National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Substances of very high concern and the transition to a circular economy

An initial inventory

RIVM Letter report 2017-0071
P.N.H. Wassenaar et al

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Colophon

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Synopsis

Substances of very high concern and the transition to a circular economy

an initial inventory

Reuse and recycling of products are key elements in a circular economy. This exploratory RIVM study shows that a great number of waste streams may contain various substances of very high concern (ZZS), which may hamper safe recycling options in the Netherlands. RIVM recommends an adequate risk management of ZZS in a circular economy.

The Dutch government takes priority action on ZZS substances as they are hazardous to people and the environment. Examples include substances that are carcinogenic, impede reproduction, or bioaccumulate in food chains. ZZS may be present in waste streams as they are intentionally used in the original processes or products, or they can be contaminants.

The Dutch governmental program 'The Netherlands circular in 2050' appoints five priority chains and sectors in the transition towards a circular economy: biomass and food, plastics, production/manufacturing, construction, and consumer products. RIVM investigated to what extent dominant waste streams in these chains and sectors contain ZZS.

It is difficult to get a complete overview of ZZS in waste streams, because information is often lacking on the actual ZZS concentrations in waste. This exploratory study, however, clearly demonstrates that various ZZS can be present in each of the investigated waste streams. Examples are flame-retardants in plastics, dyestuffs and pigments in textile, and heavy metals in agricultural waste streams.

RIVM makes recommendations with respect to prioritization of ZZS and waste streams. In addition, it is advised to develop a decision scheme to select the most appropriate waste treatment options. The results of this study are useful for the implementation of the National Waste Management Plan (LAP) that is focusing on risk control. At medium and long term the drive should be to develop safer alternatives for ZZS resulting in safe loops, irrespective of the types of end-use.

Keywords: circular economy, substances of very high concern, waste, risk management

Publiekssamenvatting

Zeer zorgwekkende stoffen en de transitie naar een circulaire economie

een eerste inventarisatie

Hergebruik en recycling van afvalstromen is een belangrijk onderdeel van de circulaire economie. Deze verkennende RIVM-studie laat zien dat in een breed spectrum van afvalstromen diverse zeer zorgwekkende stoffen (ZZS) kunnen voorkomen. Voorbeelden zijn vlamvertragers in plastics, kleurstoffen in textiel of zware metalen in reststromen van de landbouw. Dit kan de mogelijkheden om afval veilig te recyclen belemmeren in Nederland. Het RIVM doet aanbevelingen om de risico's van ZZS voor mens en milieu te beperken in de circulaire economie.

ZZS worden door de Nederlandse overheid met voorrang aangepakt, omdat ze gevaarlijk zijn voor mens en milieu. Voorbeelden zijn stoffen die kankerverwekkend zijn, de voortplanting belemmeren of zich ophopen in voedselketens. ZZS kunnen in afvalstromen zitten omdat ze bewust aan het proces of product zijn toegevoegd, of verontreinigingen zijn.

Het Rijksbrede beleidsprogramma 'Nederland circulair in 2050' benoemt vijf prioritaire ketens en sectoren voor de overgang naar een circulaire economie in Nederland: biomassa en voedsel, kunststoffen, de maakindustrie, de bouw en consumptiegoederen. Het RIVM onderzocht belangrijke afvalstromen in deze sectoren op de mate waarin ZZS voorkomen.

Het is lastig om een compleet beeld te krijgen van ZZS in afvalstromen, omdat vaak informatie ontbreekt over de werkelijke concentraties ervan in het afval. Het RIVM doet aanbeveling om aan te geven welke ZZS en afvalstromen als eerste aandacht moeten krijgen (prioriteren). Tevens wordt het aangeraden om een afwegingskader te ontwikkelen om de meest geschikte afvalverwerkingsoptie te selecteren.

De resultaten van deze studie zijn bruikbaar voor de uitvoering van het Landelijke Afvalstoffen Plan (LAP) dat gericht is op risicomanagement zo lang ZZS nog in gebruik of in omloop zijn. Het langere termijn streven moet zijn om veilige alternatieven voor ZZS te ontwikkelen, zodat ketens, ongeacht de latere toepassingen, op voorhand veilig zijn.

Kernwoorden: circulaire economie, zeer zorgwekkende stoffen, ZZS, afval, risicomanagement

Contents

Summary

The Dutch government takes priority action on ZZS substances as they are hazardous to people and the environment. Although the Dutch ZZS substances cover a broader range than the Substances of Very High Concern (SVHC) under REACH, they are identified based on the same hazard criteria as the SVHC substances (i.e. REACH article 57 (1907/2006). Examples include substances that are carcinogenic, impede reproduction, or bioaccumulate in food chains. ZZS may be present in waste streams as they are intentionally used in the original processes or products, or they can be contaminants.

The Dutch governmental program ‘The Netherlands circular in 2050’ appoints five priority chains and sectors in the transition towards a circular economy: biomass and food, plastics, manufacturing, construction, and consumer products. RIVM investigated to what extent dominant waste streams in these chains and sectors contain ZZS. The following waste streams were included: waste water from sewage treatment plants, waste as potential base for fertilizers and codigestion, plastic waste, rubber waste, cathode ray tube (CRT) glass waste, construction waste, paper and paperboard waste, textile waste and diaper waste.

This exploratory study clearly demonstrates that various ZZS can be present in most of the investigated waste streams. Except for diaper waste (no ZZS identified) and CRT glass waste (only heavy metals) a wide variety of ZZS substances can be present. ZZS classes which are frequently encountered in waste streams include heavy metals, flame-retardants, poly aromatic hydrocarbons and plasticizers (like phthalates).

We discussed multiple options to prioritize ZZS containing waste streams for the development of adequate risk management strategies. These options include the number of ZZS substances, the volume of ZZS substances, the type of end use and the origin of ZZS content. We concluded that it is difficult to appoint one prioritization approach as most powerful due to the many data gaps. Information is often lacking on the actual ZZS concentrations in waste, so our current analysis is often based on theoretical assumptions (i.e. what could be *potentially* present in that waste stream).

Long-term and structural ‘source’ solutions are emphasised for safe recycling, such as building on innovative concepts like safe-by-design and circular product design. An important driver should be to develop safer alternatives for ZZS resulting in safe loops, irrespective of the types of end-use. We have to realize, however, that we are still in an era in which we are faced with numerous ZZS substances in waste streams. For these waste streams, safe ‘end-of-pipe’ solutions have to be found in order to stimulate the circular economy and safeguard a non-toxic environment.
Within the draft of the Dutch National Waste Management Plan 2017-2029 (LAP3) a first framework for the assessment of waste processing is

described that should stimulate the development of safe ‘end-of-pipe’ solutions. The results of our study are useful for the implementation of LAP3 as it provides more insight into those ZZS that should be focused on when considering recycling of specific waste streams.

Currently, LAP3 only considers a general framework on how to assess the processing of ZZS waste streams and it needs further elaboration with more detailed instructions. For this purpose, a trigger/cut-off value on the ‘allowable’ amount of ZZS content should be established first, in order to distinct ‘safe’ from ‘potential risk’ waste streams. It is important to closely tune this approach with REACH, CLP and other legal frameworks on chemical risk management. LAP3 will also generate a practical guidance on risk analysis to be executed for those waste streams exceeding the above-mentioned trigger/cut-off value. RIVM stresses that this guidance should be very clear in distinguishing between acceptable and non-acceptable types of end use of a waste stream, either in a qualitative (precautionary principle) or quantitative way.

In order to further facilitate the assessment and decision making process for safe end-of-pipe solutions we advise, in addition to the elaboration of LAP3, to develop a decision scheme to weigh the most appropriate waste treatment options with respect to both safety and sustainability gains. The development of such a transparent and generic decision scheme is expected to contribute to the safe recycling ambitions as described in the governmental program ‘The Netherlands circular in 2050’.

1 Introduction

1.1 Transition to a circular economy

The Dutch government aims to promote sustainable use and reuse of natural resources, as outlined in the governmental program 'The Netherlands circular in 2050' [1] and the National waste management plan (LAP3; [2]). The recovery of raw materials from waste or communal wastewater can help prevent resource depletion, reduce dependence on supplies, and save energy. Within the governmental program the ambition is to develop a circular economy in the Netherlands by 2050 and to contribute to a healthy and safe environment. A first objective of this program is to decrease the use of primary resources with 50% by 2030. Besides a general transition approach to increase circularity, five specific sectors are given priority within the governmental program. These priorities are biomass and food, plastics, manufacturing, construction and consumer products [1].

Waste streams may contain valuable resources for the generation of energy and products, but may also contain hazardous substances. As a result of reusing waste, hazardous substances could be incorporated into end products, leading to potential exposure of humans and environment. The use of waste streams for the development of resources is currently in an early phase of development and shows high potential for future. However, the presence of hazardous substances may be a serious limitation of the reuse of waste streams. By identifying hazardous substances or waste streams of concern, appropriate follow-up actions can be thought out. This, subsequently, could contribute to achieve the ambition of 'safe recycling' as described in the governmental program.

1.2 Dutch substances of very high concern

Within the Netherlands, national policy is particularly focussing on substances of very high concern: the so called ZZS substances. These substances could seriously harm man and environment and are therefore of very high concern. Although the Dutch ZZS substances cover a broader range than the SVHC substances under REACH (Figure 1), ZZS substances are identified based on the same hazard criteria as the SVHC substances (i.e. REACH article 57 (1907/2006). Substances meeting one of the following criteria are considered as ZZS substances:

- Carcinogenic category 1A or 1B according to Regulation (EC) 1272/2008.
- Mutagenic category 1A or 1B according to Regulation (EC) 1272/2008.
- Toxic for reproduction category 1A or 1B according to Regulation (EC) 1272/2008.
- Persistent, Bioaccumulative and Toxic in accordance with the criteria set out in REACH Annex XIII.
- Very Persistent and Very Bioaccumulative in accordance with the criteria set out in REACH Annex XIII.
- Substances for which there is scientific evidence of probable serious effects to human health or the environment which give

rise to an equivalent level of concern to those of other substances listed above.

Further, ZZS substances are identified if they are placed on one of the following lists:

- Substances which are classified as C, M, or R category 1A or 1B according to Regulation (EC) 1272/2008.
- Substances on the candidate list for REACH Annex XIV *
- Substances which are on the POPS regulation (EC) 850/2004.
- Priority Hazardous substances according to the Water Framework Directive 2000/60/EC.
- Substances on the OSPAR list for priority action.

For the ease of reference a non-limitative list[1] is compiled. Currently it contains almost 1400 substances which comply to the ZZS criteria [3]. The ZZS substances in this list could be categorised in different classes (e.g. according to functionality, origin or chemical structure). Within the Netherlands the ZZS policy focusses on the substitution of these substances by less harmful alternatives or, if not possible, to prevent or minimize exposure.

ZZS are applied for functional reasons in a great variety of both processes and products, for example as a solvent, stabiliser or softener. In addition, ZZS, such as poly aromatic hydrocarbons (PAHs) and acrylamide, may be formed *de novo* during heating and combustion processes. ZZS may also have a natural origin, like heavy metals, which may cause them to be present in biotic waste streams.

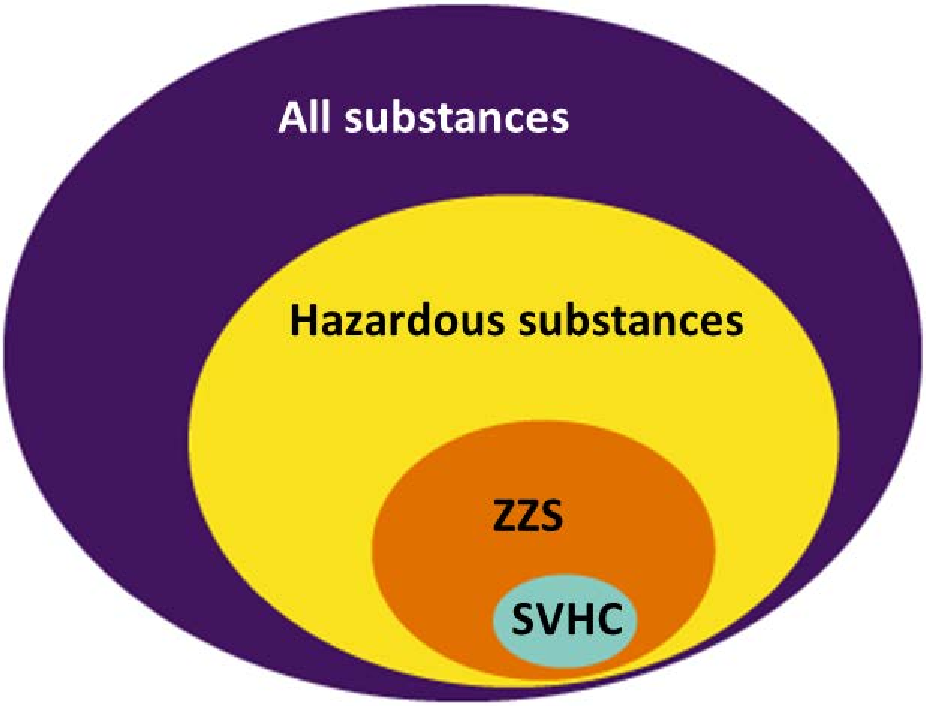

Figure 1: ZZS substance in the Netherlands [3].

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[1] ZZS-list: https://rvs.rivm.nl/zoeksysteem/ZZSlijst/Index

1.3 Aim of the report

In the transition to a sustainable environment, ZZS substances may become manifest in several different developments (i.e. circular economy, biobased economy, etc.). Because many of these circular and biobased economy activities are in an early phase of technological development, an overview of (waste) sectors in which ZSS substances are involved is not yet developed. Within this report, an overview on the presence of ZZS substances in different waste streams is drafted.
We aim to get more focus on ZZS containing waste streams. Further, we will discuss possible prioritization strategies based on this exploratory study. We address questions such as which ZZS are found to be present most often in the waste streams, and can ZZS be ranked by their volumes or their concentrations? Or would it be more relevant to make a distinction between the potential types of end-use of the waste steams (consumer products, building and construction material, etc.) as this could possibly be linked to potential risks of the ZZS?

The outcome of this report can be seen as a first step to enable policy makers to prioritize certain ZZS substances or waste streams for further study. It may also be supportive for building an adequate risk management strategy for ZZS in waste streams and in their end products after recycling or reuse. In this context, our results could support the development of the above-mentioned Dutch National waste management plan 2017-2029 (LAP3).

It should be noted that this study is of an exploratory character and should not be interpreted as a comprehensive overview.

1.4 Methodology, limitations and outline of the report

Within this exploring study, an overview of ZZS substances is given for a number of waste streams. Along with available RIVM reports on this topic, interviews with experts from RIVM and Rijkswaterstaat (RWS; see section 8.2) form the initial basis for this study. For some waste streams supplementary data were obtained from available literature. It should thus be noted that within the scope of this study, no complete overview of the data available in the literature is provided. Additionally, the categorisation of ZZS may differ between the various waste streams in this report, because we follow the primary information sources. This implies that individual ZZS (e.g. cadmium) may be reported as such for some waste streams, but may be included in a ZZS class (e.g. heavy metals or ‘others’) for other streams.

The waste streams being investigated include wastewater, potential materials for fertilisers and co-digestion, plastics, rubber, cathode ray tube glass, construction sector, paper and paperboard, textile and diapers. These streams have been divided across the five priority sectors under the governmental program ‘The Netherlands circular in 2050’:

- biomass and food (chapter 2);
- plastics (chapter 3);
- manufacturing industry (chapter 4);
- construction (chapter 5);
- consumer products (chapter 6).

In chapter 7 we present our main conclusions and recommendations.

2 Biomass and food

2.1 ZZS substances in wastewater from sewage treatment

Daily, a lot of domestic wastewater is produced, including water originating from toilet flushing (containing urine and faeces; *black water*), water originating from bath, shower, washing machine and kitchen (*grey water*), and water originating from rain water (*blue water*). This wastewater is directed through the sewer system to the sewage treatment plant (STP) in order to purify water for safe reuse, by removing solids, nutrients and organic compounds (micropollutants). In the past years, technological developments have taken place to utilize these wastes from STPs to regain resources and energy. The major products which can be regained from wastewater are biogas, phosphate, bioplastics, cellulose, alginate and biomass [4,5].

On a daily bases, each person produces approximately 135 L of domestic wastewater in the Netherlands (see Figure 2; [6]). The various wastewater streams differ in their composition. For instance, black water, consisting of faeces and urine, contains much higher concentrations of phosphorus and nitrogen compared to grey water. In domestic wastewater, up to 82% of phosphate (1.4 gram per day per person) and up to 96.5% of nitrogen (12.5 gram per day per person) originates from black water [6].

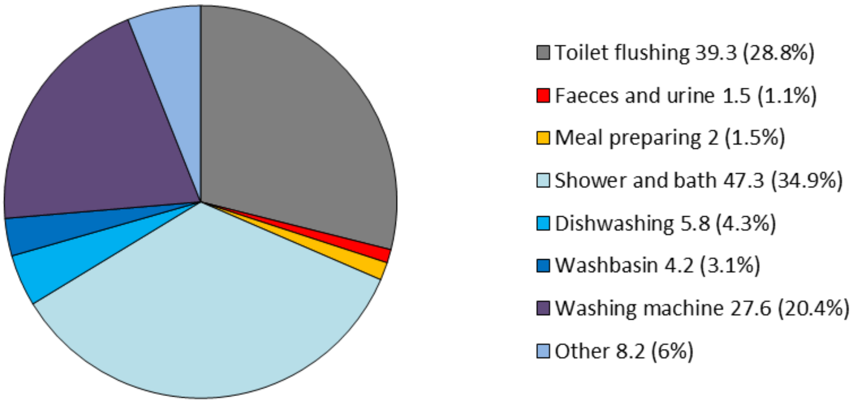

Figure 2: The amounts (in litres) and composition of domestic wastewater produced per person per day in the Netherlands [6].

Within the STP, wastewater is treated in a number of steps, including primary treatment where solids can settle and secondary treatment using activated sludge to remove organic compounds and nutrients. From the waste of the STP (i.e. the collected solids and sludge), raw materials can be recovered. Within the Netherlands, STP sludge is considered as waste and is incinerated and not applied on farmlands.

Raw materials which could be recovered at the STP are shortly described in this section (i.e. biogas, phosphate, bioplastics, cellulose, alginate and biomass), and are elaborated in more detail in a report by Derksen et al. [4]. The organic compounds which are present in sewage sludge can be converted into methane (biogas). As a result a much smaller fraction of sludge waste remains. Phosphate can be recovered from sewage sludge by precipitation with magnesium, forming struvite. Yearly, 11-12 tonnes of phosphorus end up in sewage sludge in the Netherlands. This is approximately 50-60% of the annually used phosphorus in fertilizers [7,8]. Furthermore, within the sewage sludge, volatile fatty acids (VFA) accumulate. These VFAs can be recovered and used as a source to produce polyhydroxyalkanoate (PHA) within the STP [9]. These PHAs are also known as bioplastics. Cellulose, which is present in domestic wastewater because of the use of toilet paper, can be regained from the solid waste of STPs. Approximately 150.000 tonnes of cellulose could theoretically be regained from STPs in the Netherlands [10] and can be recovered from the water or sludge phase [11]. Furthermore, in some STPs alginate is formed (i.e. when the Nereda Technology is applied). Alginate is a sugar like substance which has suitable properties to be used as a basis in coatings and can easily be recovered from STPs. In addition, attempts have been made to grow organisms (e.g. algae, duckweed and mussels) on STP effluent in order to make more valuable use of the nutrients available in wastewater streams. The obtained biomass might be used as material to produce products or biogas.

It is expected that many different chemicals are present in domestic wastewater, because of its origin (i.e. faeces, urine, detergents, etc.). Potentially, these chemicals could be ZZS substances, and might end up in recovered materials from the STPs due to the fate properties of these chemicals.

2.1.1 *ZZS substances in wastewater and recycled products*

In general, different kind of chemical substances can be present in domestic wastewater. Wastewater is likely to contain pharmaceutical residues and related metabolites, but may also contain heavy metals, flame retardants, plasticizers, biocides and pesticides [12,13]. Currently, there is still a lot of uncertainty on the presence of contaminants in wastewater derived products.

Based on information from the WATSON database [14] a great number of ZZS substances could be found in wastewater streams. The WATSON database contains measurements of chemical substances in in- and effluents of STPs in the Netherlands from 1990 to 2015. It should be noted that the information in the WATSON database is based on project specific measurements and consequently, not all ZZS substances have been investigated. Based on the measurements in this database, 69 ZZS substances have been detected somewhere in the influents of a STP in the Netherlands between 1990 and 2015 (see Table 1). Of these 69 substances, 26 ZZS substances have recently been detected in influents from STPs in concentrations ranging from 2.5 pg/L to 101.2 µg/L (between 2010 and 2015). Again we point out that the information in the WATSON database originates from water measurements being conducted in the scope of specific projects and does not specifically focus on all ZZS substances. Accordingly, more ZZS substances than those mentioned in Table 1 may be relevant.

Table 1: Overview of ZZS substances identified in influents of STPs in The Netherlands between 1990 and 2015. ZZS substances which have been detected between 2010 and 2015 are presented in italics [14].

Metals
Beryllium
Cadmium
Mercury
Nickel
Lead

Flame retardants
1,3,5,7,9,11-hexabromocyclododecane
Hexabromodiphenyl ether
Bis(pentabromophenyl) ether
2,2',4,4'-tetrabromodiphenyl ether
Pentabromodiphenyl ether

Pesticides
Alpha-endosulfan
Alpha hch
Beta-endosulfan
Beta hch
Carbendazim
Gamma-hch
Chlordecone
(1α,2α,3α,4β,5α,6β)-1,2,3,4,5,6-hexachlorocyclohexane
Diuron
Hexachlorobenzene
Linuron
Pentachlorophenol
Hexachlorocyclohexane (technical)
Tributyltin cation
Triflumizole
Vinclozolin
1,1,1-trichloro-2,2-bis(4-chlorophenyl)ethane

Endocrine disruptors
Bis(2-ethylhexyl) phthalate
Bisphenol A
Diisobutyl phthalate
Nonylphenolethoxylates and related substances
P-nonylphenol
Octylphenol

Industrial chemicals
Benzene
Benzyl butyl phthalate
Nonylphenol
Dibutyl phthalate
Dicyclohexyl phthalate
Indene
2,4,5,2',5'-pentachlorobiphenyl
2,3',4,4',5-pentachlorobiphenyl
2,2',3,4,4',5'-hexachlorobiphenyl
2,2',4,4',5,5'-hexachlorobiphenyl
2,2',3,4,4',5,5'-heptachlorobiphenyl
2,4,4'-trichlorobiphenyl
2,2',5,5'-tetrachlorobiphenyl
1,2,3,4,6,7,8-heptachlorodibenzodioxin
1,2,3,4,6,7,8,9-octachlorodibenzodioxin
1,2,3,4,7,8-hexachlorodibenzofuran
1,2,3,6,7,8-hexachlorodibenzofuran
2,3,4,6,7,8-hexachlorodibenzofuran
1,2,3,4,6,7,8-heptachlorodibenzofuran
1,2,3,4,7,8,9-heptachlorodibenzofuran
1,2,3,4,6,7,8,9-octachlorodibenzofuran
2,3,7,8-tetrachlorodibenzofuran
Pentadecafluorooctanoic acid
Trichloroethylene

Poly aromatic hydrocarbons
Acenaphthene
Anthracene
Benzo[a]anthracene
Benzo[a]pyrene
Benzo[e]acephenanthrylene
Benzo[ghi]perylene
Benzo[k]fluoranthene
Chrysene
Dibenzo[a,h]anthracene
Phenanthrene
Fluorene
Fluoranthene
Indeno[1,2,3-cd]pyrene
Naphthalene
Pyrene

In studies from STOWA and the WUR the composition of struvite recovered from STPs has been analysed [15,16]. Within these studies several heavy metals as well as some pharmaceuticals and organic compounds were identified (Table 2). This indicates that some ZZS substances could be present in struvite. The concentrations at which these substances were identified are provided in Annex I. It should be noted that the detection limits within the study of STOWA were relatively high and that the samples were not fully representative. Consequently, these results only provide an indication of the substances present in struvite. The occurrence of other (non-investigated) ZZS substances as well as the composition of other wastewater related end products remains uncertain.

Table 2: Substances which have been identified in struvite recovered from STPs. ZZS substances have been marked with '' [15,16].*

Cadmium *
Chromium *
Cupper
Mercury *
Nickel *
Lead
Zinc
Arsenic
Metoprolol
Hexadecanoic acid
Decanal
Chlorodecane
Tetradecane
Pentadecane
Dibutyltin *
Tributyltin *
Nonylphenol *
Nonylphenol ethoxylate *
Naphthalene *
Phenanthrene *
Anthracene *
Fluoranthene *
Benzo(a)anthracene *
Chrysene *
Benzo(k)fluoranthene *
Benzo(a)pyrene *
Benzo(g.h.i)perylene *
Indeno(1.2.3-c.d)pyrene *
Mineral oils *

2.1.2 *(Current) Applications of wastewater products*

Some of the recovered wastewater materials are already being applied in specific applications. For example, struvite is already being recovered (2760 tonnes per year [12]) and could be used as a fertilizer [17], cellulose as isolation or in paper, and PHA for the formation of biodegradable plastics. In addition, alginate might be used in medical material and nutrition [18].

2.2 ZZS substances in other waste as potential base for fertilizers and codigestion

Certain waste or by-products can be a potential base for (the production of) fertilizers. In addition, some of this material can potentially be applied as co-digestion material in anaerobic biogas production which results in digestate. This digestate can be used as fertilizer as well. Before waste and by-products can be applied as fertilizer, the waste stream needs to be assessed and approved by the Scientific Committee on the Nutrient Management Policy (CDM) [19]. Within such assessment the fertilization value and any environmental and human health risks are considered. Approved wastes and by-products are designated by ministerial decree and listed in Annex Aa of the Uitvoeringsregeling Meststoffenwet (Dutch Fertilizer Act).

The waste streams that are proposed as a base for fertilizers and codigestion, which were described and reviewed for application in the Netherlands (see section 2.2.1), vary a lot in their available amount: some comprise about 100 ton product per year whereas others are more than 500,000 ton product per year.

2.2.1 *ZZS substances in waste as base for fertilizers and codigestion*

The Fertilizer Act sets maximum concentration limits for specific inorganic and organic contaminants. The analysis of inorganic contaminants is mandatory, whereas analysis of organic contaminants is applicable when presence of these substances is to be expected. Consequently, test information is mainly available for those substances for which concentration limits have been set. ZZS contaminants which are regularly identified in waste which are proposed to be used as fertilizer or codigestion material are listed in Table 3. This data is based on 50 waste streams that were reviewed in the period since 2009. These waste streams varied from agricultural and forestry waste streams to industrial waste streams (e.g. from biodiesel and food production, and industrial waste water treatment plants). Nickel, PCDD/PCDF and mineral oil were detected in at least 50% of the performed analyses. Other ZZS-heavy metals were detected as well, but at a lower frequency (20-30%). Except for some PAHs, organic contaminants were rarely detected (<10%; mostly in a single sample). It should be noted however that the detection limits were relatively high in most analyses.

Table 3: Overview of (regularly) analysed ZZS substances in waste proposed as potential base for fertilizers and codigestion (based on almost 50 waste streams).

Metals
Cadmium
Mercury
Nickel
Lead

Pesticides
Alpha-HCH
Beta-HCH
Gamma-HCH
Aldrin
Dieldrin
Endrin
Isodrin
DDE, 2,4'-isomer
DDT, 2,4'-isomer
DDT, 4,4'-isomer
Carbendazim

Industrial chemicals
Hexachlorobenzene
PCB-28
PCB-52
PCB-101
PCB-118
PCB-138
PCB-153
PCB-180
PCDD/PCDF

Poly aromatic hydrocarbons
Anthracene
Benzo[a]anthracene
Benzo[a]pyrene
Benzo[ghi]perylene
Benzo[k]fluoranthene
Chrysene
Phenanthrene
Fluoranthene
Indeno[1,2,3-cd]pyrene
Naphthalene

Mineral oil
Mineral oil (C10-C40)

2.2.2 *(Current) Applications of recycled waste as fertilizers and codigestion materials*

Only waste or residual materials with no environmental and agricultural concerns may be marketed and used as fertilizer. These materials are described in Annex Aa of the Dutch Fertilizer Act. Annex Aa consists of several parts. Part I and II contain the waste and residual materials which may be traded and used as fertilizer as such. In part III are materials that can be used for the production of fertilizers. Part IV is a list of materials that may be co-digested with a minimum of 50% animal feces after which the remaining digestate is (still) considered as manure.

3 Plastics

3.1 ZZS substances in plastic waste streams

Plastics are produced from the polymerization or polycondensation of (basic) monomers, like ethylene and propylene, which are (mainly) obtained by the processing of crude oil. There are many different types of plastics (depending on the type of monomers used), and they can be grouped into two main polymer families: thermoplastics (which soften on heating and harden on cooling), and thermosets (which never soften once they have been moulded). Examples of thermoplastics includes polyethylene terephthalate (PET), low and high-density polyethylene (LDPE and HDPE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), expanded poly styrene (EPS) and polycarbonate (PC), polyamide (PA). Thermosets includes polyurethane (PUR), epoxide (EP) and unsaturated polyester resins (UP).

Each plastic type has specific properties, making them suitable for specific applications, like in packaging, building and construction applications or in electrical and electronic equipment. Furthermore additives are used in order to steer the final properties of the plastic. There are a large number of additives which can be used to improve different properties of the plastic, including antimicrobial substances, blowing agents, stabilizers, colorants, catalysts, flame retardants, monomers, cross linkers, hardeners, chain modifiers, antioxidants, plasticizers and other kind of additives. Within each polymer type and application different additives are used at varying concentrations. For instance, plasticizers could be used at concentrations up to 70%, whereas flame retardants are typically used up to 20% and antimicrobial substances up to 1% [20].

As a result of the widespread demand of plastics, a lot of plastic waste is produced. In Table 4, an overview of the amount of plastic waste per application type in the Netherlands is provided. Approximately 850,000 tonnes of plastic waste is produced in the Netherlands each year of which the biggest source of waste is packaging. Of the total plastic waste stream approximately 315,000 tonnes is recycled (37%; [21]). The remaining part is being incinerated.

Table 4: The amount of plastic waste and plastic recycling in the Netherlands per application in 1000 tonnes per year. Data obtained from [21].

Category/application	Plastic waste	Plastic recycling
Packaging	470	238
Building-/construction	82	77
Automotive	40	
Electronics (WEEE)	62	
Houseware	49	
Agriculture	38	
Other (furniture etc.)	108	
Total	**849**	**315**

Thermoplastics can be mechanically recycled by applying a re-melting processing step. It can be assumed that a relevant part of the additives present in the plastic waste stay in the material during mechanical recycling [20]. In Figure 3, a simplified overview of the thermoplastic plastic recycling chain is provided [22]. Within this recycling process, plastic waste is sorted on polymer type, grinded and further purified during a re-melting step, resulting in pelletized recyclate that functions as secondary raw material for new plastic product manufacturing.

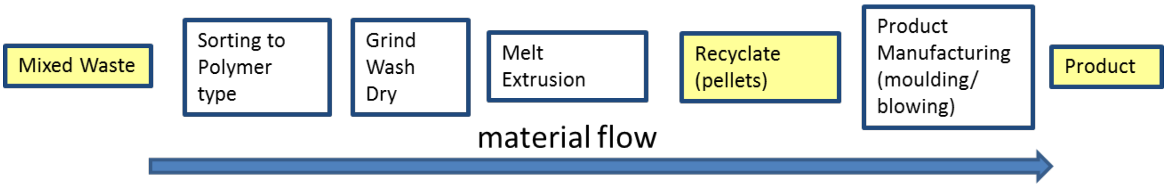

Figure 3: Simplified schedule of the thermoplastic recycling chain. Adopted from [22].

Nowadays, more emphasis is given to improve the quality of recycled polymers in order to increase the value of the obtained secondary raw material. Currently, techniques are under development with the aim to remove hazardous substances from plastic waste material, like the removal of flame retardants [23-25]. These methods are not yet available at a commercial scale.

Within the next section the presence of ZZS substances within plastic waste material will be addressed.

3.1.1 *ZZS substances within plastics*

Recently, a report has been published on handling of plastic wastes containing SVHCs [26]. This report is based on interviews with multiple actors in the plastic recycling chain in the Netherlands. Within this report, plasticizers, flame retardants and metal stabilizers are mentioned as the main plastic (SVHC) additives that may cause problems with recycling. These additives are mainly identified in long living materials (plastics used in the building and construction, automotive and electronic section). In addition, recycling possibilities of soft and hard PVC with respect to ZZS content is specifically discussed. Soft PVC is likely to contain plasticisers, whereas hard PVC is more likely to contain stabilizers (like cadmium and lead). Wastes of hard PVCs (PVC tubes and PVC window frames) are separately collected and recycled, whereas no separated recycling chain exists for soft PVC. As a result, during recycling, ZZS-free soft PVC material (and potential other plastic types without ZZS substances) could be contaminated with soft PVC containing ZZS substances.

In a report by Janssen et al. [27], the presence of several ZZS additives in plastics on the potential for recycling is addressed. Within this study PVC containing cadmium, lead or di(2-ethylhexyl) phthalate (DEHP) and EPS containing hexabromocyclododecane (HBCDD) are analysed. Despite the fact that the use of these additives in PVC and EPS has been strongly reduced during the last years (see Figure 4), plastic wastes containing these additives will become available in the upcoming years.

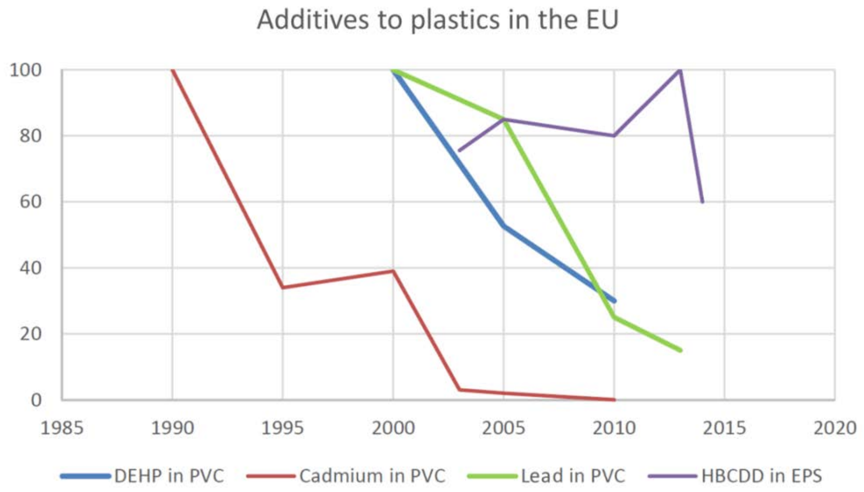

Figure 4: The addition of DEHP, cadmium and lead to PVC and HBCDD to EPS in the EU. Scaled to 100 for each additive. Adapted from [27].

In addition to stabilizers and plasticizers, flame retardants are also found in plastic waste streams. In a study conducted by the IVM/IVAM [28], plastic materials from end-of-life vehicles (ELV) and waste of electrical and electronic equipment (WEEE) in the Netherlands were analysed on the presence of the ZZS group of polybrominated diphenyl ethers (BDEs). Within this study, presence of BDEs within different sections of the plastic recycling chain were analysed, including plastics products collected by the recycler, shredded material and recycled plastic pellets. It was found that through the whole plastic recycling chain, ranging from waste to recycled products, POP-BDEs[2] and BDE209 (a decabrominated BDE) are present. The concentration range of BDEs in the different sections of the recycling chain decreases as a result of mixing/combination of multiple plastic sources and/or adding virgin material. The data demonstrates that BDEs could be present in products produced from recycled plastic (e.g. insulation and carpet padding material; [28]). The data on the BDE concentrations is summarized in Annex I.

Besides BDEs, some other chemical substances were identified in (WEEE and ELV) plastics, including the ZZS substance tris(2-chloroethyl) phosphate (TCEP) and non-ZZS substances tetrabromobisphenol-A (TBBP-A), resorcinol bis-(diphenylphosphate) (PBDPP), tris(phenyl) phosphate (TPHP), 2-ethylhexyldiphenyl phosphate (EHDP), tris(methylphenyl) phosphate (TMMP) and 2,4,6-tris(2,4,6-tribromophenoxy)-1,3,5-triazine (TTBP-TAZ) [29].

In a large survey of the Danish Environmental Protection Agency [20], the presence of hazardous substances in plastics has been explored. From a list of approximately 400 hazardous substances (based on the EU SVHC substances, ECHA’s registry of intentions, the Danish list of undesired substances and the Norwegian list of priority substances), 132 different hazardous substances or substance groups were assumed to be used or, for other reasons, could be present in plastic products. For

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[2] Tetra-, penta-, hexa- and heptabrominated BDE congeners, including BDE47, BDE99, BDE153, BDE154, BDE175 and BDE183.

these 132 substances, information on the function of the substance, the potential for release, the potential for exposure of consumers and the fate of the substance by recycling is provided. Although these substances could potentially present in plastics, for most substances no actual data is provided. Therefore the results of this study should be interpreted carefully. In addition to the list of the Danish EPA, the Swedish Chemical Agency also published a list of 46 substances which could be present in plastics [30]. On these two lists, 59 ZZS substances are listed which could potentially be present in plastics (see Table 5).

3.1.2 (Current) Applications of recycled plastics

Recycled plastics are amongst others used to develop insulation, carpet padding and certain office and kitchen products (including pens, staplers and coffee machines). Besides these products, plastic recyclates are used to manufacture a wide variety of other products including clothes and footwear, outdoor elements, furniture and design, automotive, agriculture, bags and complements, packaging and building and construction material [31].

Table 5:Overview of hazardous substances which are assumed to be used or, for other reasons, could be present in plastics according to the Danish EPA [20] and the Swedish Chemical Agency [30]. ZZS substances are indicated with an asterisk (*).

Antimicrobial substances
Arsenic and arsenic compounds *
Bis(tributyltin)oxide (TBTO) *
Organic tin compounds (tributyltin, triphenyltin) *
Triclosan

Blowing agents
C,C'-azodi(formamide) (ADCA) *
Chloromethane, methyl chloride
Fluorinated greenhouse gasses (HFCs, PFCs and SF6)
Benzenesulfonic acid, 4,4'-oxybis-, dihydrazide

Heavy metal based colorants, stabilisers and catalysts
Cadmium and cadmium compounds *
Chromium and chromium compounds *
Chromium trioxide *
Cobalt(II) diacetate *
Lead and lead compounds *
Lead chromate *
Lead chromate molybdate sulphate red (CI Pigment Red 104) *
Lead sulfochromate yellow (CI Pigment Yellow 34) *
Mercury and mercury compounds *
Antimony nickel titanium oxide yellow *

Flame retardants
Boric acid *
Brominated flame retardants *
Hexabromocyclododecane (HBCDD) and all major diastereoisomers *
Molybdenum trioxide
Tris(2-chloroethyl)phosphate *
Tris(2-chlor-1-methylethyl)phosphate (TCPP)
Bis(hexachlorocyclopentadieno) cyclooctane
Decabromodiphenyl ethane (DBDPE)
Ethylene (bistetrabromophthalimide) (EBTEBPI)
Tetrabromobisphenol A bis (2,3-dibromopropyl) ether (TBBPA-BDBPE)
Tris(tribromoneopentyl) phosphate (TTBNPP)
Tris(tribromophenoxy) triazine (TTBPTAZ)
Triphenyl phosphate
Bisphenol A bis-(diphenyl phosphate) (BAPP)
Melamine cyanurate
Melamine polyphosphate
N-alkoxy hindered amine reaction products
Phosphonate oligomer, polyphosphonate
Poly(phosphonate-cocarbonate)
Resorcinol bis-diphenylphosphate
Aluminium diethylphosphinate
Aluminium hydroxide
Ammonium polyphosphate (NH4 PO3)n
Magnesium hydroxide
Red phosphorus
Zinc borate
Tetrabromobisphenol A bis (allyl ether)
1,2,5,6- tetrabromocy-clo- octane (TBCO)
2,4,6- tribromophenyl allyl ether
Tetrabromobisphenol A bis(2,3- dibromopropyl ether) (TBBPA- DBPE), with dicumene for XPS and dicumyl peroxide for EPS, as usual synergists
Ethylenebis (tetrabro-mophthalimide) (EBTPI)
Decabromodiphenyl ethane (DBDPE)
Diphenyl cresyl phosphate
6H-Dibenz[c,e][1,2]oxaphosphorin, 6-oxide (DOPO)
Poly-(m-phenylene methylphosphonate)(Fyrol PMP)
Phosphoric acid, diethyl-, aluminium salt
1,3,4-Metheno-1H-cyclobuta[cd]pentalene (MIREX)*
Antimony trioxide
Trixylyl phosphate *
TDCP (Tris[2-chloro-1-(chloromethyl)ethyl] phosphate)
Tetrakis(2,6-dimethylphenyl)-m-phenylene biphosphate
Phenol, isopropylated, phosphate (3:1)
Boron zinc oxide (B6Zn2O11)

Phosphoric acid, tris(methylphenyl) ester

Monomers, cross linkers, hardeners, chain modifiers and catalysts

Acrylamide *
4-(1,1,3,3-tetramethylbutyl)phenol, (4-tert-Octylphenol) *
Bisphenol A (BPA) *
Formaldehyde *
Formaldehyde, oligomeric reaction products with aniline *
Phenol
Hexahydromethylphthalic anhydride and similar compounds *
Hexahydro-2-benzofuran-1,3-dione and similar compounds *
Hydrazine *
4,4'- Diaminodiphenylmethane (MDA) *
2,2'-dichloro-4,4'-methylenedianiline (MOCA) *
Other alkylphenols and ethoxylates
Certain isocyanates
Styrene
1,1-dichloroethylene, vinylidene chloride
p-dichlorobenzene, 1,4-dichlorobenzene
Acrylonitril *
1,3-butadiene *
Allyl 2,3-epoxypropyl ether, allyl glycidyl ether, prop-2-en-1-yl 2,3-epoxypropyl ether
Butyl 2,3-epoxypropyl ether , butyl glycidyl ether
1,3-bis(2,3-epoxypropoxy)benzene, resorcinol diglycidyl ether
1,2-epoxy-4-epoxyethylcyclohexane, vinylcyclohexane diepoxide
1,5-naphthylenediamine
1,2-epoxybutane
Methyloxirane (Propylene oxide) *
1,3,5-Tris(oxiran-2-ylmethyl)-1,3,5-triazinane-2,4,6-trione (TGIC) & 1,3,5-tris[(2S and 2R)-2,3-epoxypropyl]-1,3,5-triazine-2,4,6-(1H,3H,5H)-trione (β-TGIC) *
Imidazole *
1,4-Diaminobutane (Putrescine)
Vinyl acetate
Thioperoxydicarbonic diamide, dimethyldiphenyl-
Pyrimido[1,2-a]azepine, 2,3,4,6,7,8,9,10-octahydro-
Silane, ethenyltrimethoxy-

Organic based colorants

Malachite green hydrochloride, malachite green oxalate
N-[4-[(2-hydroxy-5-methylphenyl)azo]phenyl]acetamide, CI Disperse Yellow 3
1-phenylazo-2-naphthol, CI Solvent Yellow 14
Nickel, 5,5'-azobis-2,4,6(1H,3H,5H)-pyrimidinetrione complexes *
9,10-Anthracenedione, 1,4-bis[(4-methylphenyl)amino]-
1H-Indene-1,3(2H)-dione, 2-(3-hydroxy-2-quinolinyl)-

UV stabilisers, antioxidants and other stabilisers

1,4-benzenediol, 2,5-bis(1,1-dimethylethyl)-
Phenolic benzotriazols *
N-2-naphthylaniline, N-phenyl-2-naphthylamine
2-ethylhexanoic acid
Dibutyltin dichloride *
Other tin stabilizers *
TNPP (tris(nonylphenyl)phosphite) *
Benzenepropanoic acid, 3,5-bis(1,1-dimethylethyl)-4-hydroxy-, 2,2-bis[[3-[3,5-bis(1,1-dimethylethyl)- 4-hydroxyphenyl]-1-oxopropoxy]methyl]-1,3-propanediyl ester
Phenol, 2,6-bis(1,1-dimethylethyl)-4-methyl-
Phenol, 2,4-bis(1,1-dimethylethyl)-, phosphite (3:1)
Phenol, 4,4'-thiobis[2-(1,1-dimethylethyl)-5-methyl-
Benzenepropanoic acid, 3,5-bis(1,1-dimethylethyl)-4-hydroxy-, octadecyl ester
Phenol, 2,2'-methylenebis[6-(1,1-dimethylethyl)-4-methyl-
Phosphorous acid, triphenyl ester
1,2-Benzenediol, 4-(1,1-dimethylethyl)-
Calcium, bis(2,4-pentanedionato-O,O')-

Plasticisers
1,2-Benzenedicarboxylic acid, di-C7-11-branched and linear alkyl esters *
1,2-Benzenedicarboxylic acid, di-C6-8-branched alkyl esters, C7-rich (Diisoheptylphthalate) *
Alkanes, C10-13, chloro (Short Chain Chlorinated Paraffins-SCCP) *
Medium-chain chlorinated paraffins (MCCP)
Bis(2-methoxyethyl) phthalate (DMEP) *
Benzyl butyl phthalate (BBP) *
Bis (2-ethylhexyl)phthalate (DEHP) *
Di (2-ethyl-hexyl) terephthalate (DEHT)
Dibutyl phthalate (DBP) *
Diisobutyl phthalate (DiBP) *
Other phthalates *
Tributyl phosphate
Sulfonic acids, C10 – C18-alkane, phenylesters
Acetyl tributyl citrate (ATBC)
Mixture of benzoates incl DEGD
Mixture of 12-(Acetoxy)-stearic acid, 2,3-bis(acetoxy)propyl ester and octadecanoic acid, 2,3-(bis(acetoxy)propyl ester (COMGHA)
Diisononyl adipate (DINA)
Diisononyl-cyclohexane-1,2-carboxylate (DINCH)
Dipropylene glycol dibenzoate (DGD)
Glycerol triacetate (GTA)
Trimethyl pentaryl diisobutyrate (TXIB)
1,2,4-Benzenetricarboxylic acid, tris(2-ethylhexyl) ester
Hexanedioic acid, bis(2-ethylhexyl) ester
1,2-Benzenedicarboxylic acid, dimethyl ester

Solvents –neutral and reactive
2-Methoxyethanol *
Trichloroethylene *
N,N-dimethylformamide (DMF) *
1,2,3-Trichloropropane *
1,6-hexanediol diglycidyl ether
Dichloromethane, methylene chloride
1,1,2-trichloroethane
1,4-dioxane

Others
Nonylphenol and its ethoxylates *
Octylphenol and its ethoxylates *
Perfluorooctanoic acid (PFOA) and similar compounds *
Henicosafluoroundecanoic acid, heptacosafluorotetradecanoic acid, tricosafluorododecanoic acid, pentacosafluorotridecanoic acid, heptadecafluorononanoic acid and nonadecafluorodecanoic acid *
Polyaromatic Hydrocarbons (PAHs) *
Potassium hydroxyoctaoxodizincatedichromate *
Disodium tetraborates *

3.2 ZZS substances in rubber waste streams

Broadly, there are two types of rubber: natural rubbers, based on latex grown from plants, and synthetic rubbers, based on petrochemicals. Rubbers are polymers just as plastics, with the difference that rubbers consist of elastomers. Similar to plastics, also many (synthetic) rubber types exists, including styrene-butadiene (SBR), ethylene propylene diene monomer (EPDM) and polychloroprene (CR) rubber. Natural rubber on the other hand, is a polymer based on isoprene. Besides the use in tires, rubbers are used for many other applications, like shoe soles, as sealing and as shock absorber [32]. Within this current chapter we only focussed on rubber tires.

Within the Netherlands, approximately 7.5 to 8.5 million tires end up as waste each year in the Netherlands [32], which is equal to 45.000 to 94.000 tonnes per year [33]. Of the collected tires, 24% is reused and 76% is recycled. Within the recycling process, tires are shredded first, and when necessary the size is further reduced via a cutting mill. During this process, metal pieces are removed using a magnet and textile fibers are filtered off with suction. By this process, rubber granulate or rubber powders are produced. These particles can be used to develop ‘new’ products [33].

3.2.1 ZZS substances in rubbers

Recently, the RIVM published a report on the composition and health risks related to playing sports on rubber granulate fields. The results of this study indicate that multiple ZZS substances are present in rubber granulate, including poly aromatic hydrocarbons (PAHs), phthalates, phenols and polychlorinated biphenyls (PCBs; Table 6; [34]). Information on identified concentrations is provided in Annex I.

Table 6: Substances identified to be present in rubber granulate [34]. ZZS substances are marked with an asterisk (*).

PAHs
Phenanthrene *
Anthracene *
Fluoranthene *
Pyrene *
Benzo(ghi)perylene *
Benzo(c)fluorene *
Cyclopenta(cd)pyrene *
benzo(a)anthracene *
Benzo(b) + Benzo(j)fluoranthene *
Benzo(k)fluoranthene *
Benzo(a)pyrene *
Benzo(e)pyrene *
Chrysene *
Dibenzo(a,h)anthracene *

Phthalates
Di-2-ethylhexylphthalate *
Di-isobutylphthalate *
Di-isononylphthalate
Dicyclohexylphthalate *
Di-n-nonylphthalate
Diphenylphthalate
Bis(2-ethylhexyl)adipate

Benzothiazoles
Benzothiazole
2-hydroxybenzothiazol
2-mercaptobenzothiazol
2-methoxybenzothiazol
2-aminobenzothiazole
N-cyclohexyl-1,3-benzothiazol-2-amine
2,2-dithiobis-(benzothiazol)
N-cyclohexyl-2-benzothiazolsulfenamide

Phenols
4-tert-octylphenol *
bisphenol-A *

Polychlorinated biphenyls
PCB’s *

3.2.2 *(Current) Applications of recycled rubbers*

Recycled rubbers are used for multiple applications and in multiple sectors, including in synthetic turf fields, as roofing material and as floor tiles (e.g. at playgrounds, in the catering industry and in the agricultural sector). Furthermore, recycled rubbers are used as filler, as insulation material and for multiple other applications (e.g. in the automotive sector; [33]).

4 Manufacturing industry

4.1 ZZS substances in cathode ray tube glass waste

Within the previous decades, a sharp increase in the use of cathode ray tubes (CRT; like televisions and computer monitors) has been observed. A CRT consists of different glass components, including the 'neck', 'funnel' and 'screen'. The 'neck' section houses the electron gun, and the 'screen' is the viewing section. The different sections are connected with solder glass (also called the 'frit'; [35]). Although the CRTs are currently being replaced by more energy friendly flat screen monitors, many CRT are still in circulation and will become available as waste in the upcoming years.

There is no clear information on the amount of CRT glass waste in the Netherlands, and within Europe approximately 400,000 tonnes of CRT glass waste comes available year, though this may vary [36]. In addition, the amount of CRT glass waste is expected to decrease as CRTs are no longer produced. For recycling purposes, the CRT glass can be converted into glass granulate, which could be used as raw material.

4.1.1 ZZS substances in CRT glass

CRT glass structures contain different metal oxides, including lead, barium and strontium. Of these substances, lead is identified as a ZZS, and is mainly found as mono-oxide in CRT. The concentrations of these metal oxides seem to be comparable between CRT from different producers, with an average of 15-35% (w/w) lead [35].
In addition, the inside of the 'screen' compartment is coated with a mixture of fluorescent substances, which may also contain cadmium and other heavy metals, especially in older equipment [37]. In a study by Lecler et al., the chemical composition of fluorescent powders of 18 different CRTs has been analysed [38]. These CRTs were collected from a French CRT treatment/recycling facility. All powders contained significant amounts of the ZZS substances lead (17.43 mg/g) and cadmium (10.01 mg/g). It is expected that the fluorescent powders (containing lead and cadmium) can be removed from the CRT glass, as the powders are specifically mentioned within the WEEE Directive to be removed from recycled products (Annex VII of 2012/19/EC).

4.1.2 (Current) Applications of CRT glass granulate

Although ZZS substances are present in CRT glass granulates (i.e. lead), it is being reused in several applications. Recycled CRT glass, in the form of glass granulates, is used to develop new CRTs. However, only small quantities are reused for this application due to new technological developments, like the introduction of flat screens. Furthermore, CRT glass granulate is used in the Netherlands as aggregates in concrete, replacing natural sand and gravel [35].

5 Construction sector

5.1 ZZS substances in waste streams of the construction sector

Within the construction sector a lot of waste is being produced as a result of the demolition of constructions like buildings, roads and bridges. The construction sector can be divided in two sectors, the 'residential and non-residential buildings' and the 'civil engineering', which includes road and water constructions. Generally, waste which is being produced by the construction sector can consist of stone, wood and metal materials as well as plastic and paper products. Waste of plastic or paper origin is not further discussed within this section and are more elaborately considered in the plastic and paper specific chapters 3 and 6, respectively. Waste from the construction sector could include gypsum, roofing materials, concrete, brick, wood, asphalt and metals. In the scope of this exploratory study we focus on the more general fractions (i.e. stone, wood, and metal waste materials) and not specifically on all individual waste types produced by the construction sector (e.g. gypsum, roofing material, glass, etc.).

Within the Netherlands, the construction sector produced approximately 25 million tonnes of waste in 2012 [39]. This is approximately 40% of all wastes produced in the Netherlands [39]. Largely this waste stream consist of mineral waste (approximately 22 million tonnes), but also contains significant amounts of wood waste (approximately 1.5 million tonnes) and metal waste (approximately 1 million tonnes). Of this waste material over 95% is being recycled/reused. Especially stone debris can be recycled relatively easily, due to its nature [40].

As a result of the long service life of constructions (50 to 100 years; [41]), there is a high possibility that currently banned ZZS substances are present in construction waste.

5.1.1 ZZS substances in construction waste

Due to the many different types of waste derived from constructions, a high number of different ZZS substances could potentially be present. Within the construction sector, wood has been treated with biocides (like heavy metals) or flame retardants and may contain hazardous paints or adhesives [42]. For instance, the wood preservatives acid copper chromate (ACC), chromated copper arsenate (CCA), ammoniacal copper zinc arsenate (ACZA), pentachlorophenol, inorganic boron and creosote all contain a ZZS substance as active ingredient [43]. Furthermore, formaldehyde-based resins and lead paints could have been added to wood [44]. Similarly, stony waste materials may also contain hazardous paints or adhesive residues, and may include PCBs [45].

Furthermore, stony waste materials can contain multiple ZZS substances. For certain substance limit values are established and are regulated under 'besluit bodemkwalitiet'. The content and leaching concentrations of several substances in stony material in the Netherlands were investigated in 2006 to evaluate the regulatory limit values (Table 7) [46]. This data indicates that multiple ZZS substances could be present in stony waste material, including poly aromatic hydrocarbons (PAHs), mineral oils and several inorganic ZZS elements like cadmium, mercury and lead. More information on the concentrations of these substances identified in this material is provided in Annex I.

Table 7: Substances identified in stony material in the Netherlands in 2006 [46]. ZZS substances are marked with an asterisk (*).

Organics	**Inorganics**
Benzene *	Antimony
Ethyl benzene	Arsenic
Toluene	Barium
Xylenes	Cadmium *
Phenol	Chromium
Naphthalene *	Cobalt
Phenanthrene *	Copper
Anthracene *	Mercury *
Fluoranthene *	Lead *
Chrysene *	Molybdenium
Benz[a]anthracene *	Nickel *
Benzo[a]pyrene *	Selenium
Benzo[k]fluoranthene *	Tin
Indeno [1,2,3-cd]pyrene *	Vanadium
Benzo[ghi]perylene *	Zinc
Polychlorinated biphenyls *	Fluoride
Mineral Oil *	Chloride
	Sulphate
	Bromide

5.1.2 *(Current) Applications of construction waste*

As stated in section 5.1, over 95% of the construction waste is currently being recycled. However, the majority of the recycled waste cannot be considered to be purely circular (as visualized in Figure 5). The waste produced from the demolition of residential and non-residential buildings is, after recycling, mainly used in civil engineering (e.g. as road base material or as filler material). Only a very small fraction is reused in the construction of buildings (approximately 3%). The materials used in civil engineering are almost fully reused (~100%) for the same application/function. As a result, the civil engineering sector will become saturated with recycled aggregate in the future from materials coming from the residential and non-residential building sector [41].

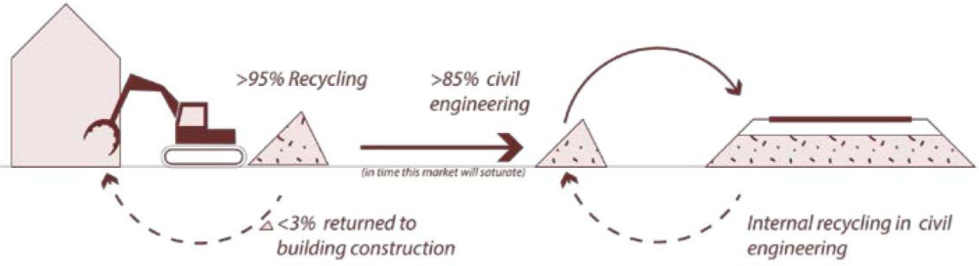

Figure 5: A schematic overview of the recycling process of construction waste, indicating the process of saturation of the civil engineering sector [41].

6 Consumer products

6.1 ZZS substances in paper and paperboard waste streams

The production of paper (and paperboard) can be divided into two phases: 'paper and pulp production' by the paper industry (i.e. different quality grades of paper) and 'paper product manufacturing' by separate industries (e.g. periodicals, packaging materials, books, etc.; [47]). During the production of paper, chemicals are added in order to improve the production process and/or the paper functionalities (like inks, pigments, glues, retention aids, sizing agents, coatings, biocides, synthetic binders, etc.; [47]).

Paper and paperboards are widely used as packaging material and as a communication aid (e.g. books, newspapers and letters). More than 90 million tonnes of paper and paperboard is produced in Europe each year and an additional 5.5 million tonnes of paper is imported into Europe and can become available for recycling [49]. Within the Netherlands, 2.8 million tonnes of paper is used each year, of which 2.3 million tonnes of paper waste is collected and recycled (which is equal to 85%; [48]). During recycling of paper, paper waste is mixed with water and chemicals and is grinded in order to form paper pulp. Subsequently, the pulp can be subjected to refinement processes in order to improve the purity (like the removal of glues, plastics and inks). Finally, the pulp is used to produce paper in a similar way as 'virgin' paper is produced [50].

6.1.1 ZZS substances in paper and paperboards

Pivnenko et al. (2015) compiled a comprehensive list of almost 10,000 substances which can potentially be found in paper and paperboards based on existing literature [47]. Subsequently, the substances on this list have been prioritized in order to obtain a shortlist of high priority substances based on hazard properties (as in line with article 57 of REACH EC/1907/2006). In addition, the substances have been prioritized on environmental fate properties in order to determine whether the substances are likely to persist in paper and paperboard after recycling. Of the almost 10,000 substances, 157 substances (potentially) meet the hazard criteria, of which 51 substances have a high affinity for solid matrices. Of the 51 substances, 24 substances are likely to be persistent, 12 inherently- and 15 readily-biodegradable. The 157 hazardous substances which are considered to be present in paper and/or paperboards were grouped according to chemical structure in: mineral oils, phthalates, phenols, parabens, inorganics and other substances (Table 8). It should be noted that within the study of Pivnenko et al. (2015) only substances for which information is available are prioritized. As a result, the number of hazardous substances, potentially needing consideration in the recycling of paper in future might be underestimated.

Table 8: Overview of hazardous substances which are assumed to be used or, for other reasons, could be present in paper and paperboards according to a literature survey of Pivnenko et al. [47]. ZZS substances are indicated with an asterisk (*).

Mineral oils

Alkanes, C12-26-branched and linear *
Distillates (petroleum), acid-treated middle *
Distillates (petroleum), heavy naphthenic *
Distillates (petroleum), hydrodesulfurized middle *
Distillates (petroleum), hydrotreated heavy naphthenic *
Distillates (petroleum), hydrotreated heavy paraffinic *
Distillates (petroleum), hydrotreated light naphthenic *
Distillates (petroleum), hydrotreated light paraffinic*
Distillates (petroleum), hydrotreated middle *
Distillates (petroleum), solvent-dewaxed heavy paraffinic *
Distillates (petroleum), solvent-dewaxed light paraffinic *
Distillates (petroleum), solvent-refined heavy naphthenic *
Distillates (petroleum), solvent-refined heavy paraffinic *
Distillates (petroleum), solvent-refined light paraffinic *
Distillates (petroleum), solvent-refined middle *
Distillates (petroleum), sweetened middle *
Distillates, C3-6, piperylene-rich (petroleum) *
Distillates, catalytic reformer fractionator residue, high- boiling (petroleum) *
Extract residues (coal), light oil alk., acid ext., indene fraction *
Extracts (petroleum), heavy naphthenic distillate solvent *
Foots oil, (petroleum) *
Gas oils (petroleum), hydrodesulfurized heavy vacuum *
Gas oils, acid-treated (petroleum) *
Hydrocarbons, C>=5, C5-6-rich; Naphtha low boiling *
Isobutan (>= 0.1% butadien) *
Lubricating oils *
Lubricating oils, petroleum, C15-30, hydrotreated neutral oil-based *
Lubricating oils, petroleum, C20-50, hydrotreated neutral oil-based *
Naphtha *
Naphtha (petroleum), heavy alkylate *
Naphtha (petroleum), heavy straight-run *
Naphtha (petroleum), hydrodesulfurized heavy *
Naphtha (petroleum), hydrodesulfurized light, dearomatized *
Naphtha (petroleum), hydrotreated heavy *
Naphtha (petroleum), hydrotreated light *
Naphtha (petroleum), light steam-cracked, debenzenized *
Naphtha, solvent-refined light(petroleum) *
Naphtha, steam-cracked middle arom. (petroleum)*
Petrolatum *
Petrolatum (petroleum), oxidized *
Petroleum distillate highly refined middle *
Petroleum gases, liquefied *
Residual oils (petroleum), solvent-dewaxed *
Residual oils, hydrotreated (petroleum) *
Slack wax, (petroleum) *
Solvent naphtha (petroleum), hydrotreated light naphthenic *
Solvent naphtha (petroleum), light arom. *
Solvent naphtha (petroleurn), light aliphatic *
Stoddard solvent *

Phthalates

BBP *
Bis(2-methoxyethyl) phthalate *
DBP *
Dicyclohexyl phthalate *
Diethyl phthalate
DEHP *
DIBP *
1,2-Benzenedicarboxylic acid, di-C6-8-branched alkyl esters, C7-rich *

1,2-Benzenedicarboxylic acid, di-C7-11-branched and linear alkyl esters *

Phenols
BPA *
Nonylphenol *
Octylphenol
Pentachlorophenol *
2-Phenylphenol
4-Chloro-3-methylphenol
4-nonylphenol *
4-tert-octylphenol *

Parabens
Butyl paraben
Ethyl paraben
Methyl paraben
Propyl paraben

Inorganics
Boric acid *
Boron oxide *
Cadmium (Cd) *
Cadmium sulphide *
Carbon disulphide
Carbon monoxide *
Chromium (Cr)
Chromium trioxide *
Cobalt(II) acetate *
Cobalt(II) carbonate *
Cobalt sulphate *
Disodium tetraborate, anhydrous *
Lead chromate molybdate sulfate red, Pigment Red 104 *
Lead sulfochromate yellow, Pigment yellow 34 *
Lead(II) chromate *
Mercury (Hg) *
Nickel(II) acetate *
Nickel dichloride *
Nickel sulphate *
Potassium dichromate *
Sodium perborate *
Sodium tetraborate decahydrate, Borax *

Others
Acetamide, N,N-dimethyl- *
Acetamide, N-methyl- *
Acetic acid, methoxy- *
Acrylamide *
Acrylonitrile *
Alkanes, C14-17, chloro
Aniline, 4,4'-oxydi- *
Aziridin
Benzene *
Bis(4-aminophenyl)methane *
DIPN
Cyclotetrasiloxane, octamethyl-
Decamethyl-cyclopentasiloxan
Dibenzofuran, 2,3,4,7,8-pentachloro-, 23478-PCDF*
Ether, bis(2-methoxyethyl) *
Ethylene oxide *
Ethyleneglycol diethyl ether *
Ethyleneglycol dimethyl ether *
Formamide *
Formamide, N-methyl- *
Glycydyltrimethylammonium chloride *
Hydrazine *
Hydrazine, 1,1-dimethyl- *
Ligroine *
Methyldithiocarbamic acid, sodium salt
N-(2-Aminoethyl)ethanolamine *
N,N-dimethylformamid *
o-Toluidine *
Oxirane, (chloromethyl)- *
PCBs *
Poly(oxy-1,2-ethanediyl), .alpha.-(nonylphenyl)-.omega.-hydroxy- *
Propylenoxide *
Styrene
Sulfuric acid, dimethyl ester *
tert-Dodecanethiol
Tetramethylthiuram disulphide
Toluene, .alpha.-chloro- *
Toluene, o-nitro- *
Trichloroethene *
Triethylenglycoldimethylether *
Tris(2,3-epoxypropyl)isocyanurate *
Tris(2-chlorethyl)phosphat *
Vinyl Chloride *
1,2,3,7,8-Pentachlorodibenzodioxin, 12378-PCDD *
1,2-Dihydro-6-Hydroxy-4-Methyl-1-3-(1-Methylethoxy)Propyl-2-Oxo-5-4-(Phenylazo)Phenylazo-3-Pyridinecarbonitrile, Disperse Orange 149 *
1,3-Benzenediol
1,3-Butadiene *
1,3-dichloro-2-propanol *
1-Methyl-2-pyrolidinone *
2,3-Epoxypropanol *
2,3-Epoxypropyl phenyl ether *

2,3,7,8-Tetrachlorodibenzo-p-dioxin, 2378-TCDD *
2-Benzimidazolecarbamic acid, methyl ester *
2-Ethoxyethanol *
2-Ethoxyethylacetat *
2-Methoxyethanol *
2-Methoxyethylacetat *
2-Methoxypropan-1-ol *
2-Methoxypropylacetat *
2-Methyl-1,3-butadiene *
2-Methylaziridin *
3,4-Dichloroanilin
4-Nitrotoluen
4,4’-bis (dimethylamino)-benzophenone (Michler's ketone) *

Within Table 8, 49 mineral oils have been listed. These substances are potentially carcinogenic and are mainly used as printing inks (solvents) in paper production. Mineral oils have been identified in different paper products in relatively high concentrations, including in newspapers and tissue paper (average concentrations of 2-3 g/kg; [51,52]), as well as in food packages (from the Netherlands) from virgin and especially recycled origin (concentrations up to 1.2 g/kg; [53]). These mineral oils can be divided in two groups: mineral oil saturated hydrocarbons (MOSH) and mineral oil aromatic hydrocarbons (MOAH). MOAH is expected to have carcinogenic properties and MOSH may cause organ damage [54]. Besides the presence of MOSH and MOAH in food packages, foodwatch also identified mineral oils in food products which are packed in paper/paperboard, indicating the potential leaching of these substance into food products [53]. The presence of mineral oils in food contact material and related food sources raised a lot of concern, and resulted in questions at the House of Representatives of the Netherlands (See 967296-150314-VGP-2016 and 864070-143528-VGP-2015).

Besides mineral oils, many other groups of hazardous substances have been identified in paper and paperboards (see Table 8). For instance the ZZS substances bisphenol A (BPA), bis (2-ethylhexyl) phthalate (DEHP), nonylphenolmonoethoxylate (NMP) and nonylphenoldi-ethoxylate (NDP) have been identified in different types of recycled food packages in concentrations up to 26.6, 39.8, 0.69 and 0.62 mg/kg, respectively [55]. Furthermore, per- and polyfluoroalkyl substances are identified in paper food contact material in the US and Europe, including the ZZS substances perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS) and perfluorodecanoic acid (PFDA) [56,57]. Paper products containing these substances are likely to end up in the waste streams.

6.1.2 (Current) Applications of recycled paper and paperboards

Today, a lot of paper is recycled in order to be used as packaging material, and is widely used as food contact material. Besides packing material, recycled paper is used as a graphical product (e.g. newspaper, magazine, etc.) and hygienic paper (e.g. tissues, etc.) [50].

6.2 ZZS substances in textile waste streams

Textile manufacturing is a complex process consisting of multiple steps. First, yarns are produced from natural (e.g. wool, cotton) or synthetic fibres (e.g. polyester). Secondly, textile fabrics can be produced by using technologies as weaving and knitting. Subsequently, these fabrics can treated in order to obtain the required functionalities and characteristics. This may include dying, printing, coating, softening, water-proofing, fire-proofing and bleaching. Within these processing steps, the choice of substances is fibre-specific [58].

It was established that in 2012 about 199 kton of textile waste was collected in the Netherlands, of which 90 kton was obtained from Dutch households and 109 kton was imported from other European countries. The non-collected textile waste stream (145 kton) is incinerated [59]. Of the collected textile, 95% is reused or recycled. In addition, it is expected that 65% of the non-collected textile waste is suitable for reuse or recycling as well. Textile waste products which are still in good condition are mainly reused and transported to developing countries, whereas damaged textile is recycled. During recycling, textile fibres are recovered from textile waste and are reused to develop new products [60].

6.2.1 *ZZS substances in textile*

Within a report of the Swedish Chemical Agency, 2400 textile-related substances were identified using multiple sources including registration dossiers within REACH, the SIN list and databased of the Swedish Chemical Agency [61]. Of these 2400 substances, approximately 10% was considered to be of potential risk for human health and 5% for the environment. It should be noted that within this study auxiliary chemicals and unintended degradation products were not considered, though it is likely that some of this substances are of concern as well (like the ZZS substances nonylphenol and nonylphenol ethoxylates). Of the 2400 textile-related substances, 368 substances were considered to be of potential concern and include 54 ZZS substances, see Table 9.

Nijkamp et al. also conducted a hazard prioritization of substances which are used in (the production) of textile products by using the registration dossiers within REACH [58]. The prioritization depends on the use of the substance (i.e. "Is the substance used in the textile production process?") and on the hazard classifications skin sensitization and carcinogenicity. Based on this research 788 substances were identified to be used within the textile sector, of which 71 substances are on the ZZS-list. Highest priority was given to 32 substances of which nine are ZZS substances, including dibutyltin-oxide, dicyclohexyl phthalate, diisobutyl phthalate, di(2-ethylhexyl) phthalate, cobalt dichloride, cobalt sulphate and hexabromocyclododecane. Though there is overlap between the results of this study and the study of the Swedish Chemical Agency, some ZZS substances are only identified in one of the two studies (e.g. dibutyltin-oxide, cobalt dichloride and cobalt sulphate). This is related to the different inclusion criteria. It should be noted that not all ZZS substances identified in the study of Nijkamp et al. are reported in this study because of confidentiality reasons.

As indicated above, there is information available on which substances could (potentially) be present in textile products. However, there is very little knowledge on substances which may be present in used textiles [62]. Therefore, we currently assume that textile-related substances could be present in the textile waste stream.

6.2.2 *(Current) Applications of recycled textile*

Most textile waste products are reused and only textile waste which is not eligible for reuse is recycled. During recycling the fibres from textile waste materials are recovered. Subsequently, these fibres can be used to develop new textile products. As indicated by Östlund et al. [62], it is challenging to identify the hazardous substances being present in textile waste material and therefore the identification of suitable recovering possibilities is difficult. Within their report they recommend the development new methods for automatic sorting by using new detection methods and new marking of textiles. Such developments are expected to improve traceability of (hazardous) chemical additives and may contribute to the selection of appropriate recycling options.

Table 9: Overview of textile related ZZS substances which are assumed to be used or, for other reasons, could be present in textile according to the Swedish Chemical Agency [61].

Stabilisers
4,4'-isopropylidenediphenol
Dibutyltin dichloride
Lead dinitrate
Pentalead tetraoxide sulphate
Trilead dioxide phosphonate
Tetralead trioxide sulphate
Dioxobis(stearato)trilead
[Phthalato(2-)]dioxotrilead
Fatty acids, C16-18, lead salts
2-(2H-Bensotriazol-2-yl)-4,6-bis(1,1- dimetylpropyl)fenol

Plasticizers
Dicyclohexyl phthalate
Diisobutyl phthalate
Dibutyl phthalate
1,2-Benzenedicarbo1ylic acid, dihe1yl ester
Benzyl butyl phthalate
Bis(2-ethylhexyl) phthalate
1,2-Benzenedicarbo1ylic acid, bis(2- metho1yethyl) ester
Dipentyl phthalate (DPP)
Diisopentyl phthalate
1,2-Benzenedicarbo1ylic acid, di-C7-11-alkyl esters, branched and linear
1,2-Benzenedicarbo1ylic acid, di-C6-8-branched alkyl esters
1,2-Benzenedicarbo1ylic acid, dipentylester, branched and linear

Flame retardants
Tris(2-chloroethyl) phosphate
Bromoethylene
Bis(pentabromophenyl) ether
Trixylyl phosphate
Hexabromocyclododecane
Benzene, 1,1'-o1ybis-, pentabromo deriv.
Benzene, 1,1'-o1ybis-, octabromo deriv.
Alkanes, C10-13, chloro

Dyestuff and pigments
"[4-[4,4'-bis(dimethylamino)benzhydrylidene]cyclohexa- 2,5-dien-1-ylidene]dimethylammonium chloride"
Benzenamine, 4-[(4-aminophenyl)(4-imino-2,5-cyclohe1adien-1-ylidene)methyl]-, monohydrochloride
1-Naphthalenesulfonic acid, 3,3'-[[1,1'-biphenyl]- 4,4'-diylbis(azo)]bis[4-amino-, disodium salt
Cadmium sulphide
Orange lead
Lead sulfochromate yellow
2,7-Naphthalenedisulfonic acid, 4-amino-3-[[4'- [(2,4-diaminophenyl)azo][1,1'-biphenyl]-4- yl]azo]-5-hydro1y-6-(phenylazo)-, disodium salt
Methanaminium, N-[4-[[4-(dimethylamino)phenyl][4-(phenylamino)-1-naphthalenyl]methylene]-2,5-cyclohe1adien-1- ylidene]-N-methyl-, chloride
2,7-Naphthalenedisulfonic acid, 3,3'-[[1,1'- biphenyl]-4,4'-diylbis(azo)]bis[5-amino-4-hydro1y-, tetrasodium salt
Lead

Lead sulphate
Chromic acid, lead(2+) salt (1:1)
Sodium chromate
Potassium dichromate
Pyrochlore, antimony lead yellow
Sodium dichromate
Lead chromate molybdate sulfate red
Cuprate(2-), [5-[[4'-[[2,6-dihydro1y-3-[(2- hydro1y-5-sulfophenyl)azo]phenyl]azo][1,1'-biphenyl]-4-yl]azo]-2-hydro1ybenzoato(4-)]-, disodium
Pentazinc chromate octahydroxide
Acetic acid, lead salt, basic
Sulfurous acid, lead salt, dibasic
6-hydroxy-1-(3-isopropoxypropyl)-4-methyl-2-oxo-5-[4-(phenylazo)phenylazo]-1,2-dihydro-3- pyridinecarbonitrile

Antioxidants
N-(1,3-dimethylbutyl)-N'-phenyl-1,4- benzenediamine

Biocides
Borax [ISO]

6.3 ZZS substances in diaper waste streams

Diapers are used by a large amount of baby's and adults, and consist of a permeable inner layer, an absorbent core and a waterproof outer layer as well as elastic bands and adhesive strips. The inner layer mainly consist of polyethylene and polypropylene, whereas the outer layer may consist of polyethylene, textile or rubber. The main components of the absorbent core are super absorbent polymers (SAPs; cross-linked sodium polyacrylate) and fluff-pulp (cotton, wood and hemp fibres; Table 10). Besides the composition of unused diapers, diaper waste contains urine and faeces [63] and pharmaceutical residues. Within the Netherlands, approximately 160 ktonnes of diaper waste is produced each year [63], and projects are currently initiated to develop closed-loop recycling of diapers.

Table 10: Composition of unused diapers and incontinence pads in 2013 [63].

Materials	**Diapers**	**Incontinence pads**
Fluff-pulp [%]	27	65
SAP [%]	38	14
Polyethylene [%]	5	5
Polypropylene [%]	24	11
Adhesives [%]	4	3
Elastic [%]	2	1
Other [%]	1	0.2
Total average weight [g]	**33.3**	**109.2**

6.3.1 ZZS substances in diapers

Within a report by Spijker et al. [63], the chemical composition of unused diapers is described. Within fluff-pulp only non-ZZS additives are likely to be present, including cationic surface-active substances which act as softeners and de-bonders. Currently, the bleaching of pulp is conducted chlorine-free, using hydrogen peroxide or ozone. As a result, dioxins are no longer formed as by-product. In addition, some residues from the production process could potentially be present including anthraquinone, anti-foaming agents, emulsion breakers and other surface-active substances. However, no specific information on the applied substances is available. During the production of SAPs, multiple substances are used or are unintentionally formed, however it does not consider ZZS substances.

Besides substances which are present in unused diapers and incontinence pads, also pharmaceutical residues could be present in this waste stream. Spijker et al. [63] investigated which population groups (i.e. age and sex) most often use diapers and incontinence pads. Subsequently, for the largest user groups, the environmental risks of ten most used pharmaceuticals have been assessed. All the investigated pharmaceuticals are not on the ZZS-list.

Based on available data, no issues with respect to ZZS content are expected for diaper waste. Though there could be issues for use of diaper waste with respect to other factors, like for instance pathogens.

6.3.2 *(Current) Applications of recycled diapers*

Currently most diaper waste is incinerated, however, as this waste stream considers a large amount of waste, projects are initiated to develop a close-loop recycling process.

7 Discussion, conclusion and recommendations

Within the Netherlands, a transition towards a circular economy is being stimulated in order to make use of resources more efficiently and decrease the environmental impact of production processes. During this transition, attention should be given to the reuse and recycling of products containing hazardous substances, as the re-introduction of these substances may result in undesired and/or unexpected environmental and human health related consequences. The governmental program 'The Netherlands circular in 2050' refers to the importance of 'safe recycling'. In Table 11 we have summarized our explorative overview of the ZZS classes found within different waste streams categorized according to the five priority sectors. This overview provides an indication of waste streams which are of potential concern with respect to the presence of ZZS substances.

7.1 Prioritization options

Prioritization of ZZS containing waste streams is needed to enable policy makers (and inspectorates, etc.) to develop adequate risk management strategies with respect to handling these streams (see section 1.4). Various prioritization methods will be discussed to assess their value:

- number of ZZS substances
- volume of ZZS substances
- type of end use
- origin of ZZS content

The general limitations and uncertainties of our analysis should be emphasized here. Actual data on ZZS presence in waste stream are often lacking, because there is no coherent analytical monitoring program for ZZS in waste. The approach we followed is in most cases partly based on theoretical assumptions. There may also be a bias in certain ZZS-classes because for some waste stream only a specific set of ZZS substances has to be analyzed following regulatory obligations (e.g. co-digestion materials). Finally, ZZS are being reported in different classes in the various waste streams (e.g. classes like 'others' or 'industrial chemicals' versus 'cadmium') which hinders making clear distinctions.

Number of ZZS substances

The idea behind this approach is that the policy attention to be paid to a waste stream is proportional to the number of ZZS in that waste stream. Based on this report (Table 11) it seems difficult to prioritize waste streams along this line as various ZZS substances could be present within nearly all waste streams. In fact, only diaper waste does not seem to contain any ZZS. This diversity of ZZS substances is reflected in a recent report of Van Leeuwen, in which it was concluded that many ZZS substances are being used in a very broad range of industry and use categories [64]. On the other hand, there seems to be some pattern in ZZS classes in waste streams: heavy metals, flame-retardants, PAHs and plasticizers (phthalates) are frequently encountered. One could argue that a more in-depth focus is initially needed on these ZZS-classes.

ZZS volume
Theoretically, it would be possible to prioritize waste streams based on their ZZS volume. The underlying generic assumption is that potential risks are correlated with the magnitude of the ZZS flow. By multiplying the concentrations of ZZS substances (in weight percentages) with the corresponding waste volume, an estimation of the total ZZS content in the various waste streams could be made. Such a prioritization on ZZS content is illustrated below for flame-retardants in end-of-life vehicles (ELV) and waste of electrical and electronic equipment (WEEE; Textbox 1). However, in this exploratory study only limited and highly fragmented data were found concerning the concentration levels of ZZS substances in the various waste streams (see Annex I). Many different ZZS substances are considered to be potentially present or have been detected in a waste stream (see above), but ZZS substances in waste streams are not commonly quantified. Furthermore, the life-stage in which the ZZS substances are quantified differs per category, ranging from virgin products, to waste streams to recycled products. This makes it difficult to rank the various waste streams based on their ZZS volumes. In addition, the few quantified ZZS substances may bias the prioritization and the selection for risk management measures. Therefore we conclude that the collected data do not allow a balanced prioritization according to the ZZS volumes per waste stream.

Type of end use
Besides prioritization on ZZS content, waste streams could be prioritized based on the potential end-use of recycled material. By prioritizing on types of end-use, it is assumed that certain uses may result in higher risks for man and environment. For instance, more critical exposure concentrations are to be expected for consumer and open wide use applications compared to certain industrial applications, and consequently higher priority could be given to these waste streams. We do not have a comprehensive overview of all the potential outlets. Nevertheless, it is clear that more weight should be given to risks from, for example, rubber granulates on artificial turf pitches and struvite as fertilizer in comparison with CRT aggregates in concrete.

Origin of ZZS content
The origin of ZZS substances (i.e. functional additive or contaminant) in the different waste streams could be a factor for prioritization. In most waste streams, ZZS substances can be considered as ‘functional’ additives, which are required to steer the performance requirements of the end product (e.g. cadmium as stabiliser in plastics). However, in some waste streams, the ZZS substances can be considered as contaminants, in which the ZZS substances do not exert an essential functionality (e.g. cadmium in wastewater derived products). This distinction might be essential for (regulatory) follow-up actions, as issues with ZZS ‘functional’ additives may be solved within the sector itself, while issues with ZZS contaminants could be more complex as they emerge from multiple sectors. In addition, a prioritization on the origin of ZZS may be linked with (im)possibilities to technically remove ZZS from the waste streams. For instance, it could be anticipated that

that ZZS substances, which are not chemically bonded to the waste material, are more easier to remove. To apply this prioritization method more information is needed on the different product manufacturing processes with respect to the use of additives etc.
Alternatively to the focus on the origin of the ZZS content, one could focus on the volume fraction of the non-legacy ZZS only and disregarding legacy ZZS (i.e. ZZS which are already banned such as PCBs or certain flame retardants). Prioritizing non-legacy ZZS over legacy ZZS may be considered more appropriate, as there may be both more and more effective risk management measures for non-legacy ZZS.

The above illustrates that multiple aspects can be considered when prioritizing waste streams for further attention on their ZZS content and origin. Currently, it is difficult to appoint one prioritization approach as most powerful due to the many data gaps. The various options can also be seen as complementary to each other. From a pure risk management perspective, however, a clear point of view on those streams with a potential consumer and/or open wide end use is undoubtedly essential.

Table 11: Overview of the potential presence of ZZS substances (grouped by their functionality, origin and/or chemical structure) in waste streams from the five priority sectors as defined in the governmental program 'The Netherlands circular in 2050'.

Waste stream		**Presence of ZZS substances grouped by their functionality, origin and/or chemical structure**
Biomass and food	Wastewater	Heavy metals Flame retardants Poly aromatic hydrocarbons Pesticides Endocrine disruptors Industrial chemicals *Others*
	Waste streams containing fertiliser minerals/organic material	Heavy metals Poly aromatic hydrocarbons Pesticides Industrial chemicals Mineral oils
Plastics	Plastics	Heavy metals Flame retardants Poly aromatic hydrocarbons Plasticizers Antimicrobial substances Blowing agents Monomers etc. Organic colorants UV stabilisers Solvents *Others*

Waste stream		**Presence of ZZS substances grouped by their functionality, origin and/or chemical structure**
	Rubbers (tires)	Poly aromatic hydrocarbons Phthalates Phenols Polychlorinated biphenyls
Manufacturing Industry	Cathode ray tube glass	Heavy metals
Construction Sector	Construction sector	Heavy metals Flame retardants Poly aromatic hydrocarbons Antimicrobial substances *Others*
Consumer Products	Paper and paperboards	Inorganics (incl. heavy metals) Phthalates Mineral oils Phenols *Others*
	Textile	Flame retardants Plasticizers Stabilisers Dyestuff and pigments Antioxidants Biocides
	Diapers	-

Textbox 1: Example – ZZS contents of waste streams

As described in section 3.1, approximately 40 ktonnes of ELV and 62 ktonnes of WEEE is produced in the Netherlands each year [21]. By combining this information with quantitative information of ZZS substances in these waste streams the total ZZS content in the waste stream could be calculated. Based on data from the IVM/IVAM on brominated flame retardants ([28]; Annex II), shredded ELV plastics may contain up to 81 µg/g of BDEs which is equal to 0.0081%. Thus, the total BDE content in the shredded ELV waste could be as high as 3.2 tonnes (Table 12). Shredded WEEE plastics, on the other hand may contain up to 3630 µg/g (0.36%) of BDEs which is equal to a BDE content of 225 tonnes per year.

Table 12: Example on how to calculate ZZS contents of waste streams for prioritization. ELV = end-of-life vehicles; WEEE = waste of electrical and electronic equipment; BDE = brominated flame retardants.

Waste category	Waste volume (tonnes)	BDE - ZZS quantity (%)	BDE - ZZS content (tonnes)
ELV	40,000	0.0081	3.2
WEEE	62,000	0.36	225

7.2 Risk management of ZZS substances in a circular economy

The current study shows a broad spectrum of waste streams that may indeed contain ZZS substances. The chemicals may re-emerge in the end-products that are manufactured from waste, resulting in potential risks for man or environment. Ideally, 'source' solutions such as safe-by-design and circular product design concepts, should be applied to fully eliminate these ZZS substances from the environment. These concepts are currently being developed and enrolled in several ways. Substituting ZZS for safe(r) alternatives is one of these long-term strategies: if ZZS do not enter our economy any longer, society is also free of their risks during the entire life cycle of our products. However, we have to realize that we are still in an era in which we are faced with numerous 'legacy' and 'current' ZZS substances in waste streams. For that reason, safe 'end-of-pipe' solutions have to be found. Distinction should then be made between those circular and biobased initiatives that are *a priori* safe and sustainable and those that need further consideration. For this purpose a generic decision scheme should be developed, which enables to weigh safety, sustainability, and societal aspects in order to make such distinctions.

Within the draft of the Dutch National Waste Management Plan 2017-2029 (LAP3) a first framework on an assessment of the processing of waste streams with ZZS substances is described (see Annex II). This considers a general framework which needs further elaboration with more detailed instructions. In LAP3 a trigger/cut-off value on the 'allowable' amount of ZZS content should be established first, in order to distinct 'safe' from 'potential risk' waste streams. It is important to closely tune this approach with REACH, CLP and other legal frameworks on chemical risk management. LAP3 will also generate a practical guidance on risk analysis to be executed for those waste streams exceeding the above-mentioned trigger/cut-off value.

Ultimately, not only a decision scheme on ZZS content, but a whole framework considering multiple sustainability modules (e.g. pathogens, microplastics, pharmaceuticals, as well as sustainability aspects like CO_2 reduction, etc.) needs to be developed, and this is one of the ambitions of the RIVM. Such approaches are needed to support transparent, swift and valid decision-making towards safe and sustainable initiatives.

7.3 Conclusion and recommendations

We have explored several waste streams and created a set of ZZS classes that are found per waste stream categorized per priority sector. A large variation of ZZS has been reported in these waste streams and our overview provides a start to further prioritize these ZZS containing waste streams. We presented a number of options for such a prioritization process.

Improving the information base on the presence of amounts of ZZS in the various waste streams should be pursued since many ZZS substances were reported to be ‘potentially’ present. We think, however, that this will be resolved when LAP3 comes into force in the Netherlands. As described in LAP3, the presence and the amount of ZZS substances in waste streams should be known in order to authorize their follow-up application. RIVM stresses that the LAP3 guidance on risk analysis should be very clear in distinguishing between acceptable and non-acceptable types of end use of a waste stream, either in a qualitative (precautionary principle) or quantitative way. Specific product concentration limits for ZZS should be taken into account in this approach, but such limits are lacking for various ZZS and product types. Moreover, product limits can only prove their value if the chemical composition of a (recycled or reused) product is fully known.

A complementary approach to gain more quantitative data is to collect and disclose data on the amounts of ZZS that are being added during the product manufacturing processes. For example, it is known that for plastics the application of certain types and amounts of ZZS is very polymer and product application specific. For such analysis, it is useful to separate the waste streams into more application specific fractions. We realize, however, that traceability and transparence within chains are critical, but challenging, factors in this approach. On the other hand, industry should take their responsibility regarding the disclosure of relevant information on chemicals in their products.

We discussed several approaches for the prioritization of ZZS containing waste streams. These approaches should be further elaborated. Selecting particular product and waste streams may structure more strategic discussions on how to create safe recycling and reuse possibilities. In addition, the development of a general decision scheme, as outlined in section 7.2, is highly recommended. Such a scheme can contribute to the assessment and decision making process in a transparent and generic approach, and may identify research needs. Furthermore, such a decision scheme is expected to contribute to achieving the ‘safe recycling’ ambitions as described in the governmental program ‘The Netherlands circular in 2050’.

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8.2 Interviews

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Annex I – Concentration specific information

Wastewater from sewage treatment

The composition of struvite derived from STPs has been reported by STOWA as well as in a report by the WUR, in which several small studies have been cited [15,16]. Within these studies several heavy metals as well as some pharmaceuticals and organic compounds have been analysed (Table 13 and Table 14). In the study from STOWA only one pharmaceutical, metoprolol (a bètablokker), was identified in one single sample at a concentration of 0.4 mg/kg dry matter. Furthermore, some other organic compounds were identified in concentrations up to maximum 11 mg/kg dry matter (including hexadecanoic acid, decanal, chlorodecane, tetradecane, pentadecane and an unknown amine and aliphatic compound). It should be noted however, that the detection limits were relatively high and that the samples were not fully representative in the study from STOWA. Therefore, these results only provide an indication of the concentrations within struvite. In the report of the WUR, the ZZS substances dibutyltin and tributyltin also have been identified (0.013 and 0.022 mg/kg dry matter, respectively) as well as nonylphenol and nonylphenol ethoxylate (0.51 and 3.2 mg/kg dry matter, respectively; [16]).

Table 13: The presence of heavy metals in struvite recovered STPs. Highest identified concentration has been shown and ZZS substances have been marked with '' [15,16].*

Heavy metals	**STOWA mg/kg dry matter (40°C)**	**WUR mg/kg dry matter**
Cadmium *	0.11	1.76
Chromium *	16.02	31
Cupper	20.62	235
Mercury *	0.27	1
Nickel *	10.64	30
Lead *	17.96	49
Zinc	71.85	921
Arsenic	0.66	0.48

Table 14:The presence of organic compounds in struvite recovered from 4 different STPs. Highest identified concentration has been shown and ZZS substances have been marked with ''; LOD = limit of detection, ranging from 0.000-0.088 mg/kg dry matter [15,16].*

Organic compound	**STOWA mg/kg dry matter (40°C)**	**WUR mg/kg dry matter**
ΣPCDD/PCDF *	<LOD	ND
α-HCH *	<LOD	ND
β-HCH *	<LOD	ND
γ-HCH (lindane) *	<LOD	ND
HCB *	<LOD	ND
Aldrin *	<LOD	ND
Dieldrin *	<LOD	ND
Σaldrin/dieldrin *	<LOD	ND
Endrin *	<LOD	ND
Isodrin *	<LOD	ND
Σendrin/isodrin *	<LOD	ND
ΣDDT+DDD+DDE *	<LOD	ND
PCB-28 *	<LOD	ND
PCB-52 *	<LOD	ND
PCB-101 *	<LOD	ND
PCB-118 *	<LOD	ND
PCB-138 *	<LOD	ND
PCB-153 *	<LOD	ND
PCB-180 *	<LOD	ND
Σ6-PCB (excl. PCB-118) *	<LOD	ND
Naphthalene *	0.067	ND
Phenanthrene *	1.251	ND
Anthracene *	0.193	ND
Fluoranthene *	2.016	ND
Benzo(a)anthracene *	0.911	ND
Chrysene *	0.659	0.025
Benzo(k)fluoranthene *	0.339	ND
Benzo(a)pyrene *	0.605	0.020
Benzo(g.h.i)perylene *	0.366	ND
Indeno(1.2.3-c.d)pyrene *	0.399	ND
Σ10-PAHs *	9.447	<0.254
Mineral oils *	1062	ND

Plastic waste streams

In a study conducted by the IVM/IVAM [28], plastic materials from end-of-life vehicles (ELV) and waste of electrical and electronic equipment (WEEE) in the Netherlands were analysed on the presence of the ZZS group of polybrominated diphenyl ethers (BDEs). The identified concentration ranges are reported in Table 15.

Table 15: Concentration range of POP-BDEs and BDE209 in a plastic recycling chain in the Netherlands [28,29].

Sample type	**Sector type**	**POP-BDEs (µg/g)**	**BDE209 (µg/g)**
Individual parts	ELV parts (EU)	<0.2	<1
	ELV parts (US/Asian)	<0.3-25,000	<2-23,000
	WEEE parts	<0.5-800	<3-72,000
Shredded material	ELV plastics	<0.1-11	0.2-70
	ELV and WEEE plastics (mixed)	<1-280	6-810
	WEEE plastics	<2-330	6-3300
Recycled material	Recycled plastic pellets	<0.7-67	5-210
New products manufactured from recycled plastics	Insulation/carpet padding	<0.001-0.04	0.01-0.08
	Office and kitchen products	<0.005	<0.03

Rubber waste streams

Recently, the RIVM published a report on the composition and health risks related to playing sports on rubber granulate fields [34]. Information on identified concentrations is provided in Table 16.

Table 16: Concentration of substances identified to be present in rubber granulate [34]. ZZS substances are marked with an asterisk (*).

Substance/substance group	**Percentage of samples above detection-limit**	**Concentration (mg/kg dry matter) (field-averages)**			**Maximum-values based on data from outside NL**
		Mediaan (P50)	**P90**	**Maximum**	
PAHs					
Phenanthrene *	38	<0.6	2.0	7.1	12.3
Anthracene *	5	<0.5	<0.5	1.1	11.9
Fluoranthene *	93	3.4	8.3	20.3	11.3
Pyrene *	98	7.5	23.6	28.7	37
Benzo(ghi)perylene *	62	4.1	6.5	7.7	29.2
Benzo(c)fluorene *	43	0.2	0.6	0.7	No data
Cyclopenta(cd)pyrene *	100	1.5	2.3	2.5	No data
benzo(a)anthracene *	27	<0.9	1.2	2.2	15.3
Benzo(b) + Benzo(j)fluoranthene[3] *	48	<1.2	1.8	3.0	15.7

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[3] Benzo(b) and benzo(j)fluoranthene cannot separately be quantified due to peak overlap.

Substance/substance group	Percentage of samples above detection-limit	Concentration (mg/kg dry matter) (field-averages)			Maximum-values based on data from outside NL
		Mediaan (P50)	P90	Maximum	
Benzo(k)fluoranthene *	1	<0.5	<0.5	0.5	7.3
Benzo(a)pyrene *	25	<1.1	1.3	2.2	10.7
Benzo(e)pyrene *	57	2.8	4.2	7.8	1.6
Chrysene *	57	1.3	1.9	3.5	7.6
Dibenzo(a,h)anthracene*	0	<0.5	<0.5	<0.5	8.1
Sum PAH (ECHA 8)[4]		5.8	10.9	19.8	
Phthalates					
Di-2-ethylhexylphthalate *	100	7.6	14.2	27.2	62
Di-isobutylphthalate *	17	<0.5	0.8	2.3	175
Di-isononylphthalate	77	35	53	61	78
Dicyclohexylphthalate *	47	0.1	0.2	0.2	Unknown
Di-n-nonylphthalate	37	0.5	0.8	0.8	Unknown
Diphenylphthalate	7	<0.1	<0.1	0.1	Unknown
Bis(2-ethylhexyl)adipate	63	0.3	0.7	1.1	Unknown
Benzothiazoles					
Benzothiazole	100	2.7	5.7	6.3	171
2-hydroxybenzothiazol	100	1.6	8.1	13.8	Unknown
2-mercaptobenzothiazol	100	2.6	6.3	7.6	No data
2-methoxybenzothiazol	100	2.6	9.7	10.2	Unknown
2-aminobenzothiazole	100	0.1	0.3	0.4	Unknown
N-cyclohexyl-1,3-benzothiazol- 2-amine	100	1.5	3.6	3.9	No data
2,2-dithiobis-(benzothiazol)	71	0.2	0.3	0.3	No data
N-cyclohexyl-2-benzothiazolsulfenamide	43	<0.02	0.04	0.04	No data
Phenols					
4-tert-octylphenol *	100	4.8	19.6	22.4	33.7
bisphenol-A *	100	0.5	2.0	2.5	Unknown
Polychlorinated biphenyls					
PCB's[5] *	29	<0.035	0.06	0.074	0.2

Waste streams of the construction sector
For certain substances limit values are established in stony material and are regulated under 'besluit bodemkwalitiet'. The content and leaching concentrations of several substances in stony material in the Netherlands were investigated in 2006 to evaluate the regulatory limit values. The highest identified concentrations are reported in Table 17 and Table 18 [46].

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[4] Benzo(a)pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, dibenzo(a,h)anthracene, benzo(j)fluoranthene, benzo(e)pyrene.

[5] Sum of PCB28, PCB52, PCB101, PCB118, PCB138, PCB153, PCB180.

Table 17: Content concentrations of several organic substances in stony material in the Netherlands in 2006. Only the maximum identified concentrations are shown [46]. ZZS substances are marked with an asterisk (*).

Substances	**mg/kg dw (Content)**
Benzene *	1.70
Ethyl benzene	1.10
Toluene	2.5
Xylenes (sum)	5.9
Phenol	62
Naphthalene *	7.8
Phenanthrene *	31
Anthracene *	5.9
Fluoranthene *	41
Chrysene *	13
Benz[a]anthracene *	16
Benzo[a]pyrene *	14
Benzo[k]fluoranthene *	7.8
Indeno [1,2,3-cd]pyrene *	11
Benzo[ghi]perylene *	10.0
PAHs (sum) *	130
Polychlorinated biphenyls (sum) *	270
Mineral Oil *	1400

Table 18: Leaching concentrations of several inorganic substances in stony material in the Netherlands in 2006. Only the maximum identified concentrations are shown [46]. ZZS substances are marked with an asterisk (*).

Substances	**mg/kg dw (Leaching concentration)**
Antimony	0.86
Arsenic	1.60
Barium	76
Cadmium *	0.0070
Chromium	6.7
Cobalt	0.090
Copper	17
Mercury *	0.0020
Lead *	1.60
Molybdenium	15
Nickel *	1.70
Selenium	2.4
Tin	0.14
Vanadium	4.2
Zinc	1.80
Fluoride	6.6
Chloride	7100
Sulphate	9100
Bromide	27

Annex II – ZZS waste management policy in LAP3

The Dutch draft National Waste Management Plan 2017-2029 (Ontwerp-LAP3) [2] describes the waste management policy for ZZS substances. Within this policy the assessment of the processing of ZZS waste is described within a step-wise approach, and considers the following waste types:

- Waste containing substances on the candidate list of REACH;
- Wastes that contain so-called 'other ZZS’;
- Waste containing POPs which are not listed in Annex IV of the POP Regulation;
- Waste containing substances on the authorization list of REACH and which are aimed to create objects.

The step-wise approach:
When the presence of certain ZZS substances in a waste stream is expected, and above a concentration limit for a certain application of a waste product or a recycled product, a risk assessment is required before permitting.

1. When waste materials contain ZZS substances which are already regulated within the POP- or REACH-Regulation, that policy is applicable;
2. Otherwise the Dutch national policy of LAP3 applies. From this risk assessment it must be clear that no ZZS-risks are involved for man and environment. The assessment involves the following aspects:
    a. Are there limit values available for the relevant application, for the ZZS substances of concern (in REACH, POP-Directive, a product regulation or within LAP3)? If risks may still be present after this initial assessment, proceed with the next steps.
    b. Are the ZZS substances sufficiently fixed within the material matrix?
    c. Is the specific application of the material assessed as acceptable?
    d. Is it possible to remove or destroy the ZZS substance(s) in a later phase of its life cycle, because the recycled material is easily traceable?

Currently, the risk assessment description within LAP3 only considers a general framework on how to assess the processing of such waste streams and needs further elaboration with more detailed instructions on how to execute such assessment.

RIVM
Committed to *health and sustainability*