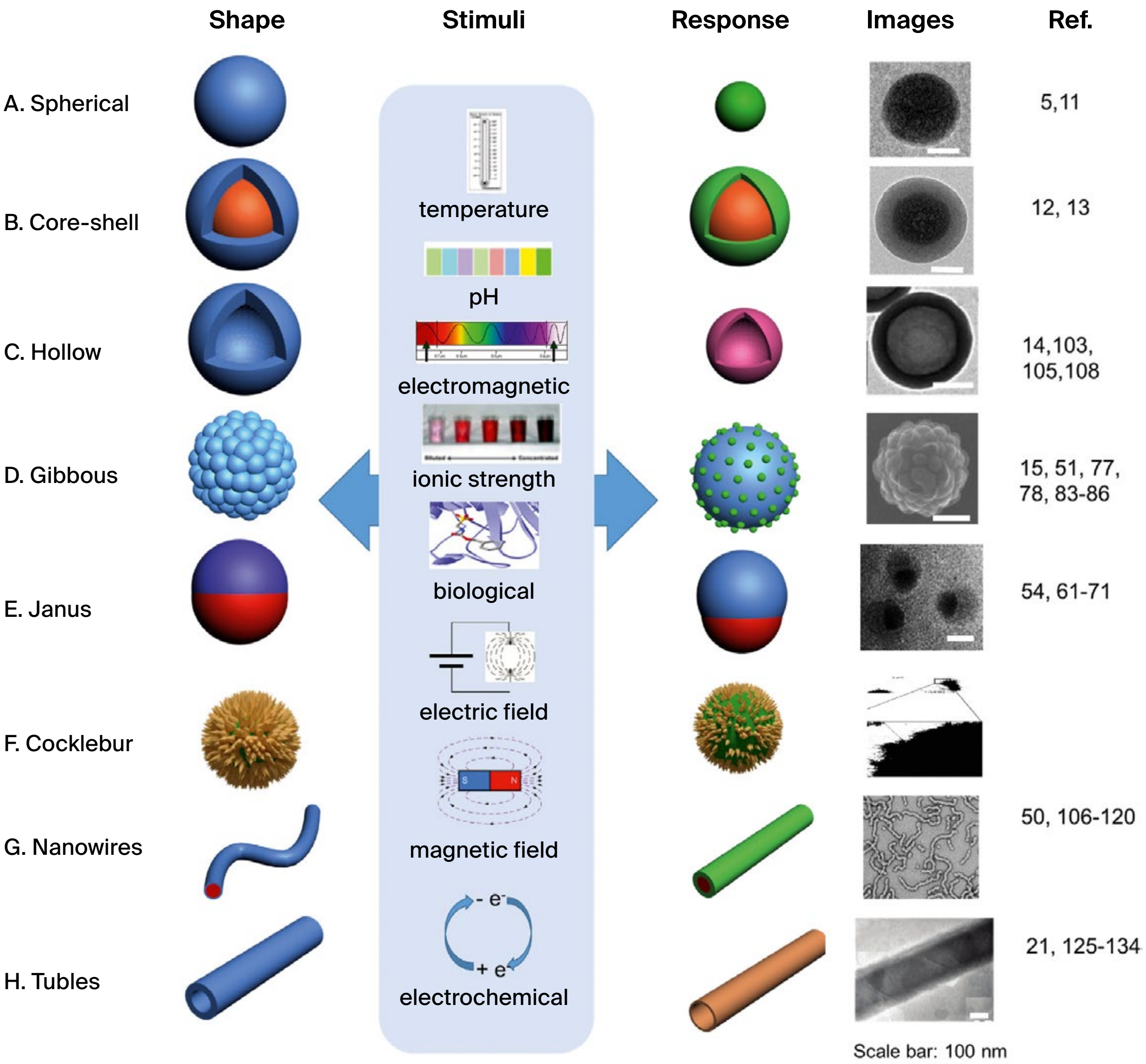

Figure 1 | Schematic representation of various shapes and morphological changes of nano-objects in response to physical or chemical stimuli, along with representative examples provided by electron microscopic images (from Lu & Urban, 2018, reprinted with permission)

Table 4 | Various types of smart materials (adapted from BBC, 2022; Mukherjee et al., 2021; TCE, 2022)

Smart Material	Altered property	Materials used	Applications
Piezoelectric materials	Change of properties when a force is applied on them	Quartz, $BaTiO_2$, $GaPO_4$, lead zirconium titanate (PZT)	Microscale energy harvesting, sensors, actuators, automobiles, clocks, stringed instruments, ultrasound machines, medical camera lenses
Electrostrictive materials	Change of properties when an electric field is applied	Lead magnesium niobate (PMN) lead magnesium niobate-lead titanate (PMN-PT) lead lanthanum zirconate titanate (PLZT)	
Magnetostrictive materials	Change in strain (deformation) when a magnetic field is applied on them	Fe, Co, Terfenol-D	Actuators and sensors, sonars, ultrasound transducers, sound bugs, vibration speaker technology
Rheological materials	Change in physical state when a magnetic or an electrical field is applied	20—40 % Fe nanoparticles suspended in mineral oil, synthetic oil, water or glycol as well as substance that prevent Fe-nanoparticles from setting	Automobile sector
Thermo-responsive material	Polymers that change form and physical properties when exposed to any temperature variation		Vehicles, aircrafts, thermostats
Shape-memory polymer and alloys	Polymer and alloys that can be returned to their original shape when heated	NiTiNol (NiTi-alloy), NiMnGa, Fe-Pd, Terfenol-D, CuZnSi, CuZnAl, CuZn, Ga, CuZnSn	Helmets, car bumpers, medical stiches, surgical plates, robotics, spectable frames, braces
Thermochromic pigments	Change in colour at specific temperatures		Mugs, spoons, battery power indicators, forehead thermometers, ink on eggs and beer
Electrochromic materials	Change in optical properties when an electric current is passed through it		Lithium-ion batteries
Fullerenes and carbon nanotubes (CNT)	Highly stable and versatile hexagons and pentagons of caged spheres consisting of carbon atoms	C_{60}, SWCNTs, MWCNTs	Electronics, corrosion resistance, crack prevention to mechanical durability
Graphite fibres	Thin, inflammable, lightweight carbon strands with excellent tensile strength, and conductance with a low coefficient of thermal expansion		Aircraft, ships and satellites to mobile phone covers, concrete, timber and steel structures
Biomimetic materials	Materials that are inspired by nature and its simple and effective geometric shapes to obtain desirable properties		Used to obtain strength, camouflage, waterproofing, mobility and self-sensing to self-repairing in buildings
Photochromic pigments	Change colour when exposed to light		Lenses for glasses, glass for welding glasses
Hydrogels	Able to absorb and release water in response to changes in temperature or pH		Artificial muscles, hair gels, nappies, expanding snow, granulates to retain water for plants

Many stimuli exist, including pH, enzymatic, redox, glucose, thermal, photo, magnetic, electrical and mechanical, and smart materials are often classified with respect to specific stimuli (Thangudu, 2020).

3.3 Application and uses of smart materials

The application of smart materials is very broad and ranges from use in composites (Gobin et al., 1996), polymers (Roy et al., 2010), aeroelastic and vibration control (Giurgiutiu, 2000), nanotextiles (Coyle et al., 2007) and nanocellulose-enabled electronics (Sabo et al., 2016), through to health (Brei, 1998), biomedical applications (Thangudu, 2020), micro- and nanorobots (Arvidsson & Hansen, 2020; Soto et al., 2022) and engineering (Aher et al., 2015) and civil engineering in general (Mukherjee et al., 2021). Some everyday items already incorporate smart materials, such as coffee pots, cars, the International Space Station and eyeglasses — and the number of applications is growing steadily (Industry Research, 2022).

Use of smart materials in the development of buildings

The use of smart materials is said to be changing the face of traditional engineering materials due to their widespread and multidisciplinary applications across all domains of human invention. When it comes to the development of buildings, they can be utilised individually as well as incorporated into existing materials to enhance a plethora of desirable properties. Major advantages of smart materials include that they can, for instance, increase resistance against corrosion, cracks, fire, chemicals and fatigue, as well as provide means to implement more environmentally friendly and energy-efficient building designs (Mukherjee et al., 2021). Examples of smart materials often mentioned include graphite fibres, which can be used in wind turbines and mouldings, transparent materials (such as aluminium and concrete), self-healing materials (such as concrete and coating), shape-memory metals (such as shape-shifting materials for use in concrete), resistant structures and pipe couplings, and aerogels used for heat and sound insulation and for capturing bacteria and dust particles. Some smart materials are already in use in the construction industry, such as self-sensing concrete, consisting of carbon fibre-reinforced concrete, smart bricks that have electrodes or basic electronic components (sensors, signal processors and a communicator) embedded along with conductive nanofiller, smart wrap, consisting of carbon nanotubes and various smart layers, for instance, to control temperature, and smart glass stimulated by sunlight, heat and electrical current (Mukherjee et al., 2021).

Use of smart nanomaterials in biomedical applications

Within the field of smart materials for biomedical applications, smart nanomaterials have received special attention due to their ability to overcome passive retention mechanisms and non-specific cellular uptake. They have been widely used in diverse biomedical fields, including cancer therapy, the delivery of drugs, genes and proteins, tissue engineering, biological imaging and biosensing, and antimicrobials (Mele, 2018).

Thangudu (2020) reviewed the applications and characteristics of smart nanomaterials in biomedical applications. Piezoelectric materials such as polydimethylsiloxane single-walled carbon nanotubes, boron titanate nanoparticles, PZT nanoribbons and enzyme/ZnO nanoarrays can be used to monitor human conditions, detect minute cellular deformations and engage in real-time biosensing, due to characteristics such as fast response times, high stability, chemical and temperature resistance and minimal invasiveness. AuNPs-PF127-HPMC and single-walled carbon nanotubes (SWCNTs) are examples of thermo- and photo-responsive materials used in drug delivery and in vivo imaging, respectively, whereas Au nanoparticles have been used as a pH-dependent material and photo-responsive material for in vivo therapy.

Use of smart materials in biodegradable packaging materials

A final area of application that has received increasing attention is the use of smart materials for developing biodegradable forms of packaging materials as an alternative to synthetic polymers (Cvek et al., 2022; Halonen et al., 2020; Sani et al., 2021). Smart packaging consists of biodegradable, film-forming materials, such as proteins, polysaccharides and lipids, and a natural pigment. The packaging can be designed to undergo a colour change in response to alternations in the ripeness, quality or safety of a food item, such as, for instance, a change in pH, temperature, moisture content, gas levels, light exposure, chemical composition or enzyme activity. Designing the packaging material so that it releases active ingredients, such as antioxidants or antimicrobials, into the food in order to protect it is also an option that is being explored. Such applications can help to reduce food waste, including animal products, and hence lower greenhouse gas emissions and the need to deploy land for food production. Nanoparticles, such as nanoclays, iron oxide (Fe_2O_3), titanium dioxide (TiO_2), silver (Ag), zinc oxide (ZnO), chitin and cellulose can be used to enhance the functional performance of these packaging materials.

The most common sensors that have been developed for applications in smart packaging materials suitable for food applications are indicators for pH, gas and time temperature (Halonen et al., 2020; Sani et al., 2021). pH indicators provide a measurable change in the pH of a packaged food that may be caused by enzymatic activity, chemical reaction or microbial growth. Natural pigments are preferred over synthetic dyes due to the increasing consumer demand for clean-label products. Anthocyanins are currently the most used natural pigments due to their ability to exhibit colour changes over a broad range of pH values. Examples of pH-sensitive indicators using anthocyanins derived from various botanical sources include saffron petal, black rice bran, purple corn and black soybean coat (Halonen et al., 2020; Sani et al., 2021). Anthocyanins are incorporated into biopolymer-based smart packaging materials and have been shown to be useful in a number of applications, including for pork, shrimp, chicken and fish. Other natural pigments include carotenoids that have been incorporated into polylactic acid films to monitor and control the oxidation of sunflower oil, whilst betacyanin has been incorporated into glucomannan/polyvinyl alcohol films as an indicator of the freshness of packaged fish. When it comes to the detection of gases, different kinds of natural pigments can be used in this regard and be incorporated into packaging materials in a variety of ways, including adhesive labels, printed layers or on the interior of films. As a result, these smart packaging materials can provide a cheap and quick way to detect different kinds of gases, including oxygen, carbon dioxide and hydrogen sulphide. Finally, the use of natural pigments as temperature sensors includes various types of anthocyanins isolated from vegetable extracts, blue flowers, pomegranate juice and the like. One example of such sensor is anthocyanin incorporated in a chitosan/cellulose matrix (Halonen et al., 2020; Sani et al., 2021).

4.

Conclusion: Health and environmental impacts and SSbD of smart materials

One of the greatest challenges when it comes to assessing safety early in the design phase of, for instance, smart materials is that data is often not available (Mech et al., 2022). However, if the new chemical is originally registered under REACH and used in a quantity above 1 ton/year, it will already have been assessed in terms of its risks (dependent on the expected tonnage) before being placed on the market. This is partly one of the culprits in current risk governance, in that for foreseen uses below 1 ton, there is not a great deal of incentive to avoid the use of SOCs.

Another challenge relates to the need for reliable data, as stakeholders need it to evaluate the safety and sustainability of chemicals. Accessible and open databases, for example, with hazard profiles for both existing and novel chemicals, are often suggested by the industry and other stakeholders but are rarely available (H&M Group et al., 2022; van der Waals et al., 2019). Many innovations, however, do not require the use of new chemicals but can make use of existing options known to be safe (i.e., not belonging to the SOCs group).

Health and environmental impacts, as well as our current lack of understanding of long-term effects, have been pointed out as some of the disadvantages of smart nanomaterials (Mukherjee et al., 2021; Thangudu, 2020). For instance, when it comes to piezoelectric nanostructured materials, Thangudu (2020) points out that "[…] further research efforts are still necessary for the evaluation of the nanomaterial biocompatibility, retention, degradability, accumulation in complex in vivo systems before actual exploitation in clinical context". Similarly, concerns about health and environmental impacts of fullerenes have been noted by Mukherjee et al. (2021). Furthermore, some smart materials consist of elements such as Ni and Cu that are well-known to be environmentally toxic and even more toxic at the nanoscale. These materials are classified according to EU regulations relating to the classification and labelling of chemical substances and could potentially be considered as causing, for instance, "chronic environmental toxicity (chronic aquatic toxicity)". Hence, they would not be considered as SSbD, as they would not meet the initial cut-off criteria in Step 1 of the framework proposed by the JRC.

For chemicals and materials that do not meet the cut-off criteria, these should only be allowed in uses proven essential for society. Although the term "essential use" is subject to discussion, it seems safe to say that there are many applications of smart materials that cannot reasonably be argued to be necessary for health, safety or the functioning of society and that there are no acceptable alternatives. These applications include inks on beer cans and eggs (see table 4). Although smart materials are often said to come at a high cost, and require delicate designs and sensitive work for high-end project applications (Mukherjee et al., 2021), it is not always what it seems, and many initial applications of emerging materials appear to be gadgets and quite meaningless. Many smart materials, furthermore, lack research and practical evidence on their application and efficiency. In general, the practical utility of smart materials has not yet been studied (Mukherjee et al., 2021).

Specific studies on the sustainability of smart materials are lacking. Mukherjee et al. (2021) mention that one kind of smart material, namely graphite fibre, is costly, low in compressive strength and non-recyclable, and hence it should not be used for general application. It is often mentioned that its use could help minimise energy consumption and CO_2 emissions, reduce waste, increase sustainability and improve economic viability (Mukherjee et al., 2021; Sani et al., 2021). However, these claims about environmental benefits are often unsubstantiated, and no data and information are currently available to support these claims. The lack of data and information about the sustainability of smart materials means that it is not possible to evaluate their performance with regard to the subsequent steps and cut-off criteria for SSbD proposed by the JRC and others — and smart materials can therefore, not be classed as SSbD.

Consequently, it is not possible to evaluate the possible (anticipated, expected, potential) risks of smart materials to environmental sustainability (i.e., to biodiversity, ecosystems, natural resources and the climate) or indications of human health, social, ethical or other concerns that may influence the development of the technology or its uptake in industry and society.

When scanning the literature on types and categories of smart materials, it is evident that many of them are based on polymers, nanomaterials or microrobots. The risk assessment and regulation of each of these has historically been challenging, and even when in their "benign" version, one can only imagine the additional challenges the smart version of a material might pose. For instance, Broomfield et al. (2016) pointed out that the regulatory definition of polymers may not be adequate for high-performance polymers that have been modified and reinforced with bio-fibres and/or nanocharges that result in materials with very advanced properties. Information on the effects of polymers on human health is still in the preliminary stage, whilst limitations in current methodologies prevent accurate human exposure/risk assessments (Paulsen et al., 2021). In addition, there is a mismatch between the technical definition of polymers and the ECHA definition of a polymer. Technically, polymers are defined as being large molecules with specific material properties and which are too large to be bioavailable from, for example, food. In contrast, ECHA defines a polymer as three repeat monomer units, which may easily be of a sufficiently small size to be bioavailable upon transfer in the gut or over intestinal barrier, regardless of their weight exceeding 1000 Da, as in the case of fluorinated compounds (Trier et al., 2011).

The (eco)toxicity of several nanomaterials used in smart materials, such as Cu, Ni and CNTs, is well-known (Denkhaus & Salnikow, 2002; Hansen, 2016; Hansen & Lennquist, 2020b, 2020a; Kjølholt et al., 2015), but establishing the (eco)toxicological hazard profiles of many nanomaterials has been challenging despite substantial effort in this regard. For instance, it remains unclear whether — and to what extent — the interactions between particle characteristics (e.g., particle size distribution, surface chemistry, volume-specific surface area) affect the overall hazard of a given nanomaterial, which again hampers its ability to be classified as SSbD (Clausen & Hansen, 2018; Hansen et al., 2022). With regard to nanorobots, Arvidsson and Hansen (2020) identified two potential hazards, namely the use of hazardous materials, such as foreign DNA, Ni, Ag and UV light, and the loss of propulsion/targeting control. The latter could be termed a novel hazard associated with nanorobots and relates to the control of their propulsion and navigation — whether by chemical propulsion, magnetic fields, sound waves, bioreceptor binding and/or light — potentially making these nanorobots travel to places in the human body and elsewhere where they are not supposed to be, for instance hazardous drugs being delivered to healthy cells. It also remains an open question as to whether the body can excrete advanced drug delivery systems, such as soft nanoparticles and amphiphilic polyfluorinated miktoarm star polymers and if not, how this may affect organs and other functions. Obtaining approval for medical products and devices is arguably one of the most lengthy, thorough and expensive regulatory processes, due to various phases of clinical testing and safety and benefit assessments. Nevertheless, regulations in the EU and elsewhere have been criticised for being insufficient when it comes to more complex drugs (Editorial, 2007). According to Arvidsson and Hansen (2020), it even remains unclear whether nanorobots should be considered a medical device or a medicinal product in the EU, which is important, as different sets of regulations would apply. The "mechanism of action" is used to decide on whether a product should be regulated as a medical device or a medicinal product. The mechanism of action can be pharmacological, immunological or metabolic. For nanorobots, this means that their categorisation according to mechanism of action is challenged by the fact that they use complex mechanisms of action combining mechanical, chemical, pharmacological and immunological properties, and they can also have both diagnostic and therapeutic functions (Hansen & Baun, 2012).

Whether polymers, nanomaterials or micro- and nanorobots, it is very important to understand the various kinds and compositions of smart materials and their unique properties with specific stimulating agents during application (Thangudu, 2020) before assessing their risks and sustainability. This is important as the kind and composition as well as unique properties of specific stimulating agents used during application influence the hazards and the potential exposure routes of a given smart material. Gaining access to this kind of information early in the development process can be very challenging. Similarly, it is not clear whether one would need to assess the materials used to form the smart materials, such as Cu, Ni and CNTs, or the smart materials themselves, as they come with and without (multi-)stimuli. When it comes to their components, hazard and/or risk assessments can be informative, although risk assessments do seem inadequate. Besides the lack of data and the challenges in this regard, the interdisciplinary nature of smart materials (physics, biology, chemistry, engineering, material science and information technology) is challenging when it comes to risk assessment and governance — as noted previously (Gee et al., 2013; Harremoës et al., 2001). More holistic approaches, such as technology assessments (similar to the one proposed by UNEP (2015) might be more helpful when it comes to assessing smart materials and their overall application. In general, it seems obvious that avoiding the use of harmful chemicals, such as substances of concern, and ensuring their potential reuse, disassembly and recycling are key considerations in making smart materials part of the solution rather than preventing zero pollution and a circular economy in which clean materials are safe to recycle.

Acknowledgements

IRGC would like to thank Janeck James Scott-Fordsmand and Aleksandra Malyska for offering comments on a first draft of this paper. The views presented in this paper are those of the authors and are not a consensus judgement by IRGC.

References

Aher, S. S., Desarda, A., Shelke, J. A., & Chaudhari, M. (2015). A review on smart materials: Future on potentials in engineering. *International Journal of Science Technology and Management Future on Potentials in Engineering, 4*(10), 7–16. ijstm.com/images/short_pdf/1444648055_P07-16.pdf

Anastas, P., & Eghbali, N. (2009). Green chemistry: Principles and practice. *Chemical Society Reviews, 39*, 301–312. doi.org/10.1039/B918763B

Arvidsson, R., & Hansen, S. F. (2020). Environmental and health risks of nanorobots: An early review. *Environmental Science: Nano, 7*, 2875–2886.

BBC. (2022). *Nanoscience and smart materials*. bbc.co.uk/bitesize/guides/z6r7xfr/revision/3

Brei, D. (1998). Smart structures: Sensing technologies for structural, health monitoring. *SAE International*. doi.org/10.4271/981508

Broomfield, M., Hansen, S. F., & Pelsy, F. (2016). *Support for 3rd regulatory review of nanomaterials – environmental legislation*. European Commission. publications.europa.eu/en/publication-detail/-/publication/cf73479b-b601-11e6-9e3c-01aa75ed71a1

Caldeira, C., Farcal, R., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Sintes, J. R., & Sala, S. (2022). *Safe and Sustainable chemicals and materials by Design Framework*. doi.org/10.2760/487955

Camboni, M. (2017). *Study for the strategy for a non-toxic environment of the 7th EAP Sub-study e: Policy means, innovation and competitiveness*. European Commission. ec.europa.eu/environment/chemicals/non-toxic/pdf/Sub-study e innovation competitiveness NTE final.pdf

Cefic. (2022). *Safe and sustainable-by-design: The transformative power behind circular and climate neutral innovations*. European Chemical Industry Council. cefic.org/media-corner/newsroom/safe-and-sustainable-by-design-the-transformative-power-behind-circular-and-climate-neutral-innovations/

ChemSec. (2021). Our view on Safe and Sustainable by Design criteria. *International Chemical Secretariat*. chemsec.org/publication/chemical-strategy/our-view-on-safe-and-sustainable-by-design-criteria/

Clausen, L. P. W., & Hansen, S. F. (2018). *Nature Nanotechnology, 13*, 766–768.

Coyle, S., Wu, Y., Lau, K.-T., Rossi, D., Wallace, G., & Diamond, D. (2007). Smart nanotextiles: A review of materials and applications. *MRS Bull, 32*(5), 434–442.

Cvek, M., Paul, U. C., & Zia, J. (2022). Biodegradable films of PLA/PPC and curcumin as packaging materials and smart indicators of food spoilage. *ACS Applied Materials & Interfaces, 14*(12), 14654–14667.

Denkhaus, E., & Salnikow, K. (2002). Nickel essentiality, toxicity, and carcinogenicity. *Critical Reviews in Oncology / Hematology, 42*(1), 35–56.

EC. (2019). *Communication from the Commission: The European Green Deal*. eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640&from=EN

EC. (2020a). *Annex to the Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions chemicals strategy for sustainability towards a toxic-free environment*. *COM (2020) 667 final*. eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A667%3AFIN#document2

EC. (2020b). *Commission Staff Working Document. Progress report on the assessment and management of combined exposures to multiple chemicals (chemical mixtures) and associated risks*. op.europa.eu/en/publication-detail/-/publication/2e7f5564-0f02-11eb-bc07-01aa75ed71a1/language-de

EC. (2020c). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Chemicals strategy for sustainability towards a toxic-free environment*. eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:667:FIN

EC. (2022a). *Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions on making sustainable products the norm*. eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0140&from=EN

EC. (2022b). *Establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/124/EC. COM (2022)*.

Editorial. (2007). Regulating nanomedicine. *Nature Materials, 6*(249).

EEA. (2019a). *Paving the way for a circular economy: Insights on status and potentials* [Publication]. eea.europa.eu/publications/circular-economy-in-europe-insights

EEA. (2019b). *The European environment — State and outlook 2020. Knowledge for transition to a sustainable Europe* [Publication]. eea.europa.eu/soer/publications/soer-2020

EEA. (2021). *Designing safe and sustainable products requires a new approach for chemicals* [Briefing]. eea.europa.eu/themes/human/chemicals/delivering-products-that-are-safe

Fantke, P., Cinquemani, C., Yaseneva, P., De Mello, J., Schwabe, H., Ebeling, B., & Lapkin, A. A. (2021). Transition to sustainable chemistry through ddigitalisationScienceDirect. *Chem, 7*(11), 2866—2882. sciencedirect.com/science/article/pii/S2451929421004745

Gee, D., Grandjean, P., Foss Hansen, S., Hove, S., MacGarvin, M., & Martin, J. (2013). *Late lessons from early warnings: Science, precaution, innovation*. European Environment Agency.

Ghosh, S. K. (2008). *Self-healing materials: Fundamentals, design strategies, and applications* (pp. 1—28). doi.org/10.1002/9783527625376

Giurgiutiu, V. (2000). Review of smart-materials actuation solutions for aeroelastic and vibration control. *Journal of Intelligent Material Systems and Structures, 11*(7), 525—544.

Gobin, P.-F., Gutnin, G., Morin, M., Salvia, M., & Tatibouet, J. (1996). Smart materials: A future for composites. *Journal of Intelligent Material Systems and Structures, 7*(3), 353—357.

Halonen, N., Pálvölgyi, P. S., Bassani, A., Fiorentini, C., Nair, R., Spigno, G., & Kordas, K. (2020). Bio-based smart materials for food packaging and sensors – A review. *Frontiers in Materials, 7*(82). frontiersin.org/articles/10.3389/fmats.2020.00082/full

Hansen, S. F. (2016). The emergence of nano risk-immunity. *Frontiers in Nanoscience and Nanotechnology, 2*(3), 131–134.

Hansen, S. F., Arvidsson, R., Nielsen, M. B., Hansen, O. F. H., Clausen, L. P. W., Baun, A., & Boldrin, A. (2022). Nanotechnology meets circular economy. *Nature Nanotechnology, 17*, 682—685.

Hansen, S. F., & Baun, A. (2012). European regulation affecting nanomaterials—review of limitations and future recommendations. *Dose-Response, 10*(3), 364—383.

Hansen, S. F., Krauss, M. P., & Tickner, J. A. (2007). Categorising mistaken false positives in regulation of human and environmental health. *Risk Analysis, 27*(1), 255—269.

Hansen, S. F., & Lennquist, A. (2020a). Carbon nanotubes added to the SIN List as a nanomaterial of Very High Concern. *Nature Nanotechnology, 15*, 3—4.

Hansen, S. F., & Lennquist, A. (2020b). SIN List criticism based on misunderstandings. *Nature Nanotechnology*. doi.org/10.1038/s41565-020-0692-7

Hansen, S. F., & Tickner, J. A. (2013). The Precautionary Principle and false alarms. *European Environment Agency*. eea.europa.eu/publications/late-lessons-2

Harremoës, P., Gee, D., MacGarvin, M., Stirling, A., Keys, J., & b, W. (2001). *Late lessons from early warnings: The precautionary principle 1896—2000*. European Environment Agency.

Hauschild, M. Z., McKone, T. E., Arnbjerg-Nielsen, K., Hald, T., Nielsen, B. F., Mabit, S. E., & Fantke, P. (2022). Risk and sustainability: Trade-offs and synergies for robust decision-making. *Environmental Sciences Europe, 34*(1), 11. doi.org/10.1186/s12302-021-00587-8

H&M Group, Tarkett, Nudie Jeans co, S., ChemSec, Shaw, Seventh generation, & EurEau. (2022). *Open letter to the Commission regarding transparency*. chemsec.org/open-letter-to-the-commission-regarding-transparency/?utm_source=Newsletter&utm_medium=E-

Industry Research. (2022). Global smart materials market outlook to 2027 | North America having largest 33% market share followed by Europe about 32% | Industry size-share, growth drivers, restraints, opportunities, product overview, scope, applications, and demand. *Industry Research*. www.globenewswire.com/en/news-release/2022/02/25/2392179/0/en/Global-Smart-Materials-Market-Outlook-to-2027-North-America-Having-Largest-33-Market-Share-Followed-By-Europe-about-32-Industry-Size-Share-Growth-Drivers-Restraints-Opportunities-P.html

IRGC. (2022). *Ensuring the environmental sustainability of emerging technologies*. EPFL International Risk Governance Center (IRGC). dx.doi.org/10.5075/epfl-irgc-292410

Kjølholt, J., Gottschalk, F., Holten Lutzhøft, H.-C., Hartmann, N., Nowack, B., & Baun, A. (2015). Environmental assessment of nanomaterial use in Denmark. *Danish Environmental Protection Agency*.

Kumara, A., & Arockiarajan, A. (2022). Evolution of nonlinear magneto-elastic constitutive laws in ferromagnetic materials: A comprehensive review. *Journal of Magnetism and Magnetic Materials, 546*, 168821. doi.org/10.1016/j.jmmm.2021.168821

Lennquist, A. (2022). *Senior toxicologist at ChemSec. Personal Communication*.

Lu, C., & Urban, M. W. (2018). Stimuli-responsive polymer nano-science: Shape anisotropy, responsiveness, applications. *Progress in Polymer Science, 78*, 24–46.

Mech, A., Gottardo, S., & Amenta, V. (2022). Safe-and sustainable-by-design: The case of Smart Nanomaterials. A perspective based on a European workshop. *Regul Toxicol Pharmacol, 128*, 105093. doi.org/10.1016/j.yrtph.2021.105093

Mele, E. (2018). Introduction: Smart materials in biomedicine. In G. Ciofani (Ed.), *Smart nanoparticles for biomedicine micro and nano technologies* (pp. 1–13). doi.org/10.1016/B978-0-12-814156-4.00001-X

Milieu Ltd, Ökopol, Risk & Policy Analysts (RPA) and RIVM. (2017). *Study for the strategy for a non-toxic environment of the 7th Environment Action Programme final report*. ec.europa.eu/environment/chemicals/non-toxic/pdf/NTE%20main%20report%20final.pdf

Mukherjee, A., Singh, D., Srivastava, P., & Sandhu, J. K. (2021). Application of smart materials in civil engineering: A review. *Proceedings Materials Today: Proceedings In Press*. doi.org/10.1016/j.matpr.2021.03.304

Packroff, R., & Marx, R. (2022). Safe and Sustainable by Design — An interdisciplinary challenge for future-proof chemistry. *ChemPlusChem, 87*, 202100534.

Paulsen, F. L., Nielsen, M. B., Shashoua, Y., Syberg, K., & Hansen, S. F. (2021). Early warning signs applied to plastic. *Nature Review Material, 7*, 68—70.

Persson, L., Carney Almroth, B. M., Collins, C. D., & et al. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environmental Science & Technology*. pubs.acs.org/doi/10.1021/acs.est.1c04158

Rogers, C. A. (1988). *US Army Research Office workshop on smart materials, structures and mathematical issues held in Blacksburg, Virginia on 15—16 September 1988*. Virginia Polytechnic Institute and State University Blacksburg. apps.dtic.mil/sti/pdfs/ADA218528.pdf

Roy, D., Cambre, J. N., & Sumerlin, B. S. (2010). Future perspectives and recent advances in stimuli-responsive materials. *Progress in Polymer Science, 35*(1–2), 278—301.

Sabo, R., Yermakov, A., Law, C. T., & Elhajjar, R. (2016). Nanocellulose-enabled electronics, energy harvesting devices. *Journal of Renewable Materials, 4*(5), 297—312. doi.org/10.7569/JRM.2016.634114

Sani, M. A., Azizi-Lalabadi, M., Tavassoli, M., Mohammadi, K., & McClements, D. J. (2021). Recent advances in the development of smart and active biodegradable packaging. *Materials Nanomaterials, 11*, 1331.

Sharp, S. R., & Clemen, G. G. (2004). *State-of-the-art survey of advanced materials and their potential application in highway infrastructure* (Issue FHWA/VTRC, pp. 5—9). rosap.ntl.bts.gov/view/dot/19660

Soto, F., Karshalev, E., & Zhang, F. (2022). Smart materials for microrobots. *Chemical Reviews, 122*, 5365—5403. pubs.acs.org/doi/full/10.1021/acs.chemrev.0c00999

Spillman, W. B., Sirkis, J. S., & Gardiner, P. T. (1996). Smart materials and structures: What are they? *Smart Materials and Structures, 5*(3). doi.org/10.1088/0964-1726/5/3/002

TCE. (2022). *Smart materials*. Thiagarajar College of Engineering. www.tce.edu/sites/default/files/PDF/RV4-Smart-Materials.pdf

Thangudu, S. (2020). Next generation nanomaterials: Smart nanomaterials, significance, and biomedical applications. In F. A. Khan (Ed.), *Application of nanomaterials in human health*. doi.org/10.1007/978-981-15-4802-4_15

Trier, X., Granby, K., & Christensen, J. H. (2011). Tools to discover anionic and nonionic polyfluorinated alkyl surfactants by liquid chromatography electrospray ionisation mass spectrometry. *Journal of Chromatography, 1218*(40), 7094–7104.

UNEP. (2015). *Anticipating the environmental effects of technology. A manual for decision-makers, planners and other technology stakeholders*. www.unep.or.jp/ietc/publications/integrative/enta/aeet/index.asp

van der Waals, J., Falk, A., Fantke, P., Filippousi, V., Flipphi, R., Mottet, D., & Trier, X. (2019). Safe-by-design for materials and chemicals: Towards an innovation programme in Horizon Europe. In *Safe-by-design for materials and chemicals: Towards an innovation programme in Horizon Europe* [Report]. doi.org/10.5281/zenodo.3254382