Journal of Environmental Management 212 (2018) 108–114

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Risk management of hazardous substances in a circular economy

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ARTICLE INFO

Article history:
Received 18 October 2017
Received in revised form
9 January 2018
Accepted 2 February 2018

Keywords:
Chemicals
Recycling
REACH
Toxicity
Sustainability

ABSTRACT

The ambitions for a circular economy are high and unambiguous, but day-to-day experience shows that the transition still has many difficulties to overcome. One of the current hurdles is the presence of hazardous substances in waste streams that enter or re-enter into the environment or the technosphere. The key question is: do we have the appropriate risk management tools to control any risks that might arise from the re-using and recycling of materials? We present some recent cases that illustrate current practice and complexity in the risk management of newly-formed circular economy chains. We also highlight how separate legal frameworks are still disconnected from each other in these cases, and how circular economy initiatives interlink with the European REACH regulation. Furthermore, we introduce a novel scheme describing how to decide whether a(n)(additional) risk assessment is necessary with regard to the re-use of materials containing hazardous substances. Finally, we present our initial views on new concepts for the fundamental integration of sustainability and safety aspects. These concepts should be the building blocks for the near future shifts in both policy frameworks and voluntary initiatives that support a sound circular economy transition.

1. Introduction

Building on the global Sustainable Development Goals (SDGs; UNEP, 2016), the circular economy concept has become a particular area of focus in many countries. Both biotic and abiotic waste streams are increasingly used in a variety of circular economy technologies. Biotic waste originates primarily from agricultural or forestry activities and may serve as a bio-based, renewable feedstock for both producing bio-energy (e.g. biogas) and manufacturing bio-based products. Abiotic waste comprises a wide range of material streams such as plastics, metals, paper, construction materials, and wastewater.

The re-use or recycling of these waste streams fits within the ambitions of many national and international sustainability objectives focusing on the reduction of the use of fossil feedstocks and on resource efficiency (European Environment Agency, 2016). The Dutch House of Representatives recently stated that, in 2030, the use of primary raw materials (minerals, fossils and metals) has to be reduced by 50% (Dutch Parliamentary document, 2016). Partly, this should be achieved by increasing the current efficiency of resource use and by further optimising recycling, hence reducing waste and the use of primary raw materials. The other part should be reached by increasing the contribution of biomass as a renewable resource, and cascading and optimising the use of this resource. In addition to resource efficiency, a circular economy offers substantial opportunities for reducing CO_2 emissions (Paris Protocol; European Commission, 2015). Greater efficiency in raw material and material chains could save 17 megatonnes of CO_2 equivalents annually in the Netherlands, being nearly 10% of its annual production of CO_2 (Dutch Parliamentary document, 2016).

The ambitions for a circular or biobased economy are high and unambiguous. Day-to-day experience, however, makes it very clear that the transition still has many difficulties to overcome. One of the current hurdles is the presence of hazardous substances in waste streams that enter or re-enter into the environment or the technosphere. Examples are stabilising agents in PVC (e.g. Pivnenko et al., 2016), plasticisers in food packaging materials (e.g. Vápenka et al., 2016), but also chemicals that were unintentionally formed during processing, like furans, dioxins or polycyclic aromatic hydrocarbons (e.g. Tue et al., 2013). An important category comprises the so-called ‘legacy substances’ which are prohibited or severely restricted by law nowadays, but may still be present in numerous materials. These hazardous chemicals may re-emerge in the end-

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https://doi.org/10.1016/j.jenvman.2018.02.014
0301-4797/

products that are manufactured from waste, resulting in potential risks for mankind and the environment. The substances may also pose hitherto unidentified risks because of different exposure and environmental emission routes from the new waste processing technologies compared to the conventional treatment. The key question is, therefore, do we have the appropriate risk management tools to control any risks that might arise.

The European framework for the concepts of waste, by-product and end-of-waste status, in practice, leads to considerable (legal) uncertainty, especially in connection with REACH, the most important regulation on the risk management of chemicals in the EU (Regulation (EC) No 1907/2006; European Commission, 2006). REACH was set up to take into account the potential risks during the entire life cycle of chemicals, including the waste phase, but, in practice, the focus has been on the production and use stages of substances. Waste legislation and substance-specific legislation have been 'living apart' for decades, but recent circular economy initiatives are now forcing them together in an accelerated way. This alliance, aimed at the seamless application of waste as a valuable resource, has led to many debates in public and political arenas, but also caused uncertainties for companies and authorities.

Beyond doubt, a circular economy demands a shift in societal views on the status of waste. The main challenge is to find the right balance between, on the one hand, sustainability targets such as resource efficiency and the reduction of greenhouse emissions and, on the other hand, environmental public safety and health targets. Such a 'reset' is not only needed from a legal point of view, but also from a scientific one, i.e. we have to find other, more integrated assessment and weighting mechanisms to assess both sustainability and safety aspects.

In this article, we present some recent cases that illustrate current practice and the complexity of the risk management of newly-formed circular economy chains. We will also highlight how separate legal frameworks are still disconnected from each other in these cases, and how circular and bio-based chemistry initiatives interlink with the REACH regulation. Finally, the focus is put on the way forward, presenting our views on new concepts for the integration of sustainability and safety aspects. With respect to safety aspects, we will present a novel scheme which describes how to decide whether a(n)(additional) risk assessment is necessary with regard to the re-use of materials containing hazardous substances. This pragmatic risk management approach aligns with the European policy strategy towards a non-toxic environment, which was announced in the EU's 7th Environmental Action Plan (European Commission, 2014) as well as with the UNEP SDGs.

2. Case studies

2.1. Lead in ray tubes

Waste from cathode ray tubes (CRT) from TV sets, computer monitors, etcetera contains lead. Lead is toxic for reproduction and for the development of children. Because of the toxicity of lead, a thorough assessment is needed when lead-containing waste is re-used in new products. Spijker et al. (2015) studied the prerequisites for the re-use of the material. CRT waste can be processed by grinding it into glass granulate. The granulate is labelled hazardous waste under the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (UNEP, 1989) because of the high lead content.

The presence of lead makes it difficult for the granulate to be re-used in new, safe products. One of the applications of CRT granulate is to use it as aggregate in concrete, replacing natural sand and gravel. This is presumed to be a safe application, because the lead is not released from the concrete. Concrete construction elements containing CRT glass granulate are brought to the Dutch market and comply with the Dutch quality criteria on construction products (Besluit Bodemkwaliteit, 2007). These quality criteria are based on the release of hazardous substances during the use phase rather than on chemical composition. Lead, i.e. lead mono-oxide, is rated a Substance of Very High Concern (SVHC) within REACH. The concrete elements are regarded as articles, for which, to date, in the scope of REACH, no restrictions apply other than the obligation to submit a notification of the presence of the chemical in the article (above 0.1% by weight and above 1 tonne per year). Furthermore, the obligation holds to communicate the presence of this chemical downstream in the supply chain (see Section 3.1). Both Dutch and EU regulations allow these concrete elements with CRT granulates as a product on the market, assuming that it will be safe. While (theoretically) safe during use, there is a problem when this concrete is turned into waste. This waste is also considered to be hazardous waste because of the presence of lead, as is shown by calculations based on data from literature on lead in CRT glass (Spijker et al., 2015). As a consequence, when CRT glass is re-used in concrete elements an up to three times larger volume of hazardous waste will be created in the future, with no current recovery options available. Mixing lead-containing concrete waste with non-hazardous concrete waste is not allowed. Therefore, concrete waste containing CRT aggregates must be processed separately from other concrete waste. However, there is no way to discern hazardous concrete from non-hazardous concrete and therefore, it can be expected that streams will sooner or later mix.

This case is a clear example where assumptions about safety, or acceptable risk, during the use phase do not take into account the future life cycle stages of the material. Both expected outcomes of this case, a three times larger volume of hazardous waste or mixing hazardous and non-hazardous waste, may be considered unacceptable from a safety point of view.

2.2. HBCDD in expanded polystyrene (EPS)

Expanded polystyrene (EPS) is used as packaging material, in fish boxes for example, but also for building and construction purposes (Albrecht and Schwitalla, 2014). The 1973 oil crisis stimulated its production enormously as numerous energy efficiency policies were released (Pohleman and Echte, 1981; Giebeler et al., 2009). EPS is highly combustible and, for safety reasons, the flame retardant hexabromocyclododecane (HBCDD) has generally been added to EPS construction and building materials at concentrations of about 0.7% w/w. The application of EPS in buildings and road works has left us with a considerable legacy of the persistent organic pollutant HBCDD. In Germany it is estimated that, between 1980 and 2012, about 35,000 tonnes of HBCDD was used in 253,000,000 m^3 EPS. In the Netherlands about 4000 tonnes of HBCDD was used between 1960 and 2015. HBCDD-containing polystyrene from buildings and construction is expected to find its way to the waste stage in the next 50 years (Albrecht and Schwitalla, 2014).

HBCDD is now regulated through different European regulations addressing both the waste stage and the application in new and recycled materials. In 2008 HBCDD was brought to the Candidate List as an SVHC under the REACH regulation and, in 2011, it was subsequently added to the REACH Authorisation List (Annex XIV). This means that HBCDD could be used until August 2015 and that its use after that date is permitted only if it is authorised by the European Commission (see Section 3.1). In 2013 the Stockholm Convention on Persistent Organic Pollutants (POPs) (UNEP, 2001) decided to include HBCDD in Annex A of the Convention, aimed at elimination. The European POP Regulation (EC Regulation 850/2004; European Commission, 2004), which is an implementation of the Stockholm Convention, does not only regulate the acceptable amount of HBCDD in new or recycled materials, but also sets limits to define which materials should be considered as POP waste or hazardous waste. These limits have been set at, respectively, 100 mg/kg and 1000 mg/kg (limit Annex IV of POP Regulation 850/2004). This implies that HBCDD containing EPS waste at concentrations below 1000 mg/kg can be used for recycling or re-use processing, whereas the HBCDD concentrations in the newly-formed products should not exceed 100 mg/kg after this waste stage. The re-use and recycling of materials containing HBCDD above the POP limit of 1000 mg/kg is not allowed under the POP-regulation. Besides the regulation limits defining POP-waste, the provisions under the Basel Convention are also of importance (UNEP, 1989). Under this convention, only a limited number of treatment methods for POP containing waste are allowed. Generally, these are limited to incineration at high temperature or controlled landfill which can be seen as a major legal obstacle for improved EPS recycling and re-use.

There are various treatment options for HBCDD-containing EPS waste as discussed in Janssen et al. (2016). From an environmental safety point of view, recycling the EPS while removing HBCDD may appear to be the most elegant option as it reduces the carbon footprint and fossil feedstock resources. The challenge is to technically lower the high levels of HBCDD in current EPS material to those that are acceptable for the new recyclate end-products. The 'solvolyse' technology can potentially reduce the HBCDD content in EPS to approximately 1/100th of the original content of 0.7% to about 70 mg HBCDD/kg. This concentration is below the acceptable value of 100 mg/kg. There was also a need to apply for the solvolyse treatment method to be recognised under the Basel Convention which was recently agreed (meeting a number of conditions). It is emphasised here, however, that the solvolyse technology is still in an experimental stage.

The HBCDD EPS case is an evident example of the complexity of a very large (future) waste stream. For this hazardous compound the REACH regulation triggered other policy frameworks (Stockholm and Basel) dealing with waste handling. These waste legislations, however, force a set of strict conditions on waste treatment that unequivocally aim at a high protection level, but do not easily facilitate any re-use or recycling possibilities. They also hamper the innovation and development of new methodologies as recycling techniques are dictated. On top of that, technological opportunities to reach the HBCDD-concentration limits for the EPS recyclate are still lagging behind. From a sustainability point of view, it is as yet unclear how the overall impact on energy use, environment and health, etcetera of this technology balances out against the incineration and landfill option. This means that decisions on the most appropriate route and technology for dealing with SVHCs need to tackle not only risk management, but also sustainability issues (see Section 5).

2.3. PAHs in rubber granulate

A lot of rubber waste contains polycyclic aromatic hydrocarbons (PAHs), of which some are identified as carcinogens. Currently, many end-of-life tyres (ELTs) are granulated and used as infill on synthetic turf fields, which are mainly used for football (soccer). In Europe there are over 13,000 synthetic turf football fields and over 47,000 mini football pitches (ECHA, 2017). Approximately 120 tonnes of rubber granulate is used on a single field, which is derived from approximately 20,000 ELTs. Moreover, for maintaining the quality of the synthetic turf fields, additional granulate needs to be added regularly because a considerable part of the granulate disappears annually into the environment. PAHs concentrations in rubber granulate derived from ELTs could be up to 19.8 mg/kg dry matter (0.00198% w/w; sum of eight ECHA PAHs; Oomen and De Groot, 2017). Besides PAHs, several other SVHC substances could be present in ELTs, including bisphenol A and di(2-ethylhexyl) phthalate (Oomen and De Groot, 2017).

Rubber granulate needs to fulfil the regulatory requirements for 'mixtures' under the REACH legislation, which describes the maximum allowable concentration of carcinogenic, mutagenic and reprotoxic substances. In general, for carcinogenic PAHs, this concentration limit is 1000 mg/kg dry matter (0.1%), except for benzo(*a*)pyrene and dibenz(a,h)anthracene for which a limit value of 100 mg/kg dry matter applies (0.01%). The amount of PAHs in rubber granulate easily satisfies this concentration limit. The concentration limits for consumer products and toys are much more stringent, consisting of 1 mg/kg dry matter (0.0001%) and 0.5 mg/kg dry matter per listed PAH (0.00005%), respectively. The amount of PAHs in rubber granulate is slightly higher than the concentration limit for consumer products and toys being considered as relevant scenarios for the infill application. Currently, a REACH restriction proposal is being drafted in order to determine a suitable concentration limit for rubber granulate.

Similarly to the case of lead in ray tubes, this case shows that assumptions about safety, or acceptable risk, during the use phase do not take into account future life cycle stages of the material. From a safety perspective, the PAHs and other chemicals in rubber granulate pose no risk to human health (Oomen and De Groot, 2017). The environmental impact of ELT rubber infill, however, definitely needs further attention. In addition, from a sustainability perspective, this re-use may not be considered as an optimal application route because much rubber granulate is spread into the environment and is not available for re-use again.

3. REACH and its relationship to circular and biobased economy initiatives

3.1. REACH and SVHCs

One of the main pieces of legislation dealing with the registration of industrial chemicals is REACH. As part of the REACH legislation, an EU Member State or the European Chemicals Agency (ECHA) can, at the request of the European Commission, propose a substance to be identified as a Substance of Very High Concern (SVHC). Such substances, like the above-discussed chemicals HBCDD, lead monoxide and certain PAHs, can have serious and often irreversible effects on human health and the environment. If identified, the substance is added to the Candidate List, which includes candidate substances for possible inclusion in the Authorisation List (Annex XIV). The inclusion of a substance in the Candidate List creates legal obligations for companies manufacturing, importing or using such substances, whether on their own, in preparations or in articles. For each substance included in Annex XIV, a deadline will be set after which use of that substance in the EU is prohibited (known as the 'sunset date'), unless authorised. Authorisation is by definition not a total ban, as some uses like production, use in scientific research and development, and use in plant protection products, biocidal products, and as motor fuel, are exempted from its scope. Furthermore, the authorisation process offers possibilities to exempt specific use categories, like diethylhexyl phthlate (DEHP) and other phthalate esters, which can still be used in the immediate packaging of medicinal products, despite their Annex XIV listing. Finally, for substances included in Annex XIV, manufacturers, importers and downstream users may apply for authorisation of their continued use after the sunset date. In order to apply they either need to show that risks are adequately controlled or that the socio-economic benefits of continued use outweigh the risks to human health and the environment and that no alternatives are available to replace the substance in question. Interestingly, an authorisation was recently granted to an industry consortium for a range of DEHP uses in a selected number of recycled PVC applications notwithstanding its SVHC status.

At present, the Candidate List comprises 174 chemicals and there are 43 chemicals included in Annex XIV. The number of REACH-SVHCs is expected to increase during the next decade. ECHA and Member States are putting considerable effort into increasing the number of chemicals assigned for either authorisation or restriction steps. This is, beyond doubt, an important objective from a safety perspective, but the rise of such new legacy chemicals - a future burden of the past - is an ongoing challenge for regulators, companies and waste treatment operators in terms of collection, separation and further treatment of waste re-use and recycling. It is important to note that once chemicals, or the products and articles in which these are incorporated, become waste they leave the scope of REACH and enter the domain of the EU waste legislation.

REACH-SVHCs and their interface with circular economy objectives are currently triggering fierce discussions in Europe. NGOs and some Member States firmly state that recycling cannot justify the perpetuation of the use and presence of hazardous legacy substances. Others advocate a more pragmatic approach in this ‘in between’ period between a linear and a circular economy, thereby realizing that fundamentally new concepts are needed to move towards a non-toxic environment.

3.2. REACH and biobased economy

Biobased chemistry includes the production of chemicals from renewable resources such as biomass or biotic waste streams, but also the manufacture of chemical products using enzymes, microorganisms and synthetic biology. Biobased chemistry may produce a variety of building block chemicals, such as glycerol and sorbitol, but also safe and sustainable substitutes for speciality chemicals of high concern. For example, alternatives from biomass for the application of bisphenol A as a dye developer in thermal paper were found to be, amongst others, derivatives of gallic acid, a component of tannin (Van Es, 2014). Tannin is common in nature and retrieved from wood and fruits. However, substances produced from biomass are not, by definition, safe and sustainable. Shifting from fossil to the bio-based production of the same chemical, will not resolve any toxicity issues, unless the toxicity was caused by impurities. So biobased produced 1,3-butadiene, for example, remains a hazardous chemical, irrespective of its feedstock. For that reason, the sound risk management of biobased chemicals should not be disregarded in advance. The European chemicals legislation REACH is often claimed to be a hurdle for innovative bio-based production companies. The question is, therefore, whether REACH is fit for purpose in a future biobased economy. Luit et al. (2017) investigated how REACH relates to using biomass for the production of chemicals. The goal was to analyse the REACH obligations and responsibilities relevant to stakeholders in biobased supply chains. The issues that companies identified as being challenging were studied, but also how REACH could instead be an opportunity for biobased chemistry. In general, REACH obligations apply to chemical supply chains as a whole and no distinction is made between the supply chains of chemicals produced in a conventional way using fossil feedstock, and those using biobased (renewable) feedstock. However, because of the nature of biobased production, some REACH obligations or exemptions will typically apply to actors in biobased chemicals supply chains, while others are of less relevance. For example, Annex IV of the REACH regulation includes a list of 33 specific natural substances (e.g. ascorbic acid, glucose, glycerines [C10-C18], and others) that are exempt from registration. The reason is that sufficient information is known about these substances and they are considered to cause minimal risks. In general, substances that occur in nature and are not chemically modified, are exempted from registration and will not be affected by authorisation requirements or restrictions, unless the substance has hazardous properties. Another exemption that is of typical relevance for bio-based companies is the exemption from registration of substances which have been registered and which are recovered from waste streams in the EU. This exemption is relevant for companies extracting or manufacturing chemicals from biotic waste such as bio-ethanol from agricultural waste streams. Biochemicals manufactured this way may, or may not, be hazardous but this hazard classification does not affect exemption from registration of a recovered substance.

REACH provides biobased companies and recyclers the opportunity to work within a circular economy, optimising resource efficiency. In general, if it is clear that the recovered material is free from hazardous chemicals, companies can produce, retrieve or work with natural substances, sometimes without registration obligations, and with a minimum risk of their chemicals being taken forward for EU wide risk management measures such as authorisation and restriction under REACH. We conclude that REACH provides an adequate framework for dealing with biobased chemicals and their potential hazardous properties. The perspective of biobased chemicals being used as an alternative for SVHCs that are regulated under REACH is as yet not fully exploited. REACH offers manufacturers of alternatives to SVHCs opportunities to submit information on these substances and their feasibility to be a replacement. We note that to date only very limited information on alternatives has become available from public consultations and no specific attention has been given to bio-based alternatives in these consultations. Although socio-economic aspects are considered when comparing alternatives for SVHCs, sustainability aspects are not sufficiently taken into account. This route needs to be stimulated in order to realise its potential as a safer alternative for a circular economy (see Section 5).

4. Safety decision scheme

In order to stimulate a transition towards a sound circular economy, a transparent weighing of both safety and sustainability factors for the re-use of waste streams is necessary (see also Section 5). Regarding safety aspects, we here propose a first scheme on how to decide whether a(n) (additional) risk assessment is necessary with respect to the re-use of materials containing hazardous substances (Fig. 1). This decision scheme is divided into two phases, a waste phase and a product phase. It should be noted that this framework has been specifically developed for Dutch substances of very high concern (NL-SVHCs), although it could also be applied to other groups of hazardous substances. NL-SVHCs are substances which meet the Article 57 criteria of REACH, similar to the REACH-SVHCs, but are identified based on several additional lists (De Poorter et al., 2011). The first section of our proposed scheme is based on a general concentration limit value of 0.1% which is the most stringent generic concentration limit applied in the EU waste directive and related CLP regulation. If this value is not exceeded no further risk analyses should be necessary and the waste-to-product processing could be approved. Some exceptions need to be taken into account, including POP-containing waste streams (which need to be disposed as described in the POP regulation) and a number of more stringent substance-specific concentration limit values as included in Annex VI of the CLP regulation (Wassenaar et al., 2017). After waste processing, when the product phase is reached, product

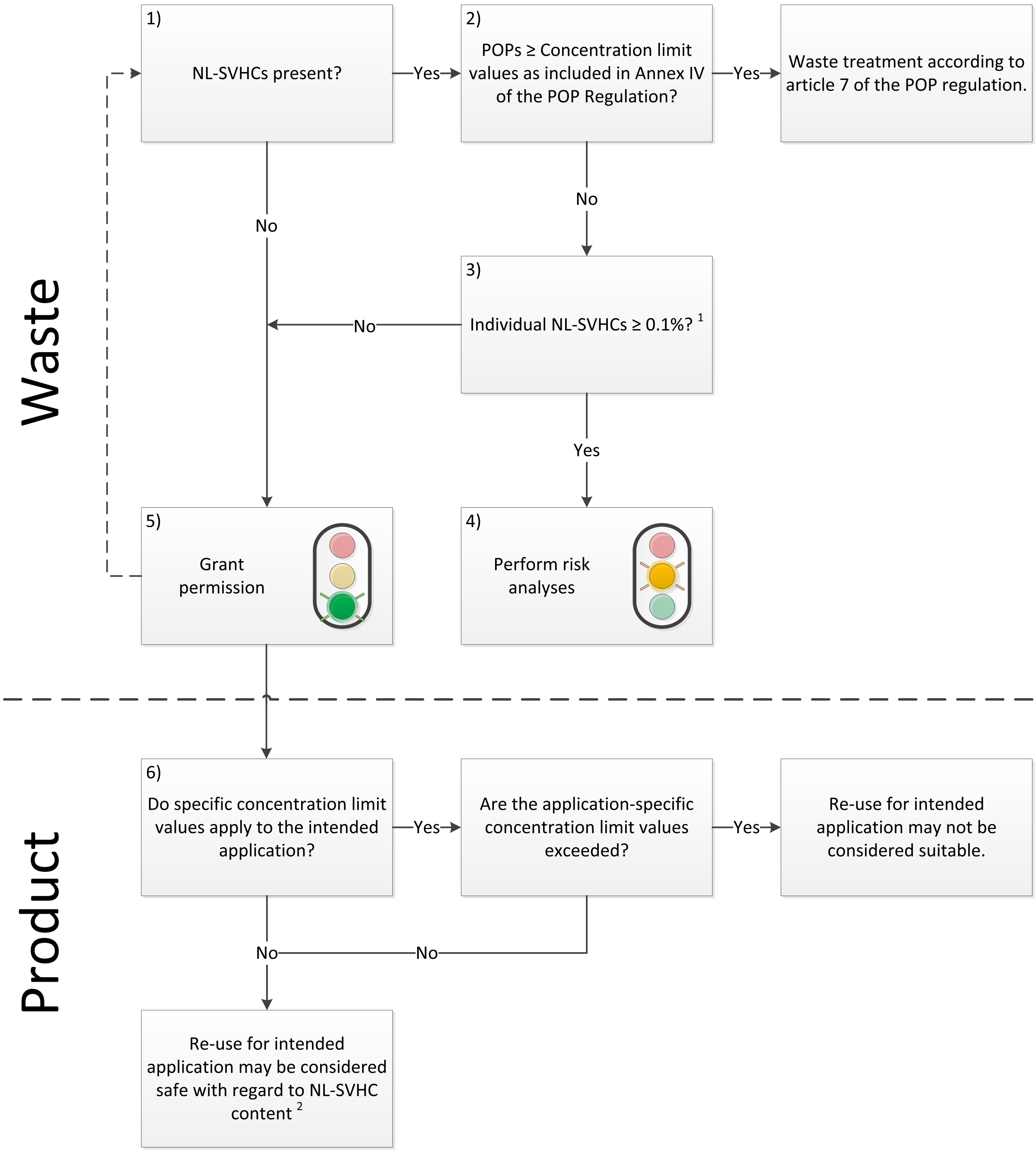

Fig. 1. Decision scheme on whether a(n) (additional) risk assessment should be performed with respect to the re-use of materials containing hazardous substances, or whether permission can be directly granted. [1] = a number of more stringent substance specific concentration limit values should be taken into account as included in Annex VI of the CLP regulation. [2] = in specific situations one may consider conducting a product risk analysis (for instance in cases where the developed application is totally different from the previous, known application).

specific regulations should be taken into account. These product requirements should be met, in the same way as any virgin product. This simple decision scheme, which indicates when there is no further concern with respect to safety of NL-SVHCs, could contribute to a swift transition towards a safe circular economy if it was applied to the Dutch National Waste Management Plan (LAP3; Ministry of Infrastructure and the Environment, 2016). We emphasise that, in some cases, the outcome of the 'technical' decision scheme needs to be complemented with societal analyses and adequate risk communication strategies (see also Section 5).

5. Discussion and conclusions

Our experience with the above cases shows, not only the legal complexity, but also that the environmental and human health risks of hazardous chemicals have not yet been fully identified and understood from a circular economy perspective. Preliminary analyses revealed that problems may arise when (potentially) hazardous substances such as SVHCs, or POPs are retained in the material cycles and re-enter the technosphere or the environment in new and unexpected ways. One of the possibilities for an improved risk management strategy for dealing with hazardous chemicals is to explicitly address the re-use and re-entrance of chemicals in material chains when these chemicals are being registered for access to the market. For this, amongst others, new exposure scenarios (e.g. REACH SPERCs) have to be developed based on our anticipations of the chemicals pathways which might exist in circular economy applications. The way REACH is currently designed, however, means that the responsibility of the registrant stops at the waste stage (end of life of the registered chemical). Especially in cases where chemicals are incorporated in materials, recovery becomes increasingly important in a circular economy. After recovery a new life cycle is initiated under the responsibility of the recovery operator who has the obligation of registering said chemical and hence has to ensure all uses downstream in his supply chain are adequately controlled. In practice, the recovery operator is allowed to simply refer to existing registration(s) of the recovered chemical and will experience legal uncertainty regarding the need for him to develop exposure scenarios for all his downstream uses.

REACH brings hazardous substances to a visible and transparent policy platform where decisions are taken on their authorisation and potential use restrictions. This may be seen as the 'end-of-pipe' solution for risk management requiring appropriate measures for controlling the risks of these (new-born) legacy chemicals, also during their second and further life. We propose that the authorisation and restriction process in REACH could also be the trigger for innovation on the development and introduction of safe(r) and sustainable alternatives. These safe(r) alternatives are important building blocks when implementing concepts like benign design or circular product design. Safe(r) biobased substitutes may be seen as an even more elegant alternative as they additionally favour the use of sustainable biomass rather than fossil feedstocks (Van Helmond et al., 2013). The socio-economic analysis (SEA) in REACH, in which potential alternatives for SVHCs are discussed, provides the only window of opportunity in REACH to address sustainability items of chemicals next to environmental and public safety. We believe that the SEA process needs better tools for decision-making if it is to address the challenges of a circular economy.

The need for new approaches for minimising the risks of novel technologies and chemicals is amongst the 21 ranked key topics for the 21st Century (UNEP, 2012). However, the development of integrated approaches to weigh safety, sustainability, and societal aspects, considering the whole life cycle of products, is lagging behind. Such approaches are needed to support transparent, swift and valid decision-making towards safe and sustainable ('benign design') initiatives. We are currently developing a tiered decision framework for comparative evaluation of the safety and sustainability aspects of chemicals throughout their life cycles. The safety decision scheme described above will be incorporated in this tiered framework. The overarching framework should enable stakeholders to compare different products and production chains to support benign design and green chemistry. The tiered approach facilitates the early-stage evaluation of products and of products that are already on the market. We emphasise the importance of incorporating societal aspects like public acceptance and perception in such a strategy. Positive results from a well-balanced, quantitative risk and sustainability assessment lack any power if society simply does not accept the application. This holds, in particular, when consumers may have direct contact with recycled materials and their hazardous components. The risk assessment outcomes should then always be accompanied with a societal dialogue and a transparent risk communication strategy.

For decision-making on the use of chemicals, the impacts of chemicals on the environment can be quantified, for instance with a Chemical Footprint method (Zijp et al., 2014) and combined with other footprints, such as the carbon footprint. Another approach is a further development of the Life Cycle Impact Assessment (LCIA). LCIA aims to assess a broad range of impact categories, such as climate change, acidification, photochemical ozone formation, human toxicity, ecotoxicity and resource depletion. There are different ways of defining and calculating these impact categories (e.g. Goedkoop et al., 2009; Huijbregts et al., 2016). LCIA can be used to underpin a comprehensive assessment of possible trade-offs and risks of various chemicals life cycles, treatment technologies versus replacement chemicals (see our HBCDD case), and so on. Because these methods still have some methodological drawbacks (Pfister and Raptis, 2014; Diamond et al., 2015), risk assessment and risk management methods of chemicals need to be adjusted to tackle the complexities of a circular economy. Continued resource use and potential impacts over much longer timeframes and variable spatial scales present serious challenges. Even the simple notion of designing biodegradable, but (eco)toxic, substances to prevent accumulation during continued re-use may be at odds with sustainability goals if this required high energy and materials input. The benign design of chemicals encompasses more than just optimising a single parameter such as (eco)toxicity or biodegradability.

Finally, it will definitely take considerable effort and time to adjust the linear economy legislation into one that is fit for a circular economy purpose. This should by no means be an obstacle for both private and non-private green initiatives. On the contrary, experimental settings may provide useful information when making new, either voluntarily or legislative, rules for a sound circular economy. The so-called Green Deal approach in the Netherlands aims to remove barriers to help sustainable initiatives get off the ground and to accelerate this process where possible. It is used to supplement existing instruments, such as legislation and regulation, market and financial incentives, and measures to stimulate innovation. Ganzevles et al. (2016) recently evaluated the Green Deals on circular economy the majority of which focused on recycling. They concluded that the approach provides a stimulating platform for cooperation and sharing knowledge between stakeholders, but, in general, the underpinning of the overall environmental benefits of the new technology is missing. Our work on building the above-mentioned integrated framework may hopefully fill this gap in the near future.

Conflict of interest

None (all authors).

Acknowledgements

The authors are grateful to our colleague Jan Roels for critically reading the draft version of this article.

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