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Testing the Applicability of the Safe-by-Design Concept: A Theoretical Case Study Using Polymer Nanoclay Composites for Coffee Capsules

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Abstract: The production and use of engineered nanomaterials and nano-enabled products is increasing, enabling innovations in many application areas, e.g., in the sector of food contact materials. However, nanosafety-relevant information for chemical risk assessment is still scarce, leading to a high level of uncertainty and making the early integration of safety to the innovation process indispensable. This study analyzed the strengths, weaknesses, and applicability of the nano-specific Safe-by-Design (SbD) concept using nanoclay-containing polymer coffee capsules as a theoretical case study. In addition, a material flow analysis was conducted to identify exposure pathways and potential risks, and a multi-stakeholder approach was applied to discursively discuss challenges when attempting to combine safety and innovation at an early stage. The results indicate that the SbD concept is generally welcomed by all stakeholders, but there is a lack of clear rules on the transfer of information between the actors involved. Furthermore, a voluntary, practical application usually requires in-depth knowledge of nanotechnology and often additional financial efforts. Therefore, incentives need to be created, as there is currently no obvious added value from a company's point of view. The SbD concept should be further developed, standardized, and integrated into existing legal frameworks to be implemented effectively.

Keywords: Safe-by-Design; chemical risk management; risk governance; nanomaterials; food contact materials; polymer nanocomposites; coffee capsules; nanoclay

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1. Introduction

Although nanotechnology is considered a key enabling technology, it has also been identified as being one of six emerging issues of environmental concern by the United Nations in 2017 [1]. This is since the unique physical, chemical, and biological properties of nanomaterials, which have a size between 1 and 100 nm in at least one dimension and enable novel functionalities and applications, are the same properties that could cause adverse effects or pose a threat in different biological contexts [2]. Nanotechnology is recognized as a contributing field to economic growth, competitiveness of industry, and societal well-being [3], but the rapidly paced production of engineered nanomaterials (ENMs) has left knowledge gaps within the fields of nanosafety research, ranging from ENM identification and classification [4], nanotoxicity [5], life cycle, and exposure assessment [6] to risk governance [7]. The scientific community has made significant advancements in the last few years, but some highly relevant questions concerning nanosafety remain open,

and thus, the design of safe(r) ENMs and nano-enabled products (NEPs) has gained increasing attention [8]. This is also to be regarded in light of new generations of ENMs in industrial products and associated increasing challenges [9]. For a safe and sustainable development of nanotechnology, it is therefore of utmost importance to further develop nano-specific early risk and safety assessment methods for ENMs and NEPs. Currently, all substances that are manufactured or imported in amounts of more than one metric ton per year in the EU have to be registered according to the European regulation EC 1907/2006 for the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) [10]. This requires risk-relevant information, such as production volume, physicochemical properties (particle size, morphology, etc.), and results from studies on both hazard and exposure assessment to be documented, but may still not fully cover all ENM types and their nano-specific properties [11].

For this reason, various European projects (NANoREG, NanoReg2, Prosafe) have aimed at developing a safe innovation approach (SIA) for ENMs and NEPs, resulting in the development of a nano-specific Safe-by-Design (SbD) concept [9]. In general, "Safe-by-Design" is a term for which different interpretations can coexist. It is derived from several similar approaches, such as "Design for Safety," "Green Chemistry," and "Quality by Design", which are described in more detail in Section S1 of the Supplementary Material. The nano-specific SbD concept, developed within the aforementioned projects, aims to identify the risks and uncertainties concerning human health and the environment at an early stage [8]. It applies the stage–gate model—first described by Cooper [12,13]—for information-gathering and decision-making in the early innovation process of ENMs and NEPs [14]. So-called safety dossiers are introduced that are primarily intended to help the standardization of ENM-specific data, which must be provided prior market launch according to REACH and its annexes regardless [11]. Thus, the SbD concept can be seen as a prelude to REACH registration. The stage–gate model is linear and structured into "stages" and "gates," where "gatekeepers" have a regulatory character and can terminate the innovation process at an early stage once unacceptably high uncertainties or risks are identified. "Gates" are decision points at the end of "stages," where an assessment is made that serves as a basis for the subsequent decision. This linear process flow is intended to facilitate the transfer of safety-relevant data. In this manner, uncertainties should be reduced along the entire product life cycle as nanosafety-relevant data and know-how are systematically collected. A more detailed description of the SbD process can be found in Tavernaro et al. [8]. Additionally, a variety of different nano-specific tools for risk assessment [15], e.g., LICARA or GUIDEnano, have been developed to support and optimize SbD actions by gathering, structuring, and processing the existing information. However, these tools do not generate new information, and serve very different purposes for varying application areas and inclusion criteria [16].

Furthermore, more recently the aspect of sustainability was promoted as an additional dimension of the SbD concept for ENMs and NEPs, which is in line with EU policy initiatives, such as the European Green Deal, the European Commission's new Action Plan for a Circular Economy, and the new European Industrial Strategy and the Chemicals Strategy for Sustainability [9]. This expanded concept is referred to as a "Safe- and Sustainable-by-Design" (SSbD) approach, integrating safety, circularity, and functionality of new materials and products (including ENMs and NEPs). This approach requires that any new material or product also be cost effective, compliant with regulations, and accepted by consumers [9]. Thus, for a holistic approach, ecologic, economic, and social impacts have to be anticipated as early as possible during the innovation process in a preventative manner, and a comprehensive safe and sustainable approach should be applied from the initial planning steps (i.e., the business idea) until the end-of-life of the respective product [8,16]. However, case studies on risk-related life cycle assessment (LCA) of ENMs and NEPs are currently sparse, with knowledge gaps still remaining, especially regarding potential impacts on the environment and human health (e.g., to determine global warming, or eco- or human toxicity potential) [9,17]. Furthermore, the economic costs of adopting and

implementing such an SbD or SSbD concept for companies on a voluntary basis, especially by small and medium-sized enterprises (SMEs), were not addressed in the frameworks of the aforementioned European projects [16].

Nevertheless, standardized quality, as well as innovation and risk management processes, are currently already being implemented in most European companies. The nano-specific SbD concept can therefore be seen as a voluntary, supplementary framework with regard to REACH [10], and further sector-specific European regulations in the food and feed sector for novel foods [18], plastic food contact materials [19], active and intelligent materials and articles [20], food additives [21], food enzymes [22], food intended for infants and young children or special purposes [23], and food information to consumers [24]. The current nano-relevant regulations provide a legal framework but still do not envisage the SbD concept as a "gold standard" with legally binding validity. To improve the current situation, the Technical Committee (TC) for Nanotechnologies of the European Committee for Standardization (CEN)—(CEN/TC352)—has adopted a preliminary work item entitled "Nanotechnologies—Safe-by-Design concept dedicated for nano scale materials (MNM) and products containing nanomaterials" [9]. To date, the International Organisation for Standardization (ISO) is not aiming to develop standards concerning SbD [9].

In order to be able to close the knowledge gaps regarding nanosafety, the EU has amended REACH. According to this amendment of the REACH Annexes in 2018, more nano-specific requirements are to be provided within the framework for the risk management of ENMs [11]. For example, nanoforms of substances or mixtures must additionally be identified and characterized, and information is to be provided on the production volume, use, and safe handling, as well as on particle size, shape, and surface properties of the nanoforms [11]. These data requirements are essential for proper safety and risk assessment of ENMs and NEPs. It is an important basis for decision-makers, since both producers and competent authorities are currently confronted with uncertainties, previously unknown risks, and numerous knowledge gaps about the latest innovations of ENMs and NEPs. Data on physicochemical characteristics, functionality, application, and production of ENM/NEP need to be linked to information on safety aspects, and thus the implementation of the SbD or even SSbD approach can lead to higher regulatory preparedness and an increase in product safety [8].

Within this paper, the SbD concept is defined as an approach attempting to include sustainability aspects. Potential project risks that are difficult to predict during early innovation phases, potential risks to human health, and the environment were considered, as well as multi-stakeholder perspectives. Food contact materials (FCMs) were identified as an upcoming sector of ENM applications and the majority of the potential applications are FCMs with nanosilver and nanoclays [25]. Therefore, polymer nanoclay composite coffee capsules were selected as a theoretical product example, as this was considered very promising regarding market revenues from the perspective of the involved plastic manufacturer (an Austrian SME specializing in compounding). Nanoclay (montmorillonite), used as an FCM, is also of special interest because strict specifications apply for FCMs for their approval [26]. Through a concrete, albeit only theoretical, example, it was possible to collect safety-relevant data on nanoclay and conduct a material flow analysis (MFA), which enables the systematic description of nanoclay substance flows along the entire life cycle of coffee capsules (from plastic production to recycling or disposal) and to identify critical exposure pathways and (previously unnoticed) risks for human health and the environment. Additionally, the case study design allowed the inclusion of various stakeholder perspectives, including experts from science, industry, and public authorities. This transdisciplinary approach resulted in the identification of strengths and weaknesses of the application of the nano-specific SbD concept and enabled a discussion surrounding possible improvements.

2. Method—An Integrative Transdisciplinary Approach

In general, studying single cases or case-study research represents an ideal methodology when a holistic, in-depth investigation is needed [27]. This approach allows the exploration of details from the viewpoint of the involved stakeholders and the examination of the interactions between them. It is therefore possible to confirm or challenge a theory, or to represent a unique or extreme case—a so-called pilot case [28]. In this case study, the SbD concept was tested for its strengths, weaknesses, and applicability by using polymer nanoclay composite coffee capsules as a theoretical case study for innovative food packaging. Nanoclay was selected as a suitable additive for food-grade polymer nanocomposites like coffee capsules, because it is already listed in the EC inventory under CAS no. 1318-93-0 and EC/List no. 215-288-5 [29] and has been allowed to be used as an FCM in the EU since 2017 [30], specifically as montmorillonite clay modified by dimethyldialkyl(C16–C18)ammonium chloride.

2.1. Description of (Theoretical) Case Study and Material Composition

Every day, millions of coffee capsules are consumed, mainly composed of multi-layer composite packaging materials that are hard to recycle and lead to increased environmental impacts compared to single-layer packaging materials (see also Section S2 in the Supplementary Material). Conventional multi-layer coffee capsules are composed of an aluminum body and the inner surface is coated with a gas-impermeable multi-layered polyolefin barrier material. The outside is covered with thermoformed polyolefin or printed lacquers to be able to color the outer layer of the capsule. The lid of the capsule often consists of aluminum, which is coex-coated inside by food-grade multi-layer thin films, usually a combination of polyethylene (PE), ethylene vinyl alcohol (EVOH), and polyamide 6 (PA6). The outside or top of the lid can also contain colored printed lacquers. This complex composition of multi-layer packing materials is difficult to recycle in general, as the mix of different polymers with aluminum significantly hampers high-quality recyclability, particularly when an end-of-life coffee capsule should become a new food and beverage packaging material. For this reason, the theoretical case study was conceptualized with a mono-layer packaging material, which should ideally be composed of a recyclable and gas-impermeable food-grade polymer. Figure 1 illustrates the novel design concept, which is based on an ENM-containing polymer and served to test the applicability of the SbD concept. Polyethylene (PE), polypropylene (PP), or polybutylene terephthalate (PBT) thermoplastics are approved FCMs [19] and modifiable with (nanoscale) plastic additives. Therefore, they are suitable host materials that can be used for the capsule body. According to Regulation (EU) 10/2011 [19] on plastic materials and articles intended to come into contact with food, nanoscale silica, titanium nitride, montmorillonite (nanoclay; EC/List no. 215-288-5), zinc oxide, kaolinite, carbon black, and some co-polymers in nanoform are approved to be used as plastic additives for FCMs. Nano-platelets especially, such as nanoclays, can improve mechanical and chemical properties of the polymer host material [31–33]. Nanoclays are layered mineral silicates, such as montmorillonite, kaolinite, or bentonite. In addition, exfoliated nanoclays can effectively form a diffusion barrier in the polymer (Figure 1) and therefore they are promising additives for polymer nanocomposites and coffee capsules. Although Echegoyen et al. [34] summarized that nanoclay and dissolved components such as aluminum or silica can possibly migrate in food simulants, the European Food Safety Authority (EFSA) concluded that "no significant migration or transfer of the nanoparticles was expected under the defined conditions of use" [35]. Störmer et al. [25] summarized that the organic surface modifications of nanoclays, which are used to enhance dispersibility and exfoliation during plastic production, also play an important role regarding toxicity and migration into food. In the case of nanoclay modified with dimethyldialkyl(C16–C18)ammonium chloride, the EFSA concluded in 2015 that "the compounds are non-genotoxic" and thus it "does not give rise to safety concerns for the consumer if the substance is used at up to 12% w/w in polyolefins in contact for long-term storage of dry foods" [36] The U.S. Food and Drug Administration (FDA) drew

the same conclusions [37]. Based on this, we selected nanoclay for our theoretical case study on polymer nanoclay composite coffee capsules. It was a prerequisite that nanoclays such as montmorillonite be authorized as FCM [30] and commercially available on the market. A list of further nanoclay types currently available on the market can be found in Bumbudsanpharoke and Ko [32].

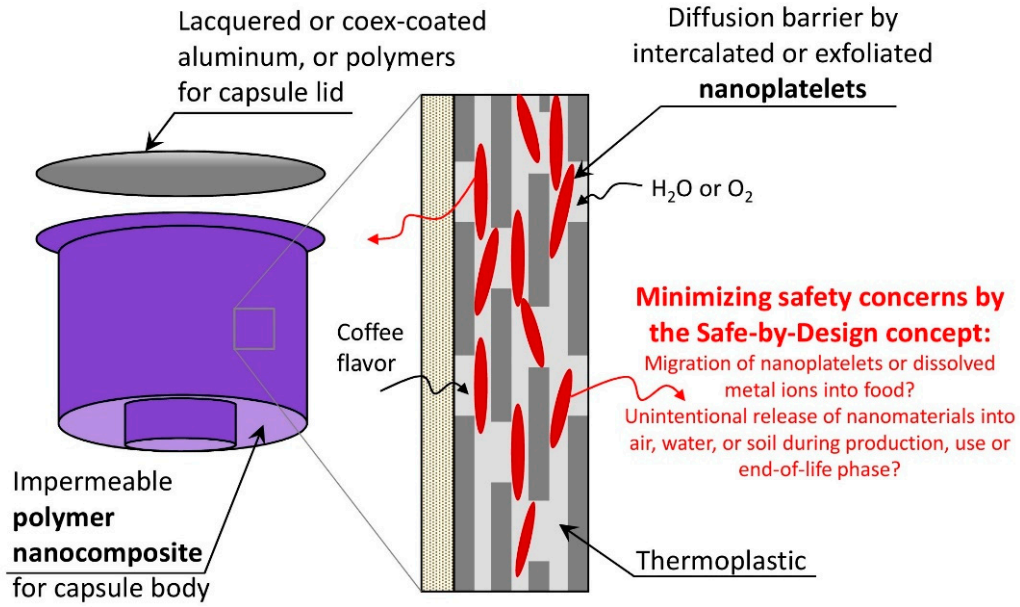

Figure 1. Schematic illustration of the architecture of nanotechnology-based innovative coffee capsules. The body of the capsule can be composed of recycling-friendly and food-grade mono-layer thermoplastics, which are modified with nanoplatelets of nanoclays to improve gas impermeability. The application of the Safe-by-Design concept should minimize potential risks at an early stage during the development and design phase.

2.2. Material Flow Analysis (MFA)

Regarding exposure assessment, which is a mandatory step when ENMs are to be placed on the European market according to REACH, the potential release of nanoclays was modeled by applying an MFA. Based on the bottom-up methodological approach of a previous study [38], a nanoclay- and coffee capsule-specific static MFA for Austria in the year 2017 (system boundaries) was conducted to identify possible exposure pathways of the nanoclay that may be released during the production, use, or end-of-life (EoL) phases. In order to quantify all material flows of nanoclays along the entire life cycle of coffee capsules, comprehensive literature research was conducted regarding nano-specific transfer coefficients [39]. Based on the safety dossiers of EFSA [36] and the FDA [40], it was concluded that the chosen nanoclays in the polymer do not migrate into the beverage during the use phase. No nanoclay-specific transfer coefficients were found in the literature for the end-of-life phase. If no material-specific coefficients are available, probabilistic approaches can be used in material flow modeling [41]. A simplified assumption can be made that the ENM behaves in the same way as its thermoplastic host material (coffee capsule) or the associated waste stream (municipal solid wastes, MSW), with the percentage partitioning of the material flows based on existing national waste statistics. In this case, it was assumed that discarded plastic coffee capsules are currently mainly disposed of as MSW.

In addition to the MFA for exposure modeling, a literature review on possible risks for human health and the environment was conducted to summarize relevant information regarding potential release pathways, amended by information gathered from a factory site visit and expert interviews with a plastic manufacturer, an Austrian company (SME) specializing in compounding plastic pellets (the masterbatch for all thermoplastic products),

which served to collect risk-relevant information and gain deeper insights into working conditions and possible exposures. The literature review drew on search engines and databases specialized in peer-reviewed scientific literature, such as PubMed, Science Direct, Web of Science, and Google Scholar. For the literature search, the keywords "Safe-by-Design," "SbD," "nanoclay," "montmorillonite," "toxicity," "hazard," "polymer nanocomposite," and "food contact material" were used, whereby methods to search for word variations were applied (e.g., through the use of wildcards that take the place of one or more characters in a search term to allow a search including variants like "Safer-by-Design" and "Safety-by-Design").

2.3. Stakeholder Involvement

Regarding the acceptance of the SbD concept, two stakeholder workshops were carried out involving experts from science and industry, as well as public authorities. The workshop format allowed the participants to be engaged in a discussion as equal discussion partners. The main topic was specified to identify and assess the strengths and weaknesses of the SbD concept applied to the chosen product example. It allowed a broad variety of opinions (based on experience and expertise) to be gained in an easily comprehensible way and enabled the gathering of information in the main areas of "knowledge and uncertainty," "innovation and safety," "resources," "societal conditions," and the "stage–gate model." Social impacts are fundamental and technological developments, e.g., nanotechnological innovations, should integrate the assessment of possible effects and perspectives of the new technology in society, considering public perception, perspectives of different stakeholders, possible changes in responsibilities, and liabilities of and between actors [14]. With regard to sustainability assessment and the SSbD approach, a synergistic use of risk assessment, life cycle, and socio-economic assessment has already been shown [16]. Such aspects and methodological approaches were also taken into account in the stakeholder surveys.

In addition to the insights gathered from the stakeholder workshops, the industry partner was also consulted about the weaknesses, strengths, and applicability of the SbD concept during a guided expert interview (the guideline can be found in the Supplementary Material). These multiple levels of information and knowledge allowed an identification of strengths and weaknesses of the concept itself, as well as possible challenges and risks along the entire value chain of the product example from a multi-stakeholder perspective. This integrative transdisciplinary approach allowed the inclusion of economic and ecologic aspects, as well as social ones.

3. Results

The SbD concept, which is based on NANoREG [42] and further developed in Prosafe and NanoReg2 [9], was adapted for application to the objective theoretical case study. In a first step of the SbD implementation, possible exposure pathways of nanoclays were identified along the product value chain of coffee capsules, which are schematically illustrated in Figure 2. Possible risks for human health and the environment are explained in more detail in the Sections 3.1 and 3.2 with regard to hazard and exposure assessment according to REACH. The applicability and the strengths and weaknesses of the SbD concept were discussed from different stakeholder perspectives and are presented in Sub-Section 3.3, wherein a focus is placed on the manufacturer's perspective in Section 3.3.1 and the various stakeholder opinions that were gathered during the stakeholder workshops are summarized in Section 3.3.2. Figure 2 schematically illustrates the relevant processes along the life cycle of nanoclay polymer composites that can be used for food packaging materials such as the coffee capsule. This approach also made it possible to identify all gatekeepers, who can come from within a company as well as from outside (e.g., officials of the competent authorities, specialized consultants, scientists, etc.).

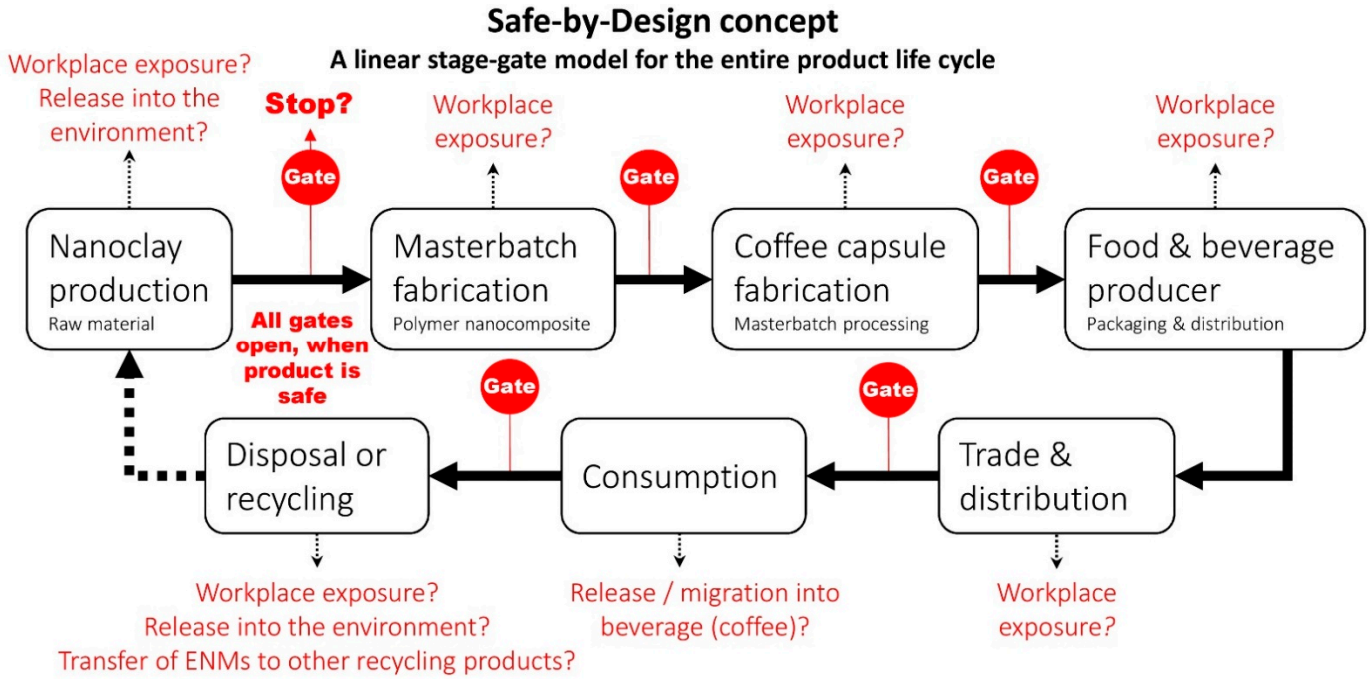

Figure 2. Schematic illustration of a linear innovation process based on the Safe-by-Design (SbD) concept and adapted to polymer-based coffee capsules that contain (surface-modified) nanoclays. The SbD concept considers the entire product life cycle, along which ENMs can potentially be released and may lead to (before unseen) risks. So-called "gatekeepers" should stop the innovation process in terms of early risk assessment when the application of the polymer nanocomposite appears to be unsafe.

3.1. State of Knowledge about the Risks for Human Health and the Environment

The MFA, shown in Figure 3, facilitated the systematic identification of possible release pathways to also conduct a targeted literature search on possible toxic effects of nanoclay. Concerning the production phase, there are concerns surrounding workplace exposure but to date there are no established occupational exposure limits (OEL) or specific regulations for airborne nanoclays and dust emissions (ultrafine particles) [43]. There are a few studies on long-term occupational exposure to bentonite (e.g., for workers in mining or processing), which can cause lung diseases, but no clear evidence from in vivo studies of systemic toxicity can be derived [44].

There are safety concerns regarding consumer exposure to ENMs in FCMs if the nanoclay migrates into a foodstuff or drink from the packaging materials. All material components, including plastic additives, permitted for use in FCMs in the EU therefore must undergo a migration test with standardized test methods. It must be stressed that, to date, there are no standardized analytical methods available to detect ENMs or nanoclays in the migrate. There is no "standalone" technique for the characterization and quantification and there are no specific legislative rules in this context [25]. Where ENMs in FCMs made of plastic materials permitted in the EU are concerned, specifications for and restrictions on use have been laid down in order to ensure that consumers are not exposed to the materials, or that if they are, the exposure is as low as possible [19]. In general, no migration of ENMs permitted in the EU for contact with food into food simulants has been determined either by the EFSA or by other bodies [45]. If migration of an ENM does occur, it has been found to be negligible in terms of any health risk, as was assessed in the case of nanoclay modified with dimethyldialkyl(C16–C18)ammonium chloride by the EFSA in 2015 [36] (cf. Section 2.1). It is noted that other surface modifiers, such as quaternary ammonium compounds (QACs), could also be used to modify and integrate the hydrophilic clay into the hydrophobic plastic material. However, these organo-modified nanoclays are not yet authorized as FCMs in the EU [25], as QACs are toxic for aquatic organisms, are persistent,

and thus take a long time to degrade biologically [46]. As a consequence, we recommend using only nanoclay modified with dimethyldialkyl(C16–C18)ammonium chloride, for which no release during the use of coffee capsules can currently be expected, and therefore could also assume no migration of nanoclay in the MFA (see "use phase" in Figure 3).

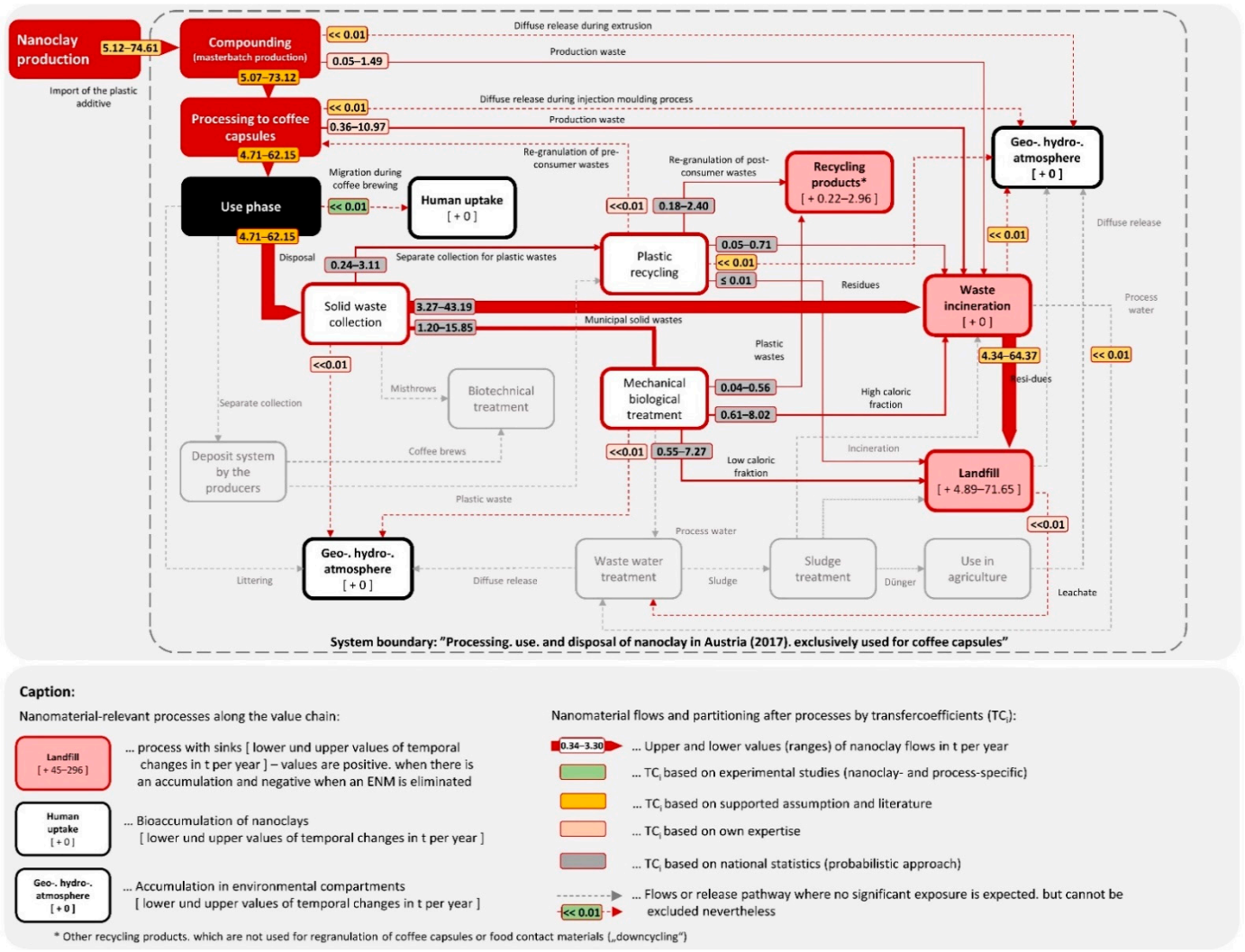

Figure 3. Material flow diagram of nanoclays in metric tons per year, which are exclusively used as additives in polymer nanocomposites. Nanoclay is currently not produced in Austria and must therefore be imported. Note that the material flow analysis (MFA) shows hypothetical material flows of nanoclays because these nanoplatelets are currently not used for food contact materials or coffee capsules in the Austrian plastic industry to our knowledge. MFA is a versatile method to identify (future) emission hotspots regarding exposure and early risk assessment.

In summary, EU regulations only relate to health risks during the use phase. ENMs that are authorized by the EFSA and are incorporated into the host polymer matrix are not considered high risk during the use phase. However, there can be risks to the environment or human health during end-of-life stages. For example, it was assumed that nanoscale additives in PET bottles may be released again when the bottles are recycled or regranulated [47]. To date, it has not yet been proven in (bio)monitoring studies that recycling polymer nanocomposites leads to an increased exposure of workers and therefore more research is needed in this area.

3.2. Exposure Modeling for Nanoclay

An MFA was carried out to model and estimate the potential exposure of nanoclays. The conducted market analysis, which is described in more detail in Section S3 in the Supplementary Material, showed that no high-grade, ultrafine nanoclay is currently produced in Austria that can be used as a raw material for compounding. For this reason, it was assumed for this MFA that nanoclays are exclusively purchased from foreign importers. To be able to estimate the import quantities as MFA input data, production-relevant material flows, such as production rejects, must be considered. The involved plastic manufacturer assumed that during the first production step of compounding or extruding plastic granules, about 1% to 2% are production rejects and thus are generated as commercial plastic waste. The produced nanoclay-containing plastic granules are further processed into coffee capsules by means of injection molding. Depending on the size of the production series, it was assumed that between 7% and 15% of the processed nanocomposite is generated as production waste. With such an amount of production waste considered, a nanoclay consumption between 4.7 and 62.2 t/y could be calculated, which would be necessary for the Austrian coffee capsule market. These lower and upper limits are used for the "MIN" and "MAX" scenarios, respectively, to reflect uncertainties resulting from the currently available data basis and from the assumptions needed for the extrapolation. Figure 3 shows the MFA results at a glance. All material flows refer to nanoclay in metric tons per year, which would be necessary to saturate the Austrian coffee capsule market ("single portion capsules or pads" have a market share of ca. 15%; cf. Section S3 of the Supplementary Material).

The MFA also showed that nanoclay emissions can occur during the end-of-life phase. However, the model calculations reveal that nanoclay emissions are negligible as long as the capsules are disposed of properly. According to the Austrian Federal Waste Management Plan [48], about 73% of mixed municipal waste is currently thermally recycled and about 27% is sent to mechanical–biological treatment. Similarly, using the probabilistic approach, it was assumed that 73% of nanoclay is incinerated and 27% is sent to a mechanical–biological treatment (MBT) facility. Based on expert estimates, it was assumed that around 95% of used plastic coffee capsules are disposed of in the residual waste. The remaining 5% are collected separately and thus recycled. Specific collection or take-back services on the part of the manufacturers were not considered for plastic coffee capsules, as no quantitative relevance is yet apparent and none are currently known of in Austria. Since the reuse of recycled or regranulated coffee capsules containing nanoclay as FCM is very unlikely, due to the high technical and hygienic requirements in the food sector, it can be assumed that the recycled quantity of 5% is used in other recycling products.

Of this 95%, which ends up in MSW, the largest proportion is treated in a waste incineration plant. Since, according to the thresholds for worker exposure [49], bulk montmorillonite (CAS No.: 1318-93-0)—which is the microscale counterpart of nanoclay—is described as "non-meltable," the same high thermal stability was assumed for nanoclay, based on incineration studies conducted with ENMs of similar material properties [50,51]. Therefore, more than 99% of the nanoclays remain in the solid combustion residues (slags and ashes) and are subsequently deposited in a residual waste landfill in Austria.

With regard to the landfilled fraction, it was assumed that nanoclays aggregate immediately under the prevailing environmental conditions due to their physicochemical properties (the high affinity to dissolved cations rapidly leads to aggregation and decreases mobility) and consequently remain in the landfill body for very long periods of time. Due to their high sorption capacity, nanoclays can even have positive effects by binding and thus immobilizing dissolved pollutants. In the present study it was therefore assumed that >99% of the deposited nanoclays remain in the landfill, and that transfer from solid wastes to landfill leachates or groundwater is very unlikely (<1%).

In summary (cf. Figure 3), with the hypothetical assumption that nanoclay was already incorporated into coffee capsules in 2017, a maximum of 74.6 t of nanoclay would have to be imported to Austria annually in order to exploit the market potential for coffee capsules

containing nanoclay. These quantities would be necessary for the compounding of plastic pellets to be further processed into coffee capsules in a further step by means of injection molding. The nano-specific market potential in terms of volume would correspond a maximum of 62.2 t/y of nanoclay. Based on this MFA, after proper waste collection, about 96% of the nanoclay originally used would be enriched in landfills via solid incineration residues. Around 4% of the nanoclays used in capsules (up to 3.0 t/y) would be recirculated via recycling, with downcycling currently appearing as the most likely scenario. This is justified by the fact that in Austria there is currently no separate collection in households or similar institutions of used coffee capsules made of plastic. Furthermore, recycling of old capsules for new coffee capsules can be ruled out due to the very high hygienic and technical requirements for FCMs.

Qualitative Description of the Environmental Fate

According to REACH Annex VIII, for manufacturers and importers it is mandatory to provide additional information about the fate and behavior of a substance in the environment. For this reason, we also described the environmental fate qualitatively on the basis of literature data.

During the production phase, mechanical processes such as sieving, shredding, or grinding can generate nanoscale emissions and thus lead to increased exposure of workers in production or recycling [39]. Inhalation of ultrafine dust or nanoscale aerosols, or skin contact with solid nanoscale residues, can lead to health damage and vascular diseases by accumulated ENMs [50,51]. Using the example of CNT-containing PP containers, aerosol measurements have shown that the highest exposure occurs during the grinding processes and during molding of the plastic parts [52,53]. However, it should be considered that the CNTs were never present in free form but in an aggregated state. Laboratory studies investigating the abrasion behavior of nanocomposites containing CNTs came to similar results [54]. Nevertheless, other experimental studies have shown that the release of individual ENMs can still occur under mechanical impact [55,56]. With regard to the objective case study of nanocomposite-based coffee capsules, no studies could be found on the ENM-specific release behavior during processing and reprocessing operations. In the present study, no significant increase in exposure of individual nanoclay platelets was assumed, due to the strong aggregation tendencies of nanoclays.

Regarding the use phase and in terms of consumer protection, nanoclay (montmorillonite) has already been evaluated by the EFSA or FDA and classified as safe (cf. Section 2.1). According to this, migration tests did not detect any significantly increased migration—compared to the control sample without ENMs—and thus this substance was approved for use in FCM. Likewise, no significantly increased migration of ammonium compounds (dimethyldialkyl(C16–C18)ammonium chloride), which are used to colloidally stabilize the nanoclay, was detected. Since nanoclay is included in the "Union list" (Regulation (EU) No. 10/2011) for approved ENMs in FCMs made of plastic, it can be assumed that there are no health concerns regarding the use of nanoclay in coffee capsules if the material is used according to the given specifications.

In general, with regard to potential release during the use phase, it cannot be entirely excluded that nanoscale additives may be released under certain conditions. For example, weathering studies on similar nanocomposites have shown that nanoscale additives can be released by photooxidative degradation [57,58]. However, it is pointed out in this context that ENM release is highly dependent on the plastic or polymer matrix used (e.g., made of epoxy, polycarbonate, or polyamide), as well as on the prevailing environmental conditions. In general, it can be assumed that the nanoclays are chemically stable and can be released only when the polymer matrix itself decomposes (for example, through oxidation, UV radiation, high temperatures, or humidity). So far, there is still a lack of reliable studies on whether nanoclay platelets or substances used for surface modification can dissolve from plastic capsules during coffee preparation and thus transfer into the prepared coffee, since

hot water at high pressure acts on the capsule material in coffee machines and a relatively low pH value is present.

During the end-of-life phase, the unintentional release of nanoclay in wastewater collection and treatment is very unlikely, as no migration of nanoclay from FCMs could be detected. Should nanoclay nevertheless enter wastewater and subsequently sewage treatment plants, no hazard potential can be assumed, since nanoclay can be retained during wastewater treatment by binding to sewage sludge flocs. Nanoclay could even lead to positive effects due to its absorbent properties, as it is described as a non-hazardous flocculant [59,60], thus favoring the purification process in sewage sludge in general. Regarding the potential release in landfills, nanoclays can also lead to positive effects due to their high sorption capacity of pollutants. If, however, when nanoclay would transfer in the worst case from solid wastes to landfill leachates, no environmental hazard is to be assumed, since the leachate of residual landfill must be appropriately collected and fed into a subsequent leachate treatment system. Regarding biological treatment and composting, studies on the biodegradability of polymer nanocomposites indicate that ENMs, such as nano-Ag, -clay or -cellulose, have no negative impact on the biodegradability (under aerobic conditions) of biobased composite materials [61–63]. Thus, nanoclay could also be used in biodegradable capsules. During such biodegradation processes, diverse ENM types can be expected to undergo transformation processes—in particular, sulfidation, complexation, or oxidation processes—which in turn affect their environmental impact. In this context, it should be mentioned that, for example, sulfidation of metal-containing ENMs, such as nano-Ag, leads to transformation into silver sulfides (Ag_2S), which have low water solubility and thus reduced bioavailability. Based on current knowledge, it can be assumed that ENMs do not lead to inhibition of the biodegradation of biogenic waste [39]. Although Gitipour et al. [64] confirmed that no differences were observed in the quality parameters measured during degradation tests compared to the control sample (without ENMs), a change in the predominant bacterial community was observed. It can be concluded that there is still a great need for research on the biodegradability of bio-based ENM-containing food-packaging materials. For example, if manufactured composts containing ENM-containing bio-based packaging materials were applied to agricultural areas, leaching or particle transport of ENMs is unlikely [65–67]. However, it was emphasized in a comprehensive literature review that further studies are needed (with different types of ENMs under varying environmental conditions) to make generally valid statements about the final environmental fate of ENMs and their influence on aerobic and anaerobic biodegradation processes [39]. In the case of waste incineration, metallic ENMs can resist combustion processes unaltered, and are as such thermally stable and persistent. Regarding the fact that bulk-shaped montmorillonite—the microscale counterpart of nanoclays—is considered "infusible" according to one report [49], it can be assumed accordingly for nanoclays that they remain thermally stable during waste incineration. With analogies to other persistent ENMs, such as nano-CeO_2, -TiO_2, or $BaSO_4$ [68–71], it can be assumed that >99% of the nanoclay used remains in the solid incineration residues.

In summary, nanoclay is persistent in the environment and therefore more detailed studies on bioaccumulation and possible endpoints should be conducted in the future, during which it will be a major challenge to detect nanoclay and possible transformation products at low concentrations in diverse organisms and complex environmental samples.

3.3. Identified Strengths and Weaknesses of the Safe-by-Design Concept

With regard to the practical implementation and general acceptance of the SbD concept, a strength–weakness analysis was conducted based on several different levels of information and knowledge. Expert interviews were conducted with the company partner, and two stakeholder workshops were conducted. For the evaluation of the practicability of the SbD concept from the manufacturer's point of view, an interview guideline was created (see Supplementary Material). The results are described and summarized in more detail in

the following sections and identified "topic areas" are summarized in Table 1. The final results and key statements of strengths and weaknesses are summarized in Table 2.

Table 1. Main topic areas and subtopics of strengths and weaknesses of the Safe-by-Design concept based on stakeholder opinions as derived from the conducted stakeholder workshops.

Main Topic Areas	Subtopics
Knowledge and Uncertainty	Analytical methods
	Uncertainty in the innovation process
	Risks to the innovation process
	Protection of in-house knowledge and expertise
	Standardization
	Differentiation between materials, products, and processes
	Variety of application areas
Innovation and Safety	Risk management
	Relation between safety and innovation
	Innovation and safety as a social process
	Integration of external knowledge
	Governance
Resources	Time, personnel, and financial resources
Social Framework	Risk acceptance
	Risk perception and communication
Stage–Gate Model	Gatekeeper
	All-or-nothing principle
	Communication
	Redundancies

Table 2. Summary of the main strengths and weaknesses of the Safe-by-Design concept.

Strengths	Weaknesses
Generation of nano-specific information and data sources along the entire value chain	Focus on the manufacturing phase (from raw material extraction to market launch of a nanomaterial or nanoproduct)
Involvement of external expertise	Unknown role of external experts (intellectual property rights); costly and time-consuming
Harmonization and documentation of possible project risks	Focus only on process risks and not on product risks
Encouraging harmonization of process flows or project management	Lack of international standardization of the SbD concept
Engaging in uncertainty management where risk management is not possible due to lack of data	Significant cost and time investment with no discernible benefit or added value
Approach for a structured handling of knowledge gaps and uncertainties	Lack of assessment options
Assembly/collection of safety-related documents	Unspecified "safety dossiers" without safety assessments
Implementation of the "precautionary matrix" (PCM) and "life cycle mapping" (LCM) planned	Insufficient description of practical implementation of methods; implementation on a voluntary basis
Strict sequence of a process (linearity)	Low practicability; lack of correction opportunities
Availability of tools for web-based safety assessment or consolidation of relevant nano-specific data	Lack of availability of information (especially on practical suitability) on tools for companies, especially SMEs
Documented evidence: taking relevant measures to the best of knowledge	Exclusively based on the processing of existing information already given by EU regulations and standards

3.3.1. Manufacturer's Perspective

The added value of the SbD concept and the intended nano-specific safety dossiers are questioned, as substances and substance mixtures used in industry need to be specified in accordance with the REACH regulation and as such, are to be labeled for shipping and

transport in accordance with the CLP regulation. The SbD concept basically only serves as a completeness check, which is already carried out by production management (in coordination with authorities). Furthermore, the exact roles, as well as responsibilities of the different "gatekeepers" along the entire value chain of NEPs, are not precisely defined. From the manufacturer's point of view, innovation processes generally do not proceed linearly from one phase to the next, but rather correspond to a "branched" iterative process, which must be adapted due to constantly changing framework conditions regarding the various product application possibilities.

In this context, it should be noted that during risk identification, all potential areas of application should theoretically already be known in the product-development phase, so that all potential nano-specific risks can be assessed. However, technical requirements and safety-related aspects are very application-specific, and the target application may not be declared by the customer in the case of manufacturing a component or intermediate product. Taking all potential application areas into account would thus be time-consuming and cost-intensive and would hinder the innovation process.

Furthermore, SbD implementation in an SME would require additional monetary resources, such as external consulting services, which in turn would result in higher selling prices. Added value of SbD implementation would only exist if the SbD concept were internationally recognized (e.g., as a "gold standard") or standardized and explicitly required by the customer. Without certification, however, the added value is not evident (e.g., for marketing purposes) and, in general, the SbD concept is currently poorly communicated in terms of perception (web presence) and understanding (process flow).

Apart from this, all nano-specific processes and formulations would have to be open to an external auditor or consultant to be able to comprehensively consider all aspects regarding worker, consumer, and environmental protection. The exact process steps and nanoformulations are often trade secrets, and thus the barriers to passing on business data to third parties would be too high. In-house material safety data sheets must be prepared anyway, and operating instructions (regarding material specifications or worker protection) have to be kept. Therefore, "safety dossiers" are redundant in most cases.

Nevertheless, the idea of the SbD approach and the introduction of early risk management is welcomed, as nano-specific uncertainties and risks can potentially be identified at an early stage. In a broader sense, SbD implementation leads to addressing nano-specific safety issues that are outside the scope of legislation of the chemicals involved. At present, however, nano-specific SbD can be considered a process to identify knowledge gaps.

3.3.2. Stakeholder Opinions Gathered during Stakeholder Workshops

In total, five main topic areas and 19 subtopics were identified and discussed during the two stakeholder workshops with representatives from industry, public authority, and research, which are summarized in Table 1.

Knowledge and Uncertainty

Concerning analytical methods: In the field of nanometrology, there is still a lack of reliable and reproducible analytical methods, and thus, a guarantee of safety is not possible. The case study shows the complexity, with composites being diverse mixtures of substances. Due to the lack of routine of analytical methods, too little information is available on the substances/materials and thus on the composites to allow an assessment by an authority regarding environmental, health, and occupational safety issues. This fact is not considered in the SbD concept, which is based exclusively on the processing of existing information. Furthermore, it shows again that standardized analytical methods for ENMs and NEPs are urgently needed.

Concerning uncertainty in the innovation process: The SbD concept, which is supposed to introduce safety into the innovation process, is very imprecisely defined. It remains open whether the concept refers to materials, products, or an industrial process. In addition, due to the absence of manufacturer information, as well as the lack of awareness

and expertise, it is difficult for SMEs to decide whether a development process involving ENMs and NEPs should continue. Additionally, there are assumptions made by manufacturers about the safety expectations of consumers, however, without the consumers' involvement in the innovation process. Retrospectives and/or interruptions in a non-linear innovation process are not represented in the idealized stage–gate model and make the model impractical for application in its current form.

Concerning risks for the innovation process: Due to the lack of standardized analytical methods for ENMs, innovative processes are conducted in an atmosphere of uncertainty. In addition, the integration of different stakeholders (e.g., authorities, experts from research and development, etc.) slows down the innovation process, making it cost-intensive and time-consuming. Therefore, existing (already standardized) tests are often used to identify potential risks instead of conducting "case-by-case" investigations. Although an "all-or-nothing" or "rapid test" approach is desirable, it poses a risk to the innovation process because ENMs are ruled out too quickly due to a lack of an adequate test method. For SMEs, the risk of innovation costs that are difficult to predict is so high that the use of ENMs is often avoided. Standardized test methods to determine potential risks and possible hazards must be further developed so as to not hinder innovation.

Concerning protection of in-house knowledge and expertise: To protect in-house expertise and minimize project costs, the innovation process must be exclusively internal. However, the necessary know-how for the successful use of ENMs may not be available "in house" and external expertise must be acquired. Due to the fear that knowledge could leak out too early, necessary information is often not publicly available in practice. Large companies do not want to disclose detailed information for competitive reasons. This, in turn, makes it more difficult to standardize process flows or evaluation methods and requires time and financial resources.

Concerning standardization: In pharmaceutical drug design, there is the so-called "tiered approach," which includes preliminary studies for risk identification, quantification of risks (monitoring), risk assessments, stakeholder involvement for validation of study results, and setting of measures. However, due to the lack of adequate analytical methods, this approach is not possible for ENMs. Although industry standards can ensure a certain level of process reliability, they are neither mandatory, nor do they provide legal certainty. Due to the lack of standardization of process flows, the approval process, which requires documents to transparently demonstrate the safety of the material or product, is also complicated. In the case of the product example (a nanoclay-containing coffee capsule), there are thus no standardized assessment methods for the detection of nanocomposites, although nanoclay (montmorillonite) has already been assessed by the EFSA and approved as a food contact material in the EU.

Concerning differentiation between materials, products, and processes: It remains vague within the SbD concept whether this refers to the development of an ENM, an NEP, or a nanotechnology-based innovation process. However, it is essential to differentiate at this point, as there must be differences in the application of the concept. Nanomaterial synthesis and product development are two completely different routes. It is relatively easy to "design safety into" a product by preventing certain materials from being released during the use phase. In the case of functionalized ENMs, it is often not the particle size that is critical, but the surface modifications (e.g., by quaternary ammonium compounds (QACs)) are problematic, and safety assessment is consequently difficult.

Concerning the variety of application areas: Due to the wide range of possible applications of ENMs and NEPs, considerations of inappropriate application (misuse) is a relevant issue. In the case of inappropriate applications, both intentional or unintentional ones, particularly at the consumer level, must be considered, e.g., the area of application of nanoclay not being limited to FCMs. If concerns arise during the SbD process for individual applications, other areas of application should be considered instead of discarding the entire process in advance.

Concerning risk management: A distinction must be made between risk analysis and risk management. Risk analysis is a data-based process that generates appropriate options for risk treatment. Recommendations can be made based on the risk evaluation results, which can then be implemented as part of a risk management process. Due to the lack of robust, reliable, and reproducible analytical methods (and therefore data) in the field of ENMs, potential risks cannot be properly identified. From a conventional risk assessment perspective, clear and well-defined decisions exist, albeit dependent on the specific assessment method used. Regarding ex-ante assessment of emerging technologies, appropriate assessment methods are still under development.

Innovation and Safety

Concerning the relation between safety and innovation: Standardized methods offer safety and are cost-saving, but they represent an "all-or-nothing" decision-making approach that can lead to a premature stop of the innovation process. In contrast, the case-by-case approach is considerably more time-consuming and cost-intensive but offers the maximum possible security for the innovation process. However, due to the extensive amount of time needed, the case-by-case approach often inhibits innovation in reality. The development of new materials requires a certain degree of openness and, under certain circumstances, a willingness to take a higher risk than when using conventional materials. In the interest of welfare and the protection of human health and the environment, generally reliable manufacturer information on the exact nanoformulation and functionalization of ENMs is necessary. To date, this information is often missing, especially for ENMs that were placed on the European market before the nano-specific amendment of REACH annexes in 2018.

Concerning innovation and safety as a social process: Possibilities of inadequate application go beyond technical aspects, and ultimately the safety of a product is mostly about a substance-related risk regarding the health of those who handle it. However, the ideas about safety expectations of consumers are not generated within the innovation process through interactions with consumers but are based on assumptions. The uncertainty factor "consumer" is not integrated, although it would be necessary to exclude potential risks for consumers at an early stage. In the SbD concept, it remains unclear when and how customer and consumer considerations can be integrated into the innovation process at an early stage.

Concerning the integration of external knowledge: Regarding ENMs, many SMEs lack the necessary know-how and expertise to make an objective decision on whether a development process can proceed or should be discontinued. In practice, the necessary information is often not available or publicly accessible, since large companies often do not disclose detailed information for competitive reasons and do not publish negative results or reveal complex nanoformulations, which could contain important relevant safety information. Consequently, external expertise is often required, demanding financial resources and time. The SbD concept could contribute to a managed data collection, such as a "positive or negative list," which would provide credible information.

Concerning governance: The creation of a "positive list" in which safe ENMs are listed should be the responsibility of public authorities. The aim would be to collect the information in a common database that is accessible to everybody. At present, the question of financing such a database has not been clarified, although government funding for the promotion of general welfare through official risk assessments could be considered. Early warning mechanisms are not governance tasks and must already be part of responsible product development by the responsible producer or manufacturer. Legislation, however, must create legal certainty for industry, allowing for innovation.

Resources

Concerning time, personnel, and financial resources: The identified resource problems of the SbD concept relate not only to financial and time factors but can also originate from the lack of internal expertise and the number of actors involved. The innovation process is

slowed down by the lack of cost-effective routine analytical methods, which in turn makes it difficult to standardize process flows and complicates approval procedures. A gap in research policy can also be identified. Innovation processes in the field of ENMs are hardly feasible for SMEs due to the lack of process structures. In the pharmaceutical industry, for example, this problem is circumvented by patenting as early as possible.

Social Framework

Concerning risk acceptance: This describes the willingness to accept a certain risk. This acceptance of risks tends to decrease over time, both in product development and in relation to products. To make decisions about the acceptability of risks, information about possible consequences is required. In many cases, however, this information is not available or accessible, and risks are accepted even when benefits are limited. The concept of benefit is relative, which once again underlines the importance of including user perspectives in the innovation process. In general, the benefits of novel foods, for example, are often questionable because they are evaluated and approved without evaluating the benefits to consumers in advance. For a company, the benefit can lie in avoiding damage to its image, as well as avoiding financial damage. When involving officials, not only financial but also social benefits would be considered. Currently, the question of benefit is often located at the end of the value chain, and therefore plays a minor role at the beginning of the innovation process. It is relevant to consider the user benefit and the user welfare in the sense of the general welfare, as well as to integrate the diverse user groups into the innovation process.

Concerning risk perception and communication: If consumers were involved in the innovation process at an early stage, the public perception of safety would also be assessed. Perception plays a central role in public risk assessment. Purely technical risks are difficult or impossible for consumers to assess, and public risk perception generally differs significantly from expert-centered risk analysis and assessment ("perceived benefits–risks"). Similarly, it is difficult for consumers to assess the actual harmfulness to health, as well as the safe use and disposal of the product. In the innovation process, science must be used as a tool to produce ENMs or NEPs with an acceptable level of risk. In the SbD concept, consumer behavior, which can hardly be controlled, must also be considered.

Stage–Gate Model

Concerning the gatekeepers: In the SbD concept gatekeepers are supposed to act as decision-makers. However, who these gatekeepers are and what exact role they are supposed to play in individual cases remains unclear. Potential gatekeepers would be end users, regulators, middlemen, or retailers. The latter would be responsible for placing ENMs and NEPs on the market that conform to REACH. Even if stages, gates, and even gatekeepers are known, not all information is currently available to generate automated safety dossiers, which are ideally to be passed on without loss of information after each production step. The schematic representation of the stage–gate model has an additional fuzziness, because strictly speaking, the "gates" are not located between the "stages," but within the "stages." It is also important to clarify whether a "stage" is within the jurisdiction of one actor or spans several different actors. "Gates" have different qualities, e.g., some development processes are path-dependent, and therefore represent a certain restriction. The task of the gatekeepers would consequently be to have a value-free overview based on a credible information base. However, not every company, especially SMEs, have the in-house know-how (e.g., in colloidal chemistry, nanometrology, or nanotoxicity) to be able to act satisfactorily as gatekeepers. In this case, external personnel would have to be engaged, for which a non-disclosure agreement (i.e., NDA) is highly recommended.

Concerning the "all-or-nothing" principle: Due to the complexity of the topic, it is obvious that the pictorial representation of the SbD concept with "stages" and "gates" by "opening or closing barriers" is a simplification. After all, it is not useful at this point to decide according to a binary "yes" or "no" principle, since the lack of a standardized test

method for chemical risk assessment means that the results of the respective methods may differ. Instead, the stage–gate model should rather be seen as a reversible process, which is evaluated at the "gates" and for which conditions are determined under which further development can take place (for example, by rethinking the application area). However, immediate exclusion or substitution should be avoided. "All or nothing" decisions should be replaced by introducing multiple courses of action on how to proceed with the process.

Concerning communication: One task of the SbD concept could be to allow the communication process among the actors involved at the different stages to take place in a controlled and standardized manner, thus not only accelerating the innovation process and ensuring gapless information transfer, but also minimizing costs. The information collected should be included in data collection managed by public authorities. This would ensure legal certainty for SMEs more quickly. Safety data sheets currently provide information on regulatory aspects, but do not capture innovative processes or the new information generated therein. A targeted approach to information exchange could achieve many benefits for innovative SMEs, as currently internal and public information processes are largely separate. The development of an innovation process is always a learning process for companies.

Concerning redundancies of industrial standards: Several industry standards already exist, but they are neither mandatory, nor do they provide legal certainty. They do, however, contribute to process reliability. The advantage is that the innovation process is hardly hindered by these industry standards. In these areas where standards already exist, an additional concept is not necessary and not desired by industry. Implementation of SbD must therefore be integrated into legal frameworks, standardized, or certified.

4. Discussion

In the course of the theoretical case study, it was shown that the earliest possible integration of "safety" into the innovation process was positively evaluated by all participating stakeholders. This is due to the continued lack of standardized analytical test methods for ENMs and innovative processes being conducted in an atmosphere of uncertainty. The SbD concept supports the collection of nano-specific information and data sources along the entire value chain and attempts to harmonize documentation of process flows and management, as well as possible project risks. However, it was shown that a voluntary implementation of the SbD concept in Austrian companies in the nanotechnology sector can only be promoted if it clearly results in added value for the company, e.g., through standardization of the SbD concept ("gold standard"). The application of SbD does not produce relevant new safety information in itself. The benefit and range of services offered by the concept must be clearly defined because legal conformity is already provided by the existing regulatory framework, and implementing an additional, voluntary safety concept is connected to cost and time investments.

The concept focuses on the manufacturing phase (from raw material extraction to the market launch of a nanomaterial or nanoproduct) and needs to be expanded to the use and disposal phase to meet the requirement that all potential risks can be identified along the entire product life cycle at an early stage. In practice, it is difficult to simply transfer the assumed linearity of the design or production phase to the other life cycle phases and to include the use and disposal phases as early as possible in the innovation process. All in all, there is a lack of correction opportunities within the innovation process when applying the SbD concept.

Moreover, there is a lack of definition of the identity, role, obligations, and decision-making powers. The possibility that external experts may have to be involved needs to be considered. This is problematic, especially for SMEs, which often do not have the financial resources for external experts. In addition, information regarding nano-specific processes and secret nanoformulations would have to be passed to an external "gatekeeper," which possibly conflicts with boundaries of intellectual property rights. Another major problem is presented by the fact that maybe no single "gatekeeper" (e.g., the project coordinator)

can be determined for the respective phase of the innovation process and that the decision-making process may be rendered beyond the control of the respective innovator. If one wants to allow safety-relevant knowledge to flow into the innovation process in the future, relevant gatekeepers must be identified according to a legislative framework, and the knowledge gained must be represented in an official, binding manner, e.g., via publicly accessible safety dossiers and via "security platforms" where all gatekeepers are officially registered.

5. Conclusions

The SbD concept itself can be seen as an additional approach for structured handling of knowledge gaps and uncertainties along the value chain of a product. However, there is insufficient description of the practical implementation and no clear added value has been provided for potential implementing companies so far. In practice, innovation processes developing novel substances, such as nanomaterials, advanced materials, or nano-enabled products, have a branching process flow (allowing some "side branches to die"), rather than following a linear stop-and-go principle like the stage–gate-model, which lacks correction opportunities. Additionally, the protection of intellectual property rights and data privacy concerning complex nanoformulations or processing methods of polymer nanocomposites can only be guaranteed by clearly defining the roles of involved stakeholders and clear rules for data transfer (in the best case, from raw material suppliers to product manufacturers and recyclers). The practical implementation of SbD on a voluntary basis seems to be problematic, leading to the conclusion that the SbD approach should be implemented in existing legal frameworks or standards. Nevertheless, the additionally conducted material flow analysis—which is not mandatory in the current SbD concept—can bring added value to the SbD concept. The MFA allowed the estimation of the market potential for ENMs and the identification of resulting material flows and exposure pathways along the entire life cycle of a nano-enabled product. However, the practical implementation of the SbD approach including an MFA is hampered by its time-consuming and costly approach and therefore incentives, particularly for innovative SMEs, need to be created. An improved SbD concept that is well structured and can be flexibly adapted to different case studies can become a useful tool in risk and project management, whereby the "gates" represent a communication platform for different stakeholders and experts, who can co-influence the final decision to continue or cancel a product innovation. In terms of sustainability, the SbD concept should be further expanded to an SSbD approach that holistically addresses ecological, social, and economical aspects.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132413951/s1. Figure S1. Boxplot diagram of the dry weights of weighed empty coffee capsules and the coffee content (n = 70 and 34 respectively). The 1st and 3rd quartile—25% and 75% of the data values are less than or equal to these characteristic values—served as the basis for extrapolating the lower and upper limits of Austrian-wide coffee capsule consumption in tonnes per year.

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