DOI: 10.1111/jiec.13103

RESEARCH AND ANALYSIS

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

How to handle the policy conflict between resource circulation and hazardous substances in the use of waste?

Three countries' regulations on contaminants in waste and their implications for resource circulation

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Editor Managing Review: Jooyoung Park

Funding information
Svenska Forskningsrådet Formas, Grant/Award Number: 2017-00219; Swedish Research Council FORMAS, 2017–00219 and the Swedish Foundation for Strategic Environmental Research (Mistra).

Abstract

A circular economy creates a policy conflict between increased resource circulation and decreased dispersal of hazardous substances. On the basis of three case studies in the EU, we have therefore identified various regulatory questions that can be posed to address the occurrence of hazardous substances in the use of waste. For each of these questions, we have proposed two possible responses influencing the design of the regulation and analyzed their consequences both from a circularity and from a toxicity perspective.

Currently, the regulations focus on reducing the dispersal of hazardous substances rather than stimulating resource circulation. The allowable contamination levels in the waste are typically regulated in relation to its mass rather than its content of valuable resources. The regulation of hazards in waste can be further developed in two general ways, by emphasizing either the risk of exposure to hazards or the total content of hazards. A risk approach is beneficial for short-term circularity and waste producers. A hazard approach is beneficial for long-term circularity and waste users. In order to improve the balancing of the policy conflict in question, values, underlying assumptions, and the effects of hazardous substances and resource circulation need to be better understood.

KEYWORDS
bottom ash, circular economy, industrial ecology, policy conflict, pollution prevention, Toxic-free environment

1 | INTRODUCTION

It is sometimes difficult to see why anyone would be interested in using waste as a resource in a circular economy instead of the well-functioning value chains with primary resources, especially because waste-based resources typically have a lower quality than primary resources. The lower quality comes partly from the inevitable quality losses from the use of a material, partly from the presence of impurities in the waste, referred to as "contaminated interactions" by Baxter, Aurisicchio, and Childs (2017). The problem of contamination has two different causes. First, in an effort to keep the material in the economy for as long as possible, hazardous substances that should really be phased out may remain as "legacy substances" (Goldberg, 2017) if they are circulated. In addition, different types of materials and substances are usually mixed during waste management. This means that the outputs from recycling processes, that is, the very resource to be circulated, typically hold higher levels of contamination than the corresponding material from the Earth's crust.

Hence, circulation may increase the distribution of hazardous substances in the environment and society, while at the same time potentially limit the exploitation of virgin natural resources. This problem is materialized by the waste composition, which typically often involves both valuable resources and hazardous substances. Such ambiguity has been identified for various waste materials such as secondary plastic (Leslie, Leonards, Brandsma, De Boer, & Jonkers, 2016), paper (Pivnenko, Eriksson, & Astrup, 2015), wood (Koyano, Ueno, Yamamoto, & Kajiwara, 2019), and scrap metals (UNEP, 2013). A particularly illustrative example of this problem is complex residual materials, that is, fine-grained leftovers such as sewage sludge (Kidd, Domínguez-Rodríguez, Díez, & Monterroso, 2007) and municipal solid waste incineration bottom ashes (Chimenos, Segarra, Fernández, & Espiell, 1999) from industrial waste treatment processes.

It is well known that sewage sludge contains nutrients such as phosphorus, while incineration bottom ashes contain scrap metals and work well as a construction aggregate. The utilization of such residual materials may thus reduce the need of virgin materials from the bedrock, such as mineral fertilizers and natural gravel. However, the level of contamination in sewage sludge and bottom ashes is typically higher and more complex than in the conventional material they replace (Johansson, 2018).

The consequence of contamination in the waste-based materials is downcycling (Zink & Geyer, 2017). This means that waste-based materials are often used in less demanding functions than the original materials (McDonough & Braungart, 2010). The failure of waste-based materials to replace the original material makes the potential substitution of the corresponding primary resources uncertain (Zink & Geyer, 2017). Hence, there is a risk that the inefficiency of a circular economy will only add more dwindling resources to the economy, through the addition of secondary resources, rather than substitute primary resources and replace the linear economy (Johansson & Henriksson, 2020).

The problem of co-recycling of hazardous substances is thus clear. However, how to balance the political ambitions to reduce the distribution of hazardous substances (toxic-free or non-toxic environment) and at the same time increase circulation (circular economy) is less covered (Friege, Kummer, Steinhäuser, Wuttke, & Zeschmar-Lahl, 2019; Johansson, Velis, & Corvellec, 2020). This policy conflict has mainly been addressed through integrating the waste and chemical regulations (EU, 2018). In this work, the upstream has been highlighted by limiting (through, e.g., REACH) or prohibiting (e.g., Stockholm Convention) the production and use of hazardous substances in products. This, often multilateral, approach has successfully reduced the use of some hazardous substances (such as DDT) in the economy. But multilateral agreements require extensive negotiations, which means they are slow instruments that only capture a small share of the hazardous substances in use. In addition, the banned substances may remain in those products with a long lifetime, such as buildings and infrastructure. Thereby, an upstream focus can create a false confidence that the problem is solved, but when the products in use later become waste, the problematic substances will resurrect themselves. In addition, many chemicals play an essential role in products and cannot therefore be prohibited.

At present, the policy conflict is therefore mainly governed downstream, where the problem often falls on the waste sector to decontaminate the waste. The trade-off between hazards and resources occurs foremost here, downstream, by setting limits of acceptable contamination levels in the use of waste such as industrial residues (Liu, Ren, Lin, & Wang, 2015). Previous studies have demonstrated that the amount of utilized residual waste such as sewage sludge (Mininni, Blanch, Lucena, & Berselli, 2015) and bottom ash (Blasenbauer et al., 2020) differs remarkably between different countries within the same region. However, the reasons for these differences are so far largely unknown. There is also a general lack of knowledge on how the design of regulations on hazardous substances in waste influences practice and the capacity to balance the conflict between resource circulation and a non-toxic environment (cf. Friege et al., 2019).

Hence, the purpose of this study is to identify regulatory questions that can be posed to address the occurrence of hazardous substances in the use of waste and analyze how different potential responses affect the conditions for a circular economy. In doing so, we study how both the circulation and contamination of residual materials, that is, sewage sludge and waste incineration bottom ash, are regulated in three countries within the EU. Based on these cases, we then identify different regulatory questions and responses influencing the design of the regulations that have been used to control hazardous substances in the use of these residual materials. In order to guide continued policy development, the potential and challenges of different regulatory responses to serve as a means for balancing the conflict between resource circulation and a non-toxic environment are discussed. The regulatory questions and the potential responses will help policy makers to navigate through this policy conflict by visualizing possible pathways and their consequences.

2 | METHODS

2.1 | Selection of cases

To study the policy conflict, two different waste types were focused on; municipal sewage sludge and waste incineration bottom ash. These residues were chosen since they are clear examples of how the policy conflict materializes in the waste composition of both resources and contaminants. In addition, the utilization of sewage sludge and bottom ash has been ongoing and debated for a long time and many countries have thus developed

TABLE 1 Respondents in the study in relation to material, stakeholder group, and country

	Bottom ash			Sewage sludge		
	Sweden	Denmark	Germany	Sweden	Denmark	Germany
Waste producers	Avfall Sverige	Afatek A/S	ITAD	Nitoves AB	Hede Denmark	DWA
Waste users	Trafikverket	Vejdirektoratet	BASt	LRF	Landbrug and Fødevarer	Deutscher Bauernverband
Additional respondents[a]	–	–	–	–	–	Isle Utilities

[a]To clarify issues not addressed by the business association.
"–," No information obtained.
ITAD, Interessengemeinschaft der Thermischen Abfallbehandlungsanlagen in Deutschland; BASt, Bundesanstalt für Straßenwesen; DWA, Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall; LRF, Lantbrukarnas riksförbund.

policies for these materials that can be studied. However, there are still uncertainties about how these residual materials should be handled and regulated. Therefore, their management is currently under investigation in many regions such as Europe (Blasenbauer et al., 2020; EU, 2020).

There are also differences between sludge and ash, both materially and in how they are regulated. For example, the use of sewage sludge is governed by an EU (1986) directive that specifies harmonized rules for its application, for example, in terms of minimum limits of hazardous substances. The use of bottom ash, on the other hand, is governed by rules that are more general and lack harmonized requirements on limit values within the region. The directive on industrial emissions (EU, 2010), for instance, requires that the operator shall minimize hazardous substances in the ash to be recycled within or outside the site.

In order to study these policies, cases were chosen that represent three different, but common, approaches toward the utilization of residues. Within the EU, Western and Central European countries tend to exhibit a (1) high use of industrial residues, while Eastern and Northern European countries show a (2) low or non-existent use (Blasenbauer et al., 2020; Mininni et al., 2015). In addition, in some countries, (3) innovative policies have been developed for the management of such residues. Based on these different approaches, three different representative countries were chosen. Denmark represents a country with (1) high use of industrial residues, since all bottom ash is used as construction aggregates (Blasenbauer et al., 2020) and over 75% of the sewage sludge is applied to farmland (Dakofa, 2012). Sweden represents a country with (2) low use since bottom ashes are not used outside landfills (Blasenbauer et al., 2020) and the application of sewage sludge to arable land is annually only around 25% (Mininni et al., 2015). Germany is developing innovative policies (3) for both waste-based aggregates (Blasenbauer et al., 2020) and fertilizers (Umweltbundesamt, 2018) and the size of the country also brings regional differences in how residual materials are used and regulated between federal states.

2.2 | Collection of information

Information has been collected through document analysis and interviews. The document analysis was used to thoroughly map different governmental documents. This includes documents on allowable contamination limits and other policy instruments that regulate both circulation and contamination of residual products in the studied countries.

The purpose of the interviews was to capture actors' perspectives and attitudes toward the policies and utilization of the waste in question. Hence, the interviews provided an opportunity to uncover additional factors, beyond the influence of policies, which may explain the management of the sludge and ashes.

Interviews were conducted with two groups of actors: (i) waste producers and (ii) waste users. In practice, there may be many potential players within each of these groups. Therefore, interviews were held with representatives from different business associations for waste producers and users in each country, Table 1. Just like in all big organizations, however, there may be controversies and different opinions between the members of the association. A respondent that represents the official standpoint was thus chosen by the organizations themselves.

2.3 | Analysis

The empirical material was analyzed in three different ways. Section 3 involves a descriptive account of how both the utilization and contamination of residual waste is regulated in the different countries. Subsequently, the regulations on allowable contamination limits in the waste are here related to other policy instruments (e.g., specific recycling targets for the residual waste) and factors such as attitudes of different actors. Thereby, a background is provided to explain the current utilization rates of the residual materials in each case study. References to the interviews are in italics, and the reviewed documents in accordance with the Harvard System. Furthermore, the regulation of cadmium is throughout the paper used as an illustrative example, since it is one of the most hazardous substances currently regulated.

A comparative analysis of the different cases was then made to identify different underlying regulatory issues in the regulations of hazardous substances in the waste to be used, presented in Section 4. These re-occurring issues are presented by proposing two different potential responses regarding how the regulation may be designed. The responses are then analyzed in terms of their consequences for waste producers and users. Most of the regulatory questions concerned the material level and how the contamination levels in the waste are regulated in different ways. Among the studied cases, we also identified different questions for how these regulations on the material level could be implemented in practice.

Lastly, in Section 5, the potential and challenges of the regulatory responses to balance the conflict between resource circulation and a non-toxic environment were discussed. First, by discussing the potential outcome of the responses based on how different responses are usually combined in practice and influenced by other factors. The underpinnings of the responses were then analyzed based on a theoretical approach that emphasized the relation between the responses and different theoretical categories of "toxicity," the degree of hazards to cause harm, and "circularity," the level of keeping resources and its value in the loop. Thereby, the capacity of the regulatory responses was revealed to balance resource circulation and the dispersal of hazardous substances.

Toxicity and circularity regulations are typically based on two different principles; "hazard" or "risk" (Scheer et al., 2014) and "resource" or "recycling" (Haupt, Vadenbo, & Hellweg, 2017), respectively. A hazard-based approach focuses only on the presence of potentially harmful agents in the waste, while a risk approach adds the dimension of exposure and thus the likelihood of the hazards causing harm. An approach based on recycling concerns the circulation of waste in terms of quantitative mass, while a resource-based approach targets the quality of circulation, that is, the preserved resource-value. For example, a resource-based approach focuses on the proportion of phosphorus that is actually circulated through the application of sewage sludge to farmland rather than just the amount of sludge that is applied to the land. Such a resource approach is thus more in line with a circular economy (Blomsma & Brennan, 2017), in which the functional value of circulation is emphasized by encouraging the development of models, innovations, and policies to retain the economic value or technical properties in the material over time.

3 | REGULATORY CONDITIONS FOR USING RESIDUAL WASTE

3.1 | Sweden

3.1.1 | Bottom ash

In Sweden, there are two different possibilities for using waste as construction aggregates: free, unrestricted use, in which the waste aggregates can be applied anywhere, or as landfill cover (Naturvårdsverket, 2010), Table 2. The use is regulated by guiding limits for both total concentrations[1] and leaching concentrations[2] of 13 different substances in the waste. The limits of total concentration for covering landfills (1.5 mg Cd/kg material) are generally less restrictive than for free use (0.2 mg Cd/kg), Table 3. The limits are guidelines and waste below the limits may be used without permission. However, when the limits are exceeded, a case-specific decision needs to be taken by the local authorities.

All incineration bottom ash is used as construction aggregates at landfills in Sweden, either to cover landfills or to build roads inside the landfill area (Avfall Sverige, 2018), Table 4. This is presently a cost-saving outlet for the waste producers because the use of waste as a construction aggregate is categorized as recycling (Naturvårdsverket, 2010), which avoids the landfill tax of €50 (CEWEP, 2017). Today, no bottom ash is used as a construction aggregate outside landfills, as "the requirements for free use are too strict, especially for the total concentrations" (*Avfall Sverige*). The potential customer, *Trafikverket*, the Swedish Transport Administration that is the procurer of all the major infrastructure projects, argues that "foreseeability is missing," since decisions by the authority are taken on a case-by-case basis. Therefore, they "prefer to use virgin ballast material," a well-functioning and established supply chain.

3.1.2 | Sewage sludge

Applying sewage sludge to agricultural land is regulated by total concentrations of seven substances in the sludge and in the targeted soil (Jordbruksverket, 2004; Naturvårdsverket, 1994; SCS, 1998), Table 2. The content of contamination in the sludge is controlled both by its total content (2 mg Cd/kg) and by annual load (0.75 g/ha and year). The limits are binding and nationally applicable, which means that sewage sludge exceeding the limits shall not be applied. In practice, sewage sludge is only allowed in growing energy crops, grains, and animal feed.

The regulatory conditions are from the 1990s and are today considered "too liberal and limited" according to the the Federation of Swedish Farmers (*LRF*), and have therefore lost legitimacy among both waste producers and users. For this reason, the Swedish Water and Wastewater.

[1] Total concentration refers to the concentration of the substances occurring in the waste.
[2] Leaching concentration refers to the concentration of substances that are released from the material in contact with fluids.

TABLE 2 Overview of the regulatory conditions for using waste as a construction aggregate and as a fertilizer in Sweden, Denmark, and Germany. A detailed description of the limit values in each case study is presented for bottom ashes in Supporting Information S1 and for sewage sludge in Supporting Information S2

	Bottom ash			Sewage sludge		
	Sweden	**Denmark**	**Germany**	**Sweden**	**Denmark**	**Germany**
Allowed use	As an aggregate according to two defined applications: free use and landfill cover	As an aggregate according to three categories; (1) partly free use (2), covered application, (3) capped application	As an aggregate according to three categories; (Z0) free use, (Z1) partly exposed application, (Z2) capped application	For fertilizer purposes in farmland	For fertilizer purposes in farmland	For fertilizer purposes in farmland
Restrictions	Stated case by case	Height, drainage and density.	Maturation for at least 3 months	Restrictions on pasture and arable land	Restrictions on the first year and water protection areas.	Restrictions on pasture land, arable land and water protection areas
Number of substances to be tested for leaching concentrations in the waste	13	14	12	–	–	–
For total concentrations in the waste	13	9 (category 1), 0 (2, 3)	12 (Z0), 12 (Z1, Z2)	7[a]	13	11
For total concentrations in the targeted soil	–	–	–	7	7	11
Legal force	Guiding	Binding	Guiding	Binding	Binding	Binding

[a] A certificate requires that 60 substances are tested in the waste.
"–," non-applicable.

TABLE 3 Requirements on total content of cadmium for applying waste to construction and sewage sludge to arable land. The requirements on sewage sludge also include limits on the targeted soil

	Sweden		Denmark		Germany		
Waste-based aggregates	Free use:0.2 mg/kg	Landfill cover:1.5 mg/kg	Category 1:0.5 mg/kg	Category 2 and 3: > 0.5 mg/kg	Category Z0:0.6 mg/kg	Category Z1:3 mg/kg	Category Z2:10 mg/kg
Sewage sludge	2 mg/kg Total load: 0.75/hr/y		0.8 mg/kg, or 100 mg/kg P		1.5 mg/kg		
Soil	0.4 mg/kg		0.5 mg/kg		Clay: 1.5 mg/kg	Silt: 1 mg/kg	Sand 4 mg/kg

mg/kg, milligram/kilogram; hr/y, hectare/year.

TABLE 4 The generation and management of bottom ash and sewage sludge in Sweden, Denmark, and Germany

	Bottom ash			Sewage sludge		
	Sweden	Denmark	Germany	Sweden	Denmark	Germany
Landfill construction	100%	–	70%	25%	–	–
Road construction	–	100%	30%	–	–	–
Landscaping	–	–	–	35%	–	13%
Farmland	–	–	–	25%	77%	29%
Mono-incineration	–	–	–	–	33%	55%
Other	–	–	–	15%	–	3%
Amount in tonnes	1,000,000	600,000	4,800,000	200,000	140,000	2,000,000

"–," non-applicable.

Association and the Farmer Federation of Sweden have entered into an agreement (REVAQ, 2019). This agreement allows only the application of certified sewage sludge. In order to obtain a certificate, the wastewater treatment plants must meet requirements that are significantly tougher than legislation, regulating the total concentration of 60 different substances.

Most of the sewage sludge (35%) has been used for landscaping, Table 3. A smaller proportion (25%) is applied to farmlands and used to cover landfills (SOS, 2018). The use of sewage sludge is primarily controlled by the demand. Most of the sludge is used for landscaping because the municipality is the customer for purchases for parks and, unlike the farmers does not need to consider downstream customers. In addition, there are no requirements for using sludge in parks. Most of the sludge is within the limits for application to arable fields (Naturvårdsverket, 2013). However, few farmers are positive as "agriculture bears the risk" and "what can our customer, the food industry, gain from the application of sewage sludge?" (*LRF*). The farmers are not compensated for accepting the sludge. In the year 2012, the Swedish government removed a policy objective that at least 60% of the phosphorus from sewage should be returned to the soil (Naturvårdsverket, 2013).

3.2 | Denmark

3.2.1 | Bottom ash

In Denmark, the use of waste as a construction aggregate is controlled by 3 categories, requiring that 14 substances shall be tested for leaching concentrations (Miljøstyrelsen, 2016), Table 2. Total concentrations of nine substances shall also be tested for Category 1. Waste that meets the requirements of the strictest category (0.5 mg Cd/kg), Table 4, can be used without special permission in a variety of applications such as landscaping. For use in accordance with the less restrictive requirements, Categories 2 and 3 (>0.5 mg Cd/kg), the use is directed to more polluted environments such as roads. Category 2 allows waste to be applied as a construction aggregate if it is covered by, for example, asphalt with safety requirements on maximum height. Category 3 has additional requirements for density, capping, and the disposal of excess water. These rules are mandatory and apply throughout Denmark.

In Denmark, all incineration bottom ash is used as a base layer in road construction, and typically passes the requirements of Category 3 (Hedenstedt, 2015). The Danish Road Directorate has a "positive attitude towards using bottom ashes as a base layer in roads" (*Vejdirektoratet*). This positivity derives partly from an earlier policy objective in the national waste plan (Miljøstyrelsen, 1999) that 70% of the bottom ash should be utilized. This "has driven tests and development of bottom ash application to roads" (*Vejdirektoratet*). The fact that policies are nationally applicable has contributed to establishing the necessary "clarity and foreseeability" (*Afatek*) for producers and users to invest in bottom ash utilization. However, the main driving force is that the Road Directorate gets paid to receive bottom ashes, while they do not need to buy natural gravel. At the same time, waste producers avoid paying significantly higher costs for landfilling, including a landfill tax of 63 €/tonne (CEWEP, 2017).

3.2.2 | Sewage sludge

The application of sewage sludge to agricultural land is regulated by the total concentration of 7 different substances in the targeted arable land (0.5 mg Cd/kg) and 13 in the waste (0.8 mg Cd/kg) (Miljøstyrelsen, 2017). The requirements are compulsory and apply throughout Denmark. For four substances in the waste, limit values are also expressed per kg of phosphorus (100 mg Cd/kg P).

In Denmark, about ¿ of all sewage sludge is used as a fertilizer on arable land, while the rest is mono-incinerated, and a few percent is stored (Dakofa, 2012). This practice is close to the policy objective in Denmark, stating that 80% of the phosphorus from sewage sludge shall be circulated by 2018 (Miljøstyrelsen, 2014). There is a consensus among the actors in Denmark and "trust between stakeholders" as well as "towards the regulatory conditions" (*Hede Denmark*). Financial incentives play a crucial role, since the farmers are often paid to receive the sludge. For Danish sewage treatment plants, sludge application is inexpensive compared to gate fees for incineration, including an incineration tax of 33 €/tonne, and landfill costs, including the landfill tax of 63 €/tonne (CEWEP, 2017).

3.3 | Germany

3.3.1 | Bottom ash

In Germany, the use of waste-based aggregates is controlled by 3 categories with requirements on leaching concentration and total concentrations for 12 different substances (Umweltbundesamt, 2003), Table 2. Category "Z0" (0.6 mg Cd/kg) allows free, unrestricted use, Category "Z1" (3 mg Cd/kg) demands partially exposed application, and Category "Z2" (10 mg Cd/kg) capped application, under comprehensive sealing. The conditions are guiding, and should be implemented by each federal region.

About 30% of all ash generated in Germany is used for road construction, under Category Z2 (Blasenbauer et al., 2020). The remaining bottom ash is used as construction aggregates within landfills or landfilled, Table 3. The management of bottom ashes depends mainly on the specific regional policies. In some regions, such as Brandenburg, the use is prohibited since "bottom ashes are classified as hazardous waste" according to the German Association of Waste-to-Energy plants (*ITAD*). In Hamburg, bottom ashes are classified as non-hazardous waste, and used relatively extensively, for example, in driveways (Hedenstedt, 2015). The customers, the infrastructure constructors, receive no compensation for accepting bottom ashes, but save on the purchase of natural ballast material. By finding a use for the waste, the waste producers avoid costs for landfilling, which does not include a landfill tax in Germany.

3.3.2 | Sewage sludge

The application of sewage sludge on arable fields is regulated by 11 different substances (1.5 mg Cd/kg) in the waste and in the targeted soil (1.5 mg Cd/kg), Table 2. The limits are expressed in total concentrations and apply to all forms of fertilizers applied to agriculture as well as landscaping (Umweltbundesamt, 2017). The requirements for arable land are controlled by three different categories depending on the soil's permeability, Table 3.

In Germany, most of the 2 million tonnes of sewage sludge is mono-incinerated, while the rest is applied to agriculture and landscaping (Umweltbundesamt, 2018), Table 3. Incineration is the most expensive option, but the preferred option for a host of policies and reasons. For example, competition from other secondary fertilizers, with higher market acceptance, such as "digestate and manure have increased in connection with growing biogas production and animal feedstock" (*Isle Utilities*). In addition, there is a political objective that the application of sewage sludge on arable land should be limited, because of the contamination risk, instead phosphorus shall be recovered from sludge (Umweltbundesamt, 2017).

4 | REGULATORY QUESTIONS TO CONTROL THE CONTAMINATION IN WASTE

Based on the studied cases, eight different regulatory questions have been identified that can be raised in order to control contaminations in waste to be utilized. Most of them are related to the material level and how the occurrence of hazardous substances in the waste can be monitored,

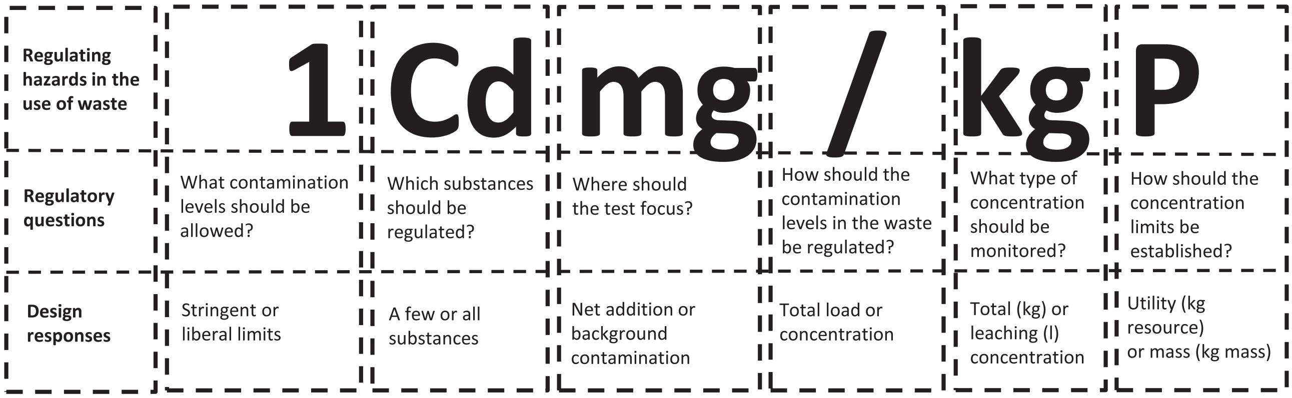

FIGURE 1 Overview of different regulatory questions that can be raised to address hazardous substances in waste and their potential responses regarding how to design the regulation. Please note that the formula visualizes only one response for each question. Alternative responses are presented in the row "design responses." Detailed description is given in the body text

evaluated, and regulated in different ways, Figure 1. Each of these regulatory questions can be addressed by two different but not always discriminate responses regarding how the regulation should be designed. The potential responses are highlighted in the text with italics and presented in relation to how they influence the possibilities for resource circulation for waste producers and users.

4.1 | Which substances should be regulated?

A key feature of any regulation on the contamination of waste concerns the selection of which and how many substances should be controlled. Among the studied cases, different approaches are used but the most common choice is to regulate *a few selected substances* to indicate whether the material is clean enough or not. For the use of sewage sludge, for instance, the number of substances to be monitored varies between 7 and 13 in the studied cases and for waste-based aggregates between 9 and 14, Table 2. However, another approach to using such indicators for contamination is to control *as many substances as possible*. The Swedish REVAQ (2019) certification that regulates the contamination in sewage sludge, for instance, requires the monitoring of about 60 substances.

Monitoring a few substances in the form of indicators for contamination is an inexpensive and manageable approach for the waste producers. But it provides limited information for the users about the pollution concerns since the waste in question may contain other hazardous substances than the regulated indicator substances (Jones-Lepp & Stevens, 2007). It is, however, not self-evident that extensive monitoring of many substances establishes user credibility. As demonstrated by the REVAQ certification where Swedish farmers remain concerned about unaddressed cocktail effects from the various contaminants occurring in the sludge.

4.2 | What contamination levels should be allowed?

Once the substances to be regulated have been selected, the allowed contamination levels for these substances in the waste must be determined. Such limits can be chosen in a *stringent* or more *liberal* manner. This choice often has an overarching impact on the possibilities for circulating the waste. In the studied cases, these contamination limits are largely different. Using cadmium as an example, free use of waste-based aggregates in Sweden means that the total concentration of cadmium needs to be about 2.5 times lower than in Denmark and Germany, Table 4. In order to apply sewage sludge on arable land, the cadmium content needs to be 2.5 times lower in Denmark than in Sweden. To clarify this point even further, comparisons can also be made with additional cases. For example, sewage sludge applied to fields in Spain may contain 50 times more cadmium than in Denmark (Mininni et al., 2015).

Allowing higher levels of contamination, as for waste-based aggregates in Denmark, means that a larger amount of the waste can meet the limits. But allowing too high contamination levels may over time damage the users' trust in the material. For example, this was the case for the Swedish farmers' confidence in using sewage sludge on arable land. According to the same logic, strict contamination limits can establish user confidence in the material, as in, for example, the utilization of sewage sludge in Denmark. However, too strict limits can also completely halt the use and development of alternatives for circulation of waste. This seems to have been the case in the failure to find a use for bottom ashes outside landfills in Sweden.

4.3 | What type of concentration should be monitored?

When designing regulations on the allowable contamination levels in waste, there is a choice to be made regarding what type of concentration these limits should monitor. In principle, the occurrence of regulated substances can either be measured by *total* (mg of substance/kg of waste) or *leaching* (mg of substance/l of leachate) *concentrations*. In the studied cases, the allowable contamination of sewage sludge is exclusively regulated by total concentrations, Table 2. For waste-based aggregates, however, different types of concentrations are used for monitoring the regulated substances. In Denmark, leaching concentrations are emphasized, while both total and leaching concentrations are considered in Sweden and Germany.

As waste such as bottom ash can contain relatively high levels of contamination in terms of total concentrations, it can often be hard for the waste producers to meet such limits. The non-existing use of bottom ash as a construction aggregate in Sweden is an illustrative example in this respect. There are greater opportunities for waste producers to meet contamination limits based on leaching concentrations even if they are strict, as the Danish case demonstrates. This is because many of the substances that occur in such waste are strongly bound to the material and therefore not possible to extract during leaching tests (Saqib & Backstrom, 2016). From a user perspective, however, it may be considered important to measure total concentrations. In the case of using sewage sludge on arable land, for instance, the uptake of different contaminants in the crops is uncertain (Juste & Mench, 2017) and the mobility of different substances in the waste may change over time (Astrup, Mosbæk, & Christensen, 2006).

4.4 | How should the concentration limits be established?

Beyond the choice between total or leaching concentrations, there are still choices to be made regarding exactly how these concentrations should be established. In virtually all of the studied cases, the concentrations are addressed by relating the occurring amount of the regulated substance to the *mass* of the waste (mg of substance/kg of waste). However, another way of expressing these concentrations is to instead compare the amount of the substance in question to the *utility*, that is, the amount of a specific resource contained in the waste. The only identified case where this is an alternative is in the Danish sewage sludge legislation (Miljøstyrelsen, 2016). Here, the allowable concentration of the regulated substances is determined in relation to the amount of phosphorus in the sludge (mg of substance/kg of P), Table 3.

For waste producers, regulating the contamination in relation to the provided resource utility of circulating the waste provides them with more options for fulfilling the concentration limits. Apart from traditional measures aiming to just reduce the level of contamination, such regulations can for instance spur them to also invest in processes for enriching the resource value of the waste. For the users, establishing allowable contamination levels in relation to the provided resource utility of the waste rather than just its mass may reduce the risk of being subjected to material with a low functional value (e.g., sewage sludge with a low nutrient content).

4.5 | Where should the test focus?

The pollution concerns of using waste is not just a matter of the *net addition* of contamination from the waste, but can also be influenced by the *background contamination* in the place where it is to be used. Among the studied cases, such a perspective is particularly pronounced for the use of sewage sludge on arable land. All studied countries have chosen to also regulate the allowable contamination levels in the soil (background contamination) where the waste is utilized, Table 2. However, this is not the case for waste-based aggregates, where only the occurrence of contaminants in the waste is regulated. The already existing background contamination at the site in question is thus not monitored.

Regulating the level of contamination only in the waste shifts the responsibility and thus the control to the waste producers. On the other hand, requiring the monitoring of the background contamination where the waste is to be utilized puts a responsibility on the user. Measuring both the background contamination and the addition of contaminants from the waste provides a more comprehensive understanding of the total pollution situation for the users. However, for waste producers, this makes it more difficult to foresee if their waste will be accepted for use given that the background contamination levels can vary widely from site to site.

4.6 | How flexible should the contamination limits be?

Another regulatory question to take into account in the construction of the contamination limits is the fact that the use of waste might exhibit different pollution concerns depending on how and where it is used. In principle, the levels of contamination in the waste can thus be locked to *one set of limits* for all types of applications or be flexible and *differentiated* based on how and where the waste is used. For the application of sewage sludge to farmland, there is only one set of contamination limits in the studied cases. This is also the situation for applying waste-based aggregates outside landfills in Sweden. In Denmark and Germany, however, there are different sets of contamination limits that vary depending on if the waste is used as a construction aggregate in roads, industrial sites, or in more sensitive areas such as beneath a pre-school, Table 3.

A flexible approach, where the allowable contamination levels in the waste are altered for different uses, often means that a larger proportion of the waste can meet the limits, as demonstrated by the utilization of bottom ash in Denmark and Germany. This is because the waste producers are also offered an outlet for more contaminated waste through applications in less sensitive environments such as industrial areas or roads. However, such applications where a higher level of contamination in the waste is allowed are often followed by different types of restrictions and requirements in terms of safety and control measures. For the users, such requirements make the utilization of waste more cumbersome and uncertain than using conventional materials (Blasenbaur et al., 2020).

4.7 | How should the contamination levels in the waste be regulated?

In the studied cases, the allowable contamination levels in the waste are typically regulated only by *concentrations* that are expressed in relation to the mass of waste (mg of substance/kg of waste). However, the addition of hazardous substances from the use of waste can also be monitored as an aggregated *total load* per area and year (mg of substance/ha/year). This is the case in Sweden where the application of sewage sludge to farmland is regulated by both concentration limits and an allowable total annual load to a certain area. In Germany and Denmark, however, the use of sewage sludge is only regulated by concentration limits for selected substances. This is also the case in all of the studied countries regarding the use of waste-based aggregates, Table 3.

Regulating the allowable contamination levels only by concentration opens up the possibility to dilute contaminated waste with cleaner materials, thereby reaching the imposed limits. Such regulations increase the possibility for waste producers to find an outlet for their waste (Johansson, Krook, & Frändegård, 2017). For the users, however, the total amount of hazardous substances that ends up in their application may not change. For them, measuring the total load of substances can thus be beneficial because it limits the amount of waste that could be utilized in a particular location and thereby also the presence of hazards. For waste producers, however, such total load restrictions could mean that they need to identify and secure additional applications for their waste, and invest in upstream prevention work or in expensive upgrading processes to reduce the contamination levels (Sarkis & Cordeiro, 2001).

4.8 | On what administrative level should the regulation be implemented?

The final regulatory question concerns the fact that regulations on the contamination in waste can be implemented at different administrative levels. For the use of sewage sludge on farmland, the allowable contamination limits are binding and *nationally applicable* in the studied countries, Table 2. However, when it comes to waste-based aggregates, there is a greater difference among the cases. For example, in Sweden and Germany the contamination limits for waste-based aggregates are only guiding and *locally applicable*. The responsibility is thus decentralized towards the local authorities to work out the detailed rules and limits. In Denmark, the corresponding regulations for waste-based aggregates are nationally applicable.

Centralized regulations, as in the case of Denmark for bottom ashes, usually lead to an increased use of the waste. This is since the regulatory conditions are foreseeable and legally robust for both waste producers and users. When such regulations are instead permitted locally and on a case-by-case basis as in Sweden and Germany, it becomes increasingly difficult for waste producers and users to foresee what contamination limits need to be fulfilled. Then, there is always a risk of appeals in such permitting processes, which might render the construction in question illegal. A potential advantage with decentralization is that it opens up the possibility of developing contamination limits that are locally adapted to the specific application and place where the waste is to be used. Experiences from Sweden, however, show that many local authorities lack the capacity and competence to set such independent limits, resulting in long and unpredictable permitting processes (Naturvårdsverket, 2015). In such settings, waste producers might opt for other, more certain disposal options for their generated waste and potential users might select conventional materials instead.

5 | THE POTENTIAL AND CHALLENGES OF THE REGULATORY RESPONSES

In this section, the regulatory responses are first (Section 5.1) discussed in combination and in relation to other factors influencing the conditions for circulation of residual waste. The underpinnings of the regulatory responses are then (Section 5.2) analyzed through different theoretical approaches to circularity and toxicity. Thereby, the capacity may be revealed of the different regulatory responses to balance the conflict between increased resource circulation and decreased dispersal of hazardous substances.

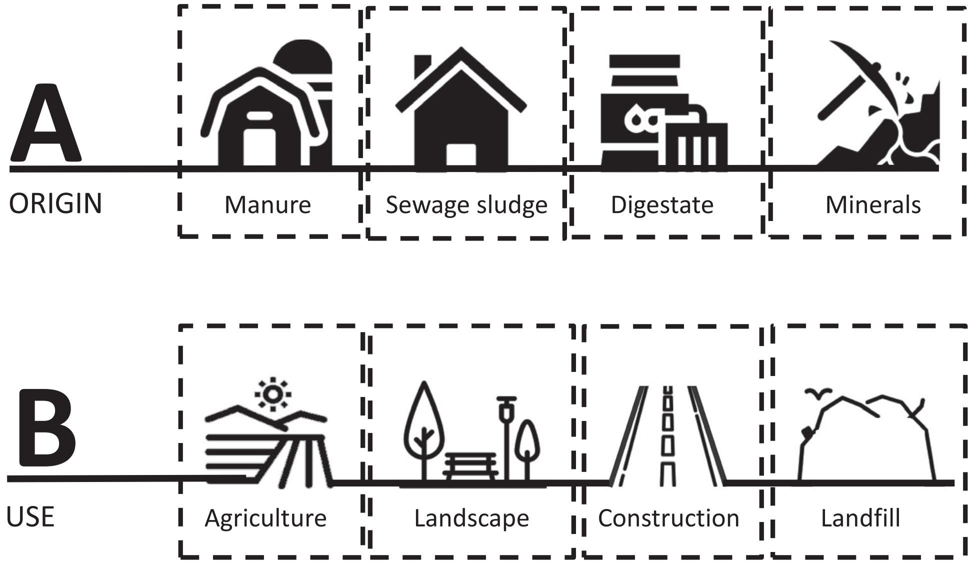

FIGURE 2 One way to manage risk is to differentiate the requirements. The differentiation can either be done based on the origin of the material (alternative A) or the use of the material (alternative B). Detailed descriptions of the alternatives are provided in the body text

5.1 | The regulatory responses and their consequences

The regulatory responses are always applied in different combinations. For example, in Sweden, the use of waste-based aggregates is regulated by combining strict guiding levels, with a focus on total concentrations and implemented at the local administrative level, without any differentiation. This has resulted in a low utilization rate of bottom ashes. But since high-quality conventional material is then used instead, the dispersal of heavy metals in society through bottom ash utilization has presumably been limited. In Denmark, on the other hand, waste-based aggregates are regulated with opposing regulatory responses; leaching concentrations that are nationally applicable and differentiated. Here, the utilization rate of bottom ash is high, but the dispersal of heavy metals has probably increased, since cleaner, primary aggregates have not been used.

However, to understand the outcome, the regulatory responses should not only be understood in combination but also in relation to other conditions that affect the willingness of producers and users to circulate waste. For example, the high use of bottom ashes in Denmark needs to be understood in its political-material context. *Policy instruments* such as bans and taxes have made earlier disposal outlets, such as landfilling of bottom ashes, insufficient for waste producers. Therefore, producers often pay a *financial compensation* to users to accept the waste, to open up for new outlets. This has created a demand for bottom ashes, not the least since accessibility to primary ballast materials in Denmark is limited. A clear customer for such secondary aggregates—bottom ashes—has also been established through the Danish *policy objective* to increase the use of bottom ash. This objective has clearly pushed authorities, in this case the Danish Road Directorate, to become a user by incorporating large amounts of bottom ashes in their road construction projects. Taken together, these contextual factors and the favorable regulatory responses have created conditions for both producers and users to establish a market for bottom ashes in Denmark.

In Sweden, on the other hand, there are no specific policy objectives for bottom ash utilization, while both users and producers have other alternatives than to use it as aggregate. For instance, there is plenty of access to primary aggregates in the Swedish bedrock for the users, while the producers of bottom ashes have a convenient and relatively cheap outlet in terms of using it as landfill cover and construction material. Together with the above described and unfavorable regulatory responses, there have thus been few reasons to use bottom ash in Sweden outside of landfills.

5.2 | The theoretical underpinnings of the regulatory responses

To illustrate how toxicity can be regulated from different theoretical approaches, the different regulatory responses for waste-based aggregates are good examples. Focusing on the *leaching* concentrations of hazardous substances from waste, as in Denmark, means that the risk (Scheer et al., 2014), that is, the likelihood of hazards causing harm, is underpinning the regulation. While, as in Sweden, focusing on the *total* concentration of hazardous substances in the waste instead means that hazards, that is, the presence of hazards, is in focus. Applying a risk perspective also means that differentiation of allowable contamination levels, like in the Danish case, can be applied. This means that higher levels of contamination are accepted where the risk of exposure is considered lower.

Such differentiation of allowable contamination levels can be based either on the origin of the material or the use of the material, Figure 2, which can be illustrated by sewage sludge. The same type of function, use of fertilizers for example, can be regulated by setting different requirements depending on the origin of the material. For example, to use sewage sludge on arable land in Sweden, 60 different substances (REVAQ, 2019) should be tested, for digestate 7 substances (Avfall Sverige, 2018) while for mineral fertilizers only 1 substance (Jordbruksverket, 2019), and manure 0 substances (Naturvårdsverket, 2013). From a user perspective, it may be reasonable to put higher demands on materials from heterogeneous sources with expected large variations in the composition and contamination levels. But to set different demands depending on the material origin creates unlevel playing fields for resource circulation (Johansson, Krook, & Eklund, 2014), which may make recycling more costly for the producers in the form of sampling.

As an alternative to differentiation based on origin, the allowable contamination levels may also differ depending on the specific function the used material shall fulfil such as fertilization, landscaping, road construction, or landfill covering. Differentiation based on use is positive for waste producers and typically increases circulation, as it offers several possible outlets for the waste.

However, differentiation based on the use needs to be thoroughly modeled under the same regulation; otherwise, there is a risk of inconsistency. For example, the cadmium limits for applying waste to construction purposes such as roads (0.2 mg Cd/kg) in Sweden is 10 times stricter than it is for farmland (2 mg Cd/kg). The requirements for using waste residues are thus less restrictive in a sensitive and essential environment such as agriculture, with a high risk of exposure through food chains, than in environments already polluted such as industrial sites and roads.

A further problem with differentiation based on use is that it is positive for circulation primarily from a short-term perspective and thus for the producer who generates the original waste in its first life cycle. In a circular economy, material circulates through several life cycles, and could thus over time potentially migrate between different applications with varying pollution and health risks. Allowing the use of residuals based on a certain type of application can thus result in problems when the material becomes waste again for the user and needs to meet the requirements for the next application.

In addition, a regulation that is constructed based on a risk approach rests on the idea that the leaching behavior of the hazardous substances is fully understood and that the safety mechanisms will keep the elevated contamination levels under control during the entire service life of the waste. However, leaching concentrations are highly dependent on environmental conditions such as pH, material permeability and vary temporarily (Van der Sloot, Hoede, & Bonouvrie, 1991). Hence, lab tests may not accurately reflect the real situation in the field. Furthermore, experience from the Netherlands (Veldhoven, 2018) has shown that contractors do not always follow the safety regulations and that over time the installed safety mechanisms may fail. Therefore, for long-term circulation, a hazard approach with one, strict category that applies to many different applications may be preferable, which for instance the Dutch regulation for waste-based aggregates is moving toward (Veldhoven, 2018).

Implementing a hazard approach also brings legislation that would be neutral in relation to the origin of the material. In the Netherlands, such neutral requirements are applied for all secondary and primary materials to be used as aggregates (Rijkswaterstaat Water, 2007). Changing focus to fertilizers, neutrality toward the origin has also been implemented in Germany, where the same requirements apply to the presence of hazardous substances in all forms of fertilizers (Umweltbundesamt, 2017).

In order to address the cocktail effect of the waste material, the regulation could focus on the effects of a mixture of several substances rather than specific limits of individual substances. For example, by testing leachates from the waste on living matter such as cell cultures and observing the response of the subject. Such effect-based methods, or bioassays, are common in the field of, for example, wastewater and foods (Christofi, 2005)

Besides analyzing the regulatory responses in relation to toxicity, such responses may also be related to the type of circularity underpinning the policies. But first, it should be noted that in the studied countries, resource circulation is always a secondary effect after the limits of contamination have been met. However, the importance of circularity is not only under-prioritized compared to toxicity, but the allowable contamination levels are virtually always expressed in relation to the mass of waste. Hence, the current regulations for controlling contamination levels mainly steer toward circulation in terms of recycled quantities rather than the utilized functional value of the waste. The problem with relating the presence of hazardous substances to mass is that the provided function and utility of the waste are excluded, which opens up for the prevailing low-value use of, for example, sewage sludge as a landfill cover in Sweden. This is in line with how the circular economy is today governed in general; based on indicators for collected and recycled amounts rather than indicators targeting the preserved resource value of such circulation (Haupt et al., 2017).

What previous research tells us is, however, that the preserved resource value through recycling systems, and thus the primary production that is being replaced, is of key importance for the environmental motives of circularity (Geyer, Kuczenski, Zink, & Henderson, 2016) and for market acceptance of waste in the long term. In order to give circularity more weight in its conflict with pollution concerns of hazardous substances, the functional value of such circulation rather than the utilized mass needs to be emphasized. Inspiration can be taken from the voluntary alternative in the Danish sewage sludge regulation (Miljøstyrelsen, 2017), where the contamination levels are related to the amount of circulated phosphorus. Or the forthcoming EU (2019) fertilizer regulation, which states maximum limits for hazardous substances as well as minimum limits for nutrients. However, the functional value does not necessarily have to be expressed in relation to the presence of resources, even if it is suitable in the case of sewage sludge. The application of waste-based aggregates could, for example, be controlled by regulating the allowable contamination levels in relation to the technical characteristics of the waste, such as its bearing capacity or the environmental savings obtained by using the waste, for example, avoided carbon dioxide emissions from replaced primary production of ballast.

However, a focus on resources brings complexity to the regulation of hazardous substances in the use of waste. As mentioned above, the requirements for hazardous substances should from a risk perspective be stricter for waste used in sensitive and important environments such as agriculture than in already polluted areas such as roads. However, from a resource perspective, it may be reasonable to allow higher levels of contamination in waste-based fertilizers than in waste-based aggregates, if nutrients are considered to have a higher financial and environmental value than the bearing capacity of such residues. But in such a case, the allowable contamination levels should be expressed in relation to the functional value and not the mass of waste.

Finally, the fact that different countries choose different regulatory responses to controlling the dispersal of hazardous substances in waste can become a problem from both a circularity and toxicity perspective. Different rules may obviously complicate the trade of waste-based resources between countries, with potential negative effects on circularity (Johansson & Forsgren, 2020). But different responses between countries may also have negative effects from a toxicity perspective. Differences in the regulation of sewage sludge between countries can be used here as an illustrative example, despite the fact that this regulation, due to the EU's (1986) sludge directive, is significantly more harmonized than for waste-based aggregates. Many crops are typically cultivated using sludge in countries with less restrictive sludge laws such as Spain (Mininni et al., 2015), but are consumed in countries with strict sludge laws such as Sweden. This means that consumers are directly affected by the waste policies of other countries, regardless of the restrictions on using waste in their home country. There is thus a need for more multilateral agreements to enhance the control of such substances of concern.

6 | CONCLUSION

This paper has identified 8 different regulatory questions and 16 potential responses for controlling hazardous substances in waste, which have different effects on resource circulation and the dispersal of hazardous substances. These questions and responses can be used as a reference guide by policy makers to find ways to control hazards in the use of waste. However, in order to further increase the capacity to develop regulations that better balance circularity and toxicity issues, more consideration should be given to what type of circularity and toxicity policy makers are aiming for. Concerning circularity, resources rather than mass should be the focus, in order to avoid low-grade circulation without clear environmental benefits. This means that the regulation should be developed with the aim of contrasting the presence of substances of concern with the functional resource value obtained by circulating the waste.

How to control toxicity in waste is a more complex issue. One alternative is to base such regulations on a risk approach. In this way, the requirements can be differentiated depending on the specific risk of exposure and thus the likelihood of the hazards causing harm. In Denmark and Germany, for example, such differentiated requirements for using waste in different construction applications exist. Such regulation design creates favorable conditions for circularity and makes it easier for waste producers to find an outlet for their materials. In addition, if a risk-based regulation was also to be contrasted against the functional value of utilizing the waste, that would potentially also increase the avoided environmental impact from the replaced primary production.

The other main alternative is to base the regulation on a hazard approach, which means that only one strict level of contamination would be allowed and applicable for all uses of the waste. The advantage of having only one strict level is a reduced need for waste users to monitor and invest in safety measures. In addition, the material can be circulated several times across different applications, which could be beneficial from a long-term circular economy perspective. But it would probably bring initial high investment costs for waste producers. Therefore, such an approach needs to be combined with other policy measures. For example, policies that challenge the existing disposal outlets for waste and set clear and foreseeable requirements and objectives for more high-quality utilization. Thereby, waste producers can foresee the outcome in the long term and see the value of such investments.

This study and the identified regulatory questions and responses are partially generalizable as they demonstrate trade-offs between circularity and toxicity that presumably are relevant to many complex materials. By studying additional cases, however, further regulatory questions and responses may be identified. Studies of countries in other socio-economic and political contexts would be especially valuable.

We believe nevertheless that there are presumably lessons from this study that can be applied to other types of waste such as secondary plastic. For example, a risk perspective would offer differentiation of contamination limits depending on whether the plastic is used in a context with a high risk of exposure, for example, in a plastic toy, or with a low risk of exposure, for example, under the hood of a car. But such differentiation may impede circulation of the plastics in the long term when the material becomes waste again.

These regulatory choices are, however, partly political and display a need for research that goes beyond the formulations and implementation of the regulations by analyzing the perspectives, roles, and values of the involved actors. Besides, as demonstrated by this study, most of the regulations only target substances of concern on the material level. In order to facilitate more informed decisions, a broader perspective on the total flows, potency, thresholds, and long-term risks of hazardous substances related to circulation of waste is needed. Here, the employment of environmental systems analysis tools could be useful for contrasting these flows and risks with other emission sources of these substances in society.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

Astrup, T., Mosbæk, H., & Christensen, T. H. (2006). Assessment of long-term leaching from waste incineration air-pollution-control residues. *Waste Management*, *26*(8), 803–814.

Baxter, W., Aurisicchio, M., & Childs, P. (2017). Contaminated interaction: Another barrier to circular material flows. *Journal of Industrial Ecology*, *21*(3), 507–516.

Blasenbauer, D., & Fagerqvist, J. (2020). Legal situation and current practice of waste incineration bottom ash utilisation in Europe. *Waste Management*, *102*, 868–883.

Blomsma, F., & Brennan, G. (2017). The emergence of circular economy: A new framing around prolonging resource productivity. *Journal of Industrial Ecology*, *21*(3), 603–614.

Cewep. (2017). *Landfill taxes and bans overview*. Retrieved from http://www.cewep.eu/wp-content/uploads/2017/12/Landfill-taxes-and-bans-overview.pdf

Chimenos, J. M., Segarra, M., Fernández, M., & Espiell, F. (1999). Characterization of the bottom ash in municipal solid waste incinerator. *Journal of Hazardous Materials*, *64*(3), 211–222.

Christofi, N. (2005). Bioassays. In P. Worsfold, A. Townshend, C. Poole, M. Miro (Eds.),*Encyclopedia of analytical science* (pp. 265–271). Oxford: Elsevier.

Dakofa. (2012). *Slam*. Retrieved from https://dakofa.dk/vidensbank/slam/

EU. (1986). Council directive on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. *Official Journal of the European Community*, *181*, 6–12.

EU. (2010). Directive 2010/75/EU on industrial emissions. *Official Journal of the European Union*, *334*, 17–119.

EU. (2018). The circular economy package. Options to address the interface between chemical, product and waste legislation. European Commission. COM(2018) 32 final https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0032&from=en

EU. (2019). Regulation laying down rules on the making available on the market of EU fertilising products. 2016/0084 (COD). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1009&from=EN

EU. (2020). *Sewage sludge*. Retrieved from https://ec.europa.eu/environment/waste/sludge/

Friege, H., Kummer, B., Steinhäuser, K. G., Wuttke, J., & Zeschmar-Lahl, B. (2019). How should we deal with the interfaces between chemicals, product and waste legislation? *Environmental Sciences Europe*, *31*(1), 51.

Geyer, R., Kuczenski, B., Zink, T., & Henderson, A. (2016). Common misconceptions about recycling. *Journal of Industrial Ecology*, *20*(5), 1010–1017.

Goldberg, T. (2017). What about the circularity of hazardous materials? *Journal of Industrial Ecology*, *21*(3), 491–493.

Haupt, M., Vadenbo, C., & Hellweg, S. (2017). Do we have the right performance indicators for the circular economy? *Journal of Industrial Ecology*, *21*(3), 615–627.

Hedenstedt, A. (2015). *International outlook of regulations for bottom ashes.* SP. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A963481&dswid=840

Johansson, N. (2018). *How can conflicts, complexities and uncertainties in a circular economy be handled?* Retrieved from http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1250611&dswid=1849

Johansson, N., & Forsgren, C. (2020). Is this the end of end-of-waste? Uncovering the space between waste and products. *Resources, Conservation and Recycling*, *155*, 104656.

Johansson, N., & Henriksson, M. (2020). Circular economy running in circles? A discourse analysis of shifts in ideas of circularity in Swedish environmental policy. *Sustainable Production and Consumption*, *23*, 148–156.

Johansson, N., Krook, J., & Eklund, M. (2014). Institutional conditions for Swedish metal production: A comparison of subsidies to metal mining and metal recycling. *Resources Policy*, *41*, 72–82.

Johansson, N., Krook, J., & Frändegård, P. (2017). A new dawn for buried garbage? *Waste Management*, *60*, 417–427.

Johansson, N., Velis, C., & Corvellec, H. (2020). Towards clean material cycles: Is there a policy conflict between circular economy and non-toxic environment? *Waste Management & Research*, *38*(7), 705–707.

Jones-Lepp, T. L., & Stevens, R. (2007). Pharmaceuticals and personal care products in biosolids/sewage sludge. *Analytical and Bioanalytical Chemistry*, *387*(4), 1173–1183.

Jordbruksverket. (2004). *Jordbruksverkets föreskrifter och allmänna råd*. SJVFS 2004:62. https://djur.jordbruksverket.se/download/18.2da5afd014dde384c9695a58/1434091543400/2015-021.pdf

Jordbruksverket. (2019). *Om du tillverkar, marknadsför eller handlar med mineralgödsel eller kalk*. Retrieved from https://www.jordbruksverket.se/amnesomraden/odling/vaxtnaring/handelimportochexport/mineralgodselocheggodsel.4.1cb85c4511eca55276c8000759.html

Juste, C., & Mench, M. (2017). Long-term application of sewage sludge and its effect on metal uptake by crops. In D. C. Adriano (Ed.), *Biogeochemistry of trace metals* (pp. 171–206). Boca Raton, FL: CRC Press.

Kidd, P. S., Domínguez-Rodríguez, M. J., Díez, J., & Monterroso, C. (2007). Bioavailability and plant accumulation of heavy metals and phosphorus in agricultural soils amended by long-term application of sewage sludge. *Chemosphere*, *66*(8), 1458–1467.

Koyano, S., Ueno, D., Yamamoto, T., & Kajiwara, N. (2019). Concentrations of POPs based wood preservatives in waste timber from demolished buildings and its recycled products in Japan. *Waste Management*, *85*, 445–451.

Leslie, H. A., Leonards, P. E. G., Brandsma, S. H., De Boer, J., & Jonkers, N. (2016). Propelling plastics into the circular economy—weeding out the toxics first. *Environment International*, *94*, 230–234.

Liu, A., Ren, F., Lin, W. Y., & Wang, J. Y. (2015). A review of municipal solid waste environmental standards with a focus on incinerator residues. *International Journal of Sustainable Built Environment*, *4*, 165–188.

McDonough, W., & Braungart, M. (2010). *Cradle to cradle: Remaking the way we make things.* Albany, CA: North Point Press.

Miljøstyrelsen. (1999). *Regeringens affaldsplan 1998 – 2004*. København: Miljø- og energiministeriet.

Miljøstyrelsen. (2014). *Danmark uden affald*. Vejledning nr. 4, 2014. https://www2.mst.dk/Udgiv/publikationer/2014/05/978-87-93178-55-7.pdf

Miljøstyrelsen. (2016). *Bekendtgørelse om anvendelse af restprodukter, jord og sorteret bygge- og anlægsaffald*. BEK nr, 1672. https://www.retsinformation.dk/eli/lta/2016/1672

Miljøstyrelsen., (2017). Bekendtgørelse om anvendelse af affald til jordbrugsformål. BEK nr 843 af 23/06/2017. https://www.retsinformation.dk/eli/lta/2018/1001

Mininni, G., Blanch, A. R., Lucena, F., & Berselli, S. (2015). EU policy on sewage sludge utilization and perspectives on new approaches of sludge management. *Environmental Science and Pollution Research*, *22*(10), 7361–7374.

Natursvårdsverket. (2013). *Hållbar återföring av fosfor*. Report 6580. http://www.naturvardsverket.se/Documents/publikationer6400/978-91-620-6580-5.pdf

Naturvårdsverket. (1994). *Kungörelse med föreskrifter om skydd för miljön, särskilt marken, när avloppsslam används i jordbruket*. 1994:2. https://www.naturvardsverket.se/Documents/foreskrifter/nfs1994/snfs-1994-2.pdf

Naturvårdsverket. (2010). *Återvinning av avfall i anläggningsarbeten*. Swedish EPA. Report 2010:1. https://www.naturvardsverket.se/Documents/publikationer/978-91-620-0164-3.pdf?pid=2591

Naturvårdsverket. (2015). *Utvärdering av Naturvårdsverkets handbok för återvinning av avfall i anläggningsarbeten*. Retrieved from http://www.naturvardsverket.se/Documents/publikationer/978-91-620-0164-3.pdf

Pivnenko, K., Eriksson, E., & Astrup, T. F. (2015). Waste paper for recycling: Overview and identification of potentially critical substances. *Waste Management*, *45*, 134–142.

REVAQ. (2019). *Regler för certifieringssystem*. Retrieved from https://www.svensktvatten.se/globalassets/avlopp-och-miljo/uppstromsarbete-och-kretslopp/revaq-certifiering/revaq.regler-2019-gul.pdf

Rijkswaterstaat Water. (2007). Verkeer en Leefomgeving; Regeling bodemkwaliteit. Soil Quality Regulation. https://wetten.overheid.nl/BWBR0023085/2020-06-09

Saqib, N., & Backstrom, M. (2016). Chemical association and mobility of trace elements in 13 different fuel incineration bottom ashes. *Fuel*, *172*, 105–117

Sarkis, J., & Cordeiro, J. J. (2001). An empirical evaluation of environmental efficiencies and firm performance: Pollution prevention versus end-of-pipe practice. *European Journal of Operational Research*, *135*(1), 102–113.

Scheer, D., Benighaus, C., Benighaus, L., Renn, O., Gold, S., Röder, B., & Böl, G. F. (2014). The distinction between risk and hazard: Understanding and use in stakeholder communication. *Risk Analysis*, *34*(7), 1270–1285.

SCS. (1998). *Förordning (1998:944) om förbud m.m. i vissa fall i samband med hantering, införsel och utförsel av kemiska produkter*. Swedish code of statues. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-1998944-om-forbud-mm-i-vissa-fall_sfs-1998-944

SOS. (2018). *Utsläpp till vatten och slamproduktion 2016*. Sveriges officiella statistik. MI 22 SM, 1801. https://www.scb.se/contentassets/4d4d22ee07cf4baa9f47e5bab805c00c/mi0106_2016a01_sm_mi22sm1801.pdf

Sverige, Avfall (2018). *Svensk avfallshantering 2017*. Avfall Sverige. https://www.avfallsverige.se/fileadmin/user_upload/Publikationer/svensk_avfallshantering_2017.pdf

Umweltbundesamt. (2003). *Länderarbeitsgemeinschaft Abfall; Mitteilungen der Länderarbeitsgemeinschaft Abfall*. (LAGA) 20, Anforderungen an die stoffliche Verwertung von mineralischen. Reststoffen/Abfällen, https://www.proenvi.de/recht/LAGA/5-Auflage_LAGA_M20.pdf

Umweltbundesamt. (2017). *Verordnung über die Verwertung von Klärschlamm, Klärschlammgemisch und Klärschlammkompost*. AbfKlärV. https://www.gesetze-im-internet.de/abfkl_rv_2017/AbfKl%C3%A4rV.pdf

Umweltbundesamt. (2018). *Sewage sludge management in Germany*. Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/sewage_sludge_management_in_germany.pdf

UNEP. (2013). *Metal recycling: Opportunities, limits, infrastructure*. United Nations Environment Programme. https://wedocs.unep.org/handle/20.500.11822/8423

Van der Sloot, H. A., Hoede, D., & Bonouvrie, P. (1991). *Comparison of different regulatory leaching test procedures for waste materials and construction materials* (No. ECN-C–91-082). Petten, The Netherlands: Netherlands Energy Research Foundation (ECN.).

Veldhoven, I. (2018). *AEC-bodemassen*. Ministerie van Infrastructuur en Waterstaat. IenW/BSK-2018/249314. https://www.rijksoverheid.nl/documenten/kamerstukken/2018/11/20/aec-bodemas

Zink, T., & Geyer, R. (2017). Circular economy rebound. *Journal of Industrial Ecology*, *21*(3), 593–602.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Johansson N, Krook J. How to handle the policy conflict between resource circulation and hazardous substances in the use of waste? Three countries' regulations on contaminants in waste and their implications for resource circulation. *Journal of Industrial Ecology*. 2021;1–15. https://doi.org/10.1111/jiec.13103