Control of Substances of Very High Concern in Recycling

Review of techniques for detection, quantification and removal

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Review

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Preface

This study was commissioned by the Swedish Environmental Protection Agency and conducted by EnviroPlanning AB. The aim of this report was to provide an overview of existing and future techniques which can be used in industrial recycling processes to detect, quantify and/or remove substances of very high concern (SVHCs).

The study is part of an ongoing dialogue between the Swedish Environmental Protection Agency and the Swedish Chemicals Agency regarding how to increase material recycling without recirculating substances of concern. The scope and the focus of the report has been defined by the agencies, but the literature review and data collection have been conducted by EnviroPlanning AB. There has been a dialogue between the consultant and the agencies during the project period. However, the analysis, reasoning and conclusion presented in this report is the sole responsibility of the authors, EnviroPlanning AB. Any opinions and conclusions expressed in this report are those of the consultant and do not necessarily reflect or represent the views or opinions of the Swedish Environmental Protection Agency and/or the Swedish Chemicals Agency.

The authors of this report and project participants were Helena Norin (project leader), Hanna Oskarsson, Malin Brodin and Maja Halling, EnviroPlanning AB and Rickard Sallermo, Ensucon AB. Technical review of the report was performed by Martijn van Praagh, ÅF Infrastructure, Environment.

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Summary

Chemical substances, including substances hazardous to the environment and/or human health, can enter recycling processes through articles and mixtures which become waste. Some substances have such hazardous properties that they should, as far as possible, be phased out. Of special interest are Substances of Very High Concern (SVHCs), as defined in REACH, as well as cadmium, mercury and lead. Once in the recycling process, there is a possibility that hazardous substances, including SVHCs, end up in the recycled material, and hence recirculated into new products.

The aim of this report is to provide an accessible review of techniques that can be used to control SVHCs in recycling processes. This includes techniques that can detect, quantify and/or remove hazardous substances in any of the different steps during a recycling process. The review is intended to provide information in a clear and comprehensible manner and to be easily accessible for work regarding instruments and actions for phasing out SVHC in recycling processes.

Literature and interview studies were performed to investigate available and coming techniques. A large number of different possible techniques of interest for the study were initially identified. Of these, a certain number were selected, primarily based on their applicability with regard to the set requirements (i.e. to detect, quantify and/or remove hazardous substances and SVHCs), as well as the frequency with which the techniques were mentioned in the literature and in interviews. Hence, techniques that were only mentioned briefly or by single references were generally not selected for further investigation. The results from the study are presented as technical summaries, in Appendix 1.

The review showed that there are a number of available techniques that perform control of different hazardous substances, although sometimes as a valuable side effect from sorting material streams into more homogeneous fractions. Mechanical recycling is the predominant type of recycling today, although several initiatives are developing techniques for chemical recycling. It was, however, difficult to evaluate the potential of the chemical recycling techniques with regard to control of SVHCs.

Other aspects revealed during the interviews include difficulties with regard to limited markets for recycled materials, a need for policy action regarding stricter regulations and lower limit values for SVHCs and other hazardous substances in articles and mixtures, as well as a need for testing standards with recommendations for continuous measurements with SVHC-specific techniques.

Aims and Scope

The aim of this report is to provide an accessible review of techniques that can be used to control SVHCs in recycling processes. This includes techniques that can either detect, quantify and/or remove SVHCs in different steps of recycling processes.

The report includes a review and description of available techniques, as well as an assessment of techniques that can be predicted to be commercially available within a five to ten-year period.

Most of the available techniques are not sufficiently specific to control substances with SVHC properties. Some of these techniques can, however, be used to control materials or hazardous substances that can indicate the presence of SVHCs. Control of substances that can be used as indications of SVHCs has therefore also been included in the report.

The review focuses on material streams of plastics, metals, textiles, rubber, glass and paper/paperboard. Waste streams in focus in relation to these material streams were packaging, silage stretch film, batteries, end-of-life vehicles (ELV), electrical and electronic equipment (WEEE) including light bulbs and certain luminaires, tyres, recycled paper, office paper and construction and demolition (C&D) waste.

Background

Hazardous substances in waste

The manufacturing processes for the vast number of articles and mixtures in modern society involve a large number of chemicals, from pesticides used in cotton cultivation to process chemicals and various additives for desired properties of produced materials, such as plasticisers, colourants and fire retardants. Many of the chemicals used in manufacturing remain in the material when it reaches the consumer and are therefore also present when the material has reached its end of life and is discarded as waste (RISE Research Institutes of Sweden, 2019, Swerea IVF, 2018).

The use of hazardous substances, including SVHCs, in articles and mixtures is associated with certain requirements and regulations. Nevertheless, the substances may still be legal for specific purposes and therefore end up in waste streams and possibly also in recycled materials. An example is waste electrical and electronic equipment (WEEE), which may contain problematic substances regulated by the RoHS Directive, such as cadmium, chromium, lead, phthalates and brominated flame retardants (BFRs) (Nordic Council of Ministers, 2017). Recycled material from these waste streams has been shown to contain some of these regulated substances, although often in concentrations below the regulatory limit (RISE Research Institutes of Sweden, 2019). In addition, repeated inspections by the Swedish Chemicals Agency show that restricted substances are used in imported articles on the Swedish market (Swedish Chemicals Agency, 2019). Furthermore, substances that are now restricted may still occur in articles and mixtures manufactured prior to the present regulations and will consequently enter the waste and recycling streams in the future.

The issue of SVHCs in waste and recycling has received increasing attention in recent years. The European Chemicals Agency (ECHA) is, for example, in the process of establishing a database concerning the presence of SVHCs in articles, which will be in use by 2021. The aim of the database is to improve the risk management of chemicals during waste recovery and to promote non-toxic material cycles.

Control of hazardous chemicals is to some extent regulated through the Waste Framework Directive (Directive 2008/98/EC). Waste should always be classified according to the European list of waste. The European Commission has developed guidance documents to make it easier for the waste generator to classify correctly. The classification system is based on the CLP Regulation (Regulation (EC) No 1272/2008) for the content of hazardous chemicals. Waste can be hazardous or non-hazardous. A special case is persistent organic pollutants (POPs) identified in the Stockholm Convention, which contains specific limits that shall not be exceeded.

Definition of hazardous substances

The term hazardous substances relates to chemical substances classified as hazardous (to health or the environment) according to the CLP Regulation (Regulation (EC) No 1272/2008) and to substances that meet the criteria of the CLP Regulation, but are not yet classified.

Definition of Substances of Very High Concern

Substances identified as SVHC have properties that could be so hazardous to human health and the environment that they ought to be phased out and replaced by other substances (Swedish Ministry of the Environment, 2012).

The definition of SVHC in this report corresponds to Article 57 of the REACH Regulation No 1907/2006, which includes: substances that are cancerogenic, mutagenic or toxic for reproduction, i.e. CMR 1A/1B, in accordance with the CLP Regulation (Regulation (EC) No 1272/2008); substances that are persistent, bioaccumulative and toxic (PBT), or very persistent and very bioaccumulative (vPvB), according to criteria set in Annex XIII to the REACH Regulation; and other substances for which there is an equivalent level of concern and scientific evidence of probable serious effects on human health or the environment.

The definition in this report also includes endocrine disruptive substances and strongly allergenic substances, as well as the heavy metals mercury, cadmium and lead, as included in the definition of SVHC by the Swedish Ministry of the Environment (Swedish Ministry of the Environment, 2012).

Methods

Collection of information

To identify present and coming techniques in recycling processes that have the potential to control hazardous substances or SVHCs, deliberately or as a side effect during the process, a literature review in combination with an interview study was performed.

The interviews were performed as semi-structured interviews in digital meetings or by telephone during the autumn of 2019. One interview was conducted by e-mail. Representatives from different sectors associated with the recycling industry in Sweden were interviewed, including recycling industries, professional organisations, sales sectors and research and educational institutes (Table 1). Some of the interviewees represented organisations operating in several European countries. A total number of 20 interviews were performed. The interviews were not intended to be used for specific citations, and the interviewed representatives are therefore not named in this report or in the technical summaries. For greater readability, references were not added within the technical summaries, however all literature references used are listed in the reference list at the end of this report, for more in-depth reading.

Table 1. Organisations from which representatives were interviewed, organised by sector and alphabetical order. Three representatives from RISE were interviewed, while one representative from each of the remaining organisations was interviewed.

Sector	Organisation
Sorting facilities and recycling industries	Fiskeby, Ragn-Sells, re:newcell, Renova, STENA recycling international, Svensk glasåtervinning, VanWerven Plastic recycling, Wargön Innovation
Industry associations	BASTA, Bil Sweden, SDAB, Svensk Ensilageplast Retur, Sveriges byggindustrier
Research and education institutes	RISE, Swedish School of Textiles, Trollboken
Sales sector	Holger Andreasen AB, Tarkett

A total of 85 techniques related to recycling were identified during the review process. Of these, 29 techniques were selected for further description in the report (Table 2, Appendix 1). The selection was primarily based on the techniques' potential to detect, quantify and/or remove SVHCs, but also on their technical and commercial readiness, as well as frequency of mention in the literature and in interviews. Hence, techniques that were only mentioned briefly or in single references were generally not selected for further investigation. Some techniques were difficult to separate due to ambiguous terminology in the previous literature and in interviews (e.g. some chemical recycling techniques) and were therefore grouped. The same was done for those laboratory analysis techniques that are described in detail elsewhere.

The collected information of each identified technique was summarised and presented in technical summaries, each presenting core information of one technique or a few related techniques each (Appendix 1). The selection of relevant techniques and assembly into groups resulted in a total of 21 technical summaries, further described in the section headed 'The technical summaries'.

Limitations

The literature study was mainly based on reports and reviews from authorities, independent organisations and research institutes. The project did not focus on the scientific literature, as the aim was not to describe techniques in detail but to provide an overview of available and coming techniques.

During the initial review process, a large number of techniques were suggested during interviews and identified in the literature. Techniques that were not found to have potential to control SVHCs or materials and other hazardous substances that can indicate presence of SVHCs were excluded from further investigation. Techniques suggested during the review process but not included in technical summaries were listed separately (Appendix 2). Appendix 2 also lists techniques that were excluded due to assessed limited commercial potential in the near future (5-10 years) or limited available information to assess the potential of controlling for SVHCs in recycling processes.

The project has focused on use and development of recycling techniques in Europe, and techniques used outside Europe were therefore excluded from further investigation but listed in Appendix 2.

For some techniques, a limited amount of information could be retrieved through the literature and complementing interviews, sometimes due to corporate confidentiality. In such cases the technique has not been described in a separate technical summary but is mentioned elsewhere in the text. Nor does the report portray specific projects or pilot plants as separate techniques, if such techniques could be described in more general terms within the scope of other technical summaries.

The technical summaries

This information is also available in Appendix 1.

The findings of the literature and interview studies are presented in technical summaries, Appendix 1, as well as being summarised in Table 2 of this report. The concept of the technical sheets is intended to be a user-friendly guide, an accessible review of the topic. Present-day techniques in the recycling industry are generally not specific to intended identification or removal of SVHCs, and control of SVHCs is often a result for example of 'co-removal' during sorting processes aimed at producing homogenous material streams. The technical summaries are nonetheless intended to provide a review of present-day techniques with potential to control SVHCs in different material types and waste streams, as well as assessments of when new techniques might be in commercial and industrial use. The intention has not been to provide in-depth insight into each technique, but to provide a summary, a stand-alone guide of the technical prerequisites for recycling of different material types and waste streams.

A few techniques have been organised into general groups (dissolution-based chemical recycling, thermal recycling, extractive metallurgy and laboratory analysis techniques), while all other techniques are presented in separate summaries.

Reading guide to Appendix 1 and table 2

All techniques are described with a brief summary at the top headed ‘At a Glimpse’, including the main properties of the respective techniques. The collected information from the literature and interview studies has been organised under different headings, similar for all techniques. The type of information of each heading is described below.

RECYCLING STREAM

‘Recycling stream’ refers to examples of both waste and material streams that the technique can be applied to, for example plastics and/or ELV.

HAZARDOUS SUBSTANCEs

‘Hazardous substances’ refers to examples of which types of SVHC can be controlled by the technique. It also includes materials or other hazardous substances that can be indications of SVHCs and controlled by the technique.

APPLICATION

‘Application’ refers to what the technique is used for in the recycling industry. Some techniques can be used for several purposes, and the terminology found during the literature and interview review regarding these was sometimes ambiguous. Some techniques that are used for detection are often referred to as sorting techniques, while some techniques for sorting indirectly can be used for removal of material with SVHC. Several techniques have therefore been classified for multiple applications. The following applications were used:

- Detection techniques: techniques that can detect certain substances, including SVHCs, in material streams, but are reliant on other techniques, such as air jets, for the actual sorting.
- Quantification techniques: techniques that can quantify the amount of certain substances, including SVHCs, in material streams.

- Sorting techniques: i) techniques that sort incoming waste materials into more homogenous fractions, based on different material properties, and therefore can also indirectly identify or detect materials with SVHC; and ii) techniques that can detect certain substances, including SVHC, but are reliant on other techniques for the actual sorting.
- Removal techniques: i) techniques that have the potential to eliminate SVHCs from material streams; and ii) techniques that can separate (sort) material fractions with possible SVHC content and hence potentially be used to remove these fractions from re-circulation.

TECHNICAL READINESS

'Technical readiness' refers to whether the identified technique is in commercial use today ('in use'), or whether it is estimated to be in commercial use within a short period of time ('in use within 5 – 10 years').

DESCRIPTION

This section provides a short description of the technique, its areas of use, what materials and waste streams the technique is applicable to, as well as which SVHCs, materials or hazardous substances indicating presence of SVHC can be either detected, quantified, sorted or removed using the technique.

FUTURE POTENTIAL

'Future potential' refers to an assessment of the technique's potential to be in industrial use, potential developments and/or potential for control of SVHCs.

ACCURACY

'Accuracy' refers to assessments of the technique's accuracy in controlling SVHCs, including precision with which the technique can identify or indicate the presence of an SVHC (as an element, as a group, or as a specific regulated compound), as well as precision in quantification, such as detection limits.

ADVANTAGES AND LIMITATIONS

'Advantages and limitations' refers to different aspects of the techniques that were identified during the review, for example costs, risks associated with handling of the equipment and difficulties associated with the technique.

Techniques for control of hazardous substances in recycling

Material recycling processes

Material recycling is the process of turning collected waste into new materials and products. It is preferred to energy recovery in accordance with the waste management hierarchy presented in the Waste Framework Directive (Directive 2008/98/EC). Material recycling is furthermore a necessity for circular economy, aspired by the European Union and described in Closing the loop – An EU action plan for the Circular Economy (European Commission, 2015). Collected waste destined for material recycling goes through several steps and possibly several facilities before the desired material has been separated and made available for use in new products.

There are several waste streams that are industrially recycled into new products at present, such as specific plastics, metals and certain paper grades. It is important that these streams are safe to use (Swedish Chemicals Agency, 2012) and of good and even quality to enable their use in new products. Different sorting steps are combined to separate different materials and to make these valuable recycling streams as clean as possible. It is common for residual fractions produced during the recycling process to be destined for either energy recovery, construction material or landfill. Such fractions can for example be what are known as 'fines' from end-of-life vehicles, which can include rust, glass fragments, sand and gravel less than 7 mm; certain fractions containing hazardous substances such as high level of chlorine; plastics from electronic devices, textile fractions and separated plastic fractions in paper and paperboard recycling.

Mechanical recycling

The term mechanical recycling is often used to describe the dominant material recycling processes today. Mechanical, physical and thermal techniques are all used in mechanical recycling.

It is common to handle different incoming waste streams of plastics, metals, textiles, rubber, glass and paper/paperboard in relatively similar ways, a process that often starts with combinations of various steps of sorting and size reductions, where different materials in a waste stream are separated from each other to obtain more homogeneous fractions of waste for further processing.

For several waste streams, initial manual sorting takes place before the next steps in the process. Examples are dismantling of end-of-life vehicles (ELV) and manual removal of valuable metals from waste of electrical and electronic equipment (WEEE), but also removal of larger pieces of foreign materials and contaminations from the waste stream, as for all of the materials in focus: plastics, metals, textiles, rubber, glass and paper/paperboard recycling. For plastics and metals, manual sorting is often combined with different screening techniques such as X-ray techniques or infrared spectrometry techniques, while sorting of glass, for example, is often combined with camera techniques using colour as indications for sorting.

Different screening techniques are further used as automated sorting techniques in online processes, coupled for example with air-jet separation, or used in combination with sorting steps such as magnetic separation and density separation. Some of the automatic techniques can be applied both before and after shredding or grinding the materials into smaller pieces. Such screening techniques can also be used to verify a successful sorting process (Swerea, 2018).

In the present-day recycling industry, some facilities focus on sorting incoming waste material into more homogeneous fractions, while other facilities perform the subsequent processing steps and packaging of well-separated recycled materials, and yet other facilities perform both sorting steps and recycling steps. The distinction between such sorting facilities and other recycling facilities is not clear, and many of the sorting steps can be performed at either type of facility.

Chemical recycling

The term chemical recycling refers to a number of processes used to degrade the chemical structure of polymers and/or to separate polymers by chemical methods. Different chemical recycling schemes can be applied to plastic polymers (including plastic textile fibres) and polysaccharides (typically being cellulosic textile fibres such as cotton, viscose and rayon).

The terminology in chemical recycling is not harmonised, and terms used for different chemical recycling techniques include chemical depolymerisation, thermal depolymerisation, solvolysis and solvent extraction. The terms are sometimes intertwined and sometimes used differently by different people.

The chemical recycling techniques can be roughly divided into two groups. In the thermal techniques (such as pyrolysis and gasification), the polymers are depolymerised into chemical building blocks or monomers that can be further cracked or fractionated through additional processes. These thermal techniques have potential to recycle most plastic recycling streams (Thunman *et al*., 2019). The solvent-based techniques use specific solvent systems to dissolve polymers so that these can be separated from other materials (Keith *et al*., 2016; Palme *et al*., 2017). This can be especially useful for mixed materials such as composites, textiles and plastic laminates. Some polymers need to be depolymerised (i.e. chemical depolymerisation) to be dissolved, whereas others are soluble in their polymeric form in specific solvents (Palme *et al*. 2017; Le, 2018). These techniques are sometimes referred to as solvolysis or solvent-based extraction processes.

The chemical recycling techniques are still immature, and most initiatives are at pilot scale in Europe, such as re:newcell (textiles) and CreaSolve (plastics). There are nevertheless a few commercial facilities, predominantly outside of Europe. Chemical recycling techniques are attracting attention in the recycling industry since they have potential to recycle waste streams that are not used for material recycling at present, such as most textiles and composites and some plastic types (Job *et al*., 2016; Keith *et al*., 2016; Thunman *et al*., 2019; Palme *et al*., 2017).

Screening, detection and quantification

This review shows that a number of different techniques are used in the recycling industry today for screening of certain substances, often to ensure that prior sorting processes have been performed adequately. Such screening techniques can also be used to identify SVHCs, or for indications of potential presence of SVHCs. Screening refers to detection techniques that can be used in online processes, and these can often also be used for approximate quantifications. A requirement for such screening and semi-quantitative techniques is that they are quick, with adequate accuracy. However, laboratory destructive analyses are required for measurements and quantifications of high accuracy. Such methods are generally more expensive and time-consuming, limiting the potential for using them in online processes or for continuous sampling.

Online screening techniques are also used for sorting of incoming materials into more homogeneous fractions to improve the subsequent recycling processes. In these sorting steps, some materials that can contain SVHCs are sorted out and removed, and their removal is hence a side-effect from material sorting.

Techniques in use and technical developments

Based on the review of this project, the present techniques for mechanical recycling appear to be similar across Europe, with no clear differences between countries. There are ongoing projects regarding chemical recycling techniques in several different European countries with pilot plants (existing or under construction in 2019) for chemical recycling of textiles in Sweden (re:newcell), Finland (Ioncell F) and the Netherlands (Sax-cell), and for recycling of plastics in the Netherlands (CreaSolve), Germany (Newcycling technology), Switzerland (GR3N), Italy (Aquafil, headquarter), France (Soprema, Carbios) and the UK (perPETual) (Swedish Environmental Protection Agency, 2015, Zero waste Europe, 2019). The different techniques for chemical recycling used in these projects are classified in the general category of ‘dissolution-based chemical recycling’ in the report, and are not further described separately (Table 2, Appendix 1).

Review of present and future techniques

The results from the literature and interview studies are presented as technical summaries in Appendix 1, with a summary presented below (Table 2).

Based on the definitions in the methods section, the 21 techniques or groups of techniques identified in this review were classified according to four areas of applications (detection, quantification, sorting and removal).

- X-ray techniques, spectroscopic techniques, RFID and QR, were classified as techniques for detection, quantification and sorting.
- Laboratory analyses were classified as techniques for detection and quantification
- The droplet test was classified as a detection technique.
- Manual sorting, density sorting, magnetic separation and melt filtration were classified as sorting and removal techniques, and
- Citric/acetic acid, deinking processes, thermal depolymerisation, dissolution-based chemical recycling and extractive metallurgy were classified as removal techniques.

In general terms, the review shows that the X-ray techniques (ED-XRF, WD-XRF and XRT) are readily available tools to detect elements of interest for control of SVHC, such as the halogens bromine and chlorine and to some extent fluorine. However, these techniques are unspecific with regard to SVHCs and can only be used as indications. For more detailed information on specific compounds, for example which BFRs are present in a material stream, it can be useful to employ the different spectroscopic techniques identified (NIR, FT-IR, sliding spark spectroscopy, LIBS or Raman spectroscopy). The droplet technique was identified as a technique that could be used to detect perfluorinated substances but is non-specific with regard to which perfluorinated compound.

For specific quantifications of high accuracy in the recycling industry today, it is necessary to apply laboratory analyses, as the online quantification techniques (X-ray techniques, and spectroscopic techniques) can be regarded as semi-quantitative in comparison to laboratory techniques. RFID and QR codes could be a future option for high-accuracy online detection and quantification.

The current detection and sorting techniques can generally be used for removal of metal-containing fractions, which could result in removal of SVHCs such as the heavy metals cadmium, chromium, lead and mercury. Most of these techniques can also be used to remove fractions with halogenated compounds such as BFRs, or fractions with halogens, as indications of the presence of SVHC or other hazardous substances.

The majority of identified techniques in this review with potential to control SVHCs were applicable to plastic recycling. Several techniques applicable to metal and textile were also identified, while fewer were identified for rubber, glass and paper/paperboard.

Table 2. Summary of the techniques described in Appendix 1, listed by type of application. The table includes information regarding: i) Recycling streams (examples of material streams and waste streams applicable to each technique); ii) Application (detection of SVHC, quantification of SVHC, sorting of materials into fractions and/or removal of SVHC); iii) SVHC (which SVHC, or SVHC-indicative material or element, can be detected, quantified, sorted and/or removed from the recycling process by the technique); and iv) Reference to page with further description of the technique in the technical summaries (Appendix 1).

*** Assessed technical readiness within 5–10 years. Other techniques are in industrial use today.**

+ No available data to assess technical readiness.

	Recycling streams							Application				SVHCs	
Recycling technique	Plastics	Metals	Textiles	Rubber	Glass	Paper / Paperboard	Waste streams	Detection	Quantification	Material sorting	Removal	Examples of controlled substances	Page, Appendix1
Manual sorting	x	x	x	x	x	x	Several waste streams			x	x	Materials with SVHCs	4
Density separation	x						WEEE ELV C&D			x	x	PVC, plasticisers, BPA, BFRs, heavy metals	5
Magnetic separation		x					WEEE ELV C&D	x		x	x	Ferromagnetic metals, such as cobalt	6
Melt filtration	x						WEEE ELV			x	x	Phenol formaldehyde and epoxy plastics	7
ED-XRF	x	x	x				WEEE ELV C&D	x	x	x		Heavy metals, bromine, chlorine	8
WD-XRF	x	x	x				WEEE ELV C&D	x	x	x		Heavy metals, bromine, chlorine, fluorine	9
XRT	x	x						x	x	x		Heavy metals and bromine	10
NIR	x					x	WEEE C&D	x	x	x		BFRs and plastic types such as HDPE	11
FT-IR	x		x					x	x	x		BFRs	12

	Recycling streams							Application				SVHCs	
Recycling technique	Plastics	Metals	Textiles	Rubber	Glass	Paper / Paperboard	Waste streams	Detection	Quantification	Material sorting	Removal	Examples of controlled substances	Page, Appendix1
Sliding spark spectroscopy	x							x	x	x		BFRs, PFOS and PVC	13
LIBS	x	x					WEEE	x	x	x		Can potentially detect all elements	14
Raman spectroscopy*	x		x					x	x	x		BFRs	15
RFID*			x				Clothes and other textiles	x	x	x		Any, known at the time of manufacturing	16
QR*			x				Clothes and other textiles	x	x	x		Any, known at the time of manufacturing	17
Droplet test*			x					x		x		Perfluorinated substances	18
Laboratory analyses, incl. GC, GC/MS, Pyro-GC/MS, TED GC/MS, HPLC	x	x	x	x	x	x	Most waste streams	x	x			A large number of organic and inorganic substances	19
Citric acid / acetic acid^{+}					x						x	Heavy metals	20
Deinking processes							x				x	Heavy metals and contaminants such as BPA, DEHP	21
Thermal depolymerisation techniques*, incl. pyrolysis and gasification	x		x	x		x					x	Potentially removes hazardous substances and SVHCs	22
Dissolution-based chemical recycling, incl. solvent-based extraction, chemical depolymerisation and solvolysis	x		x								x	Potentially removes hazardous substances and SVHCs	23
Extractive metallurgy, incl. pyrometallurgical and hydrometall-urgical methods		x					Batteries WEEE				x	Heavy metals	24

Reflections

Removal of Substances of Very High Concern – a valuable side effect

This review was able to identify a large number of different techniques involved in different types of recycling processes and to show that several processes in use today have potential to control SVHCs during recycling processes. This includes techniques to detect, quantify, sort and/or remove material fractions containing problematic substances, including SVHCs. Some examples are heavy metals, halogens and brominated flame retardants that can be identified by several types of screening techniques. Removal of SVHCs from waste fractions is, however, in most cases a side effect from sorting the material into homogeneous fractions more suited for further recycling processes. The initial sorting steps in the recycling process, such as manual sorting and dismantling, as well as density separation in combination with common automatic screening techniques, appear to be effective in removing problematic materials and fractions. If not further separated or sorted, residual fractions resulting from such separation are likely to be destined for either energy recovery or landfill.

Few techniques, other than laboratory analyses, are used for the specific purpose of controlling SVHCs in recycling processes. Problematic substances bound to waste material could therefore risk to be overlooked and recirculated into new articles.

Difficult to judge the potential of chemical recycling

Chemical recycling was suggested during some interviews as a promising area of technological development, particularly in the textile and plastic recycling industries. The future potential for chemical recycling was assessed by the interviewed representatives as being lower for waste streams with metals, for tyres and for heterogeneous waste streams such as ELV, WEEE and C & D waste. It was, however, judged to be a possible future complement to more traditional mechanical recycling, which according to experience is easier, already established, and capable of handling large volumes of waste. Several interviewed representatives assessed chemical recycling as being expensive in comparison to present-day mechanical techniques. Arguments used were large industrial investments necessary to enable commercial chemical recycling, lack of raw material to effectively run the processes, as well as probable high costs of running chemical recycling processes. Another argument presented was a weaker market for recycled material as virgin materials often command lower prices, in more specified grades and with more information regarding ingoing substances. No estimation of actual costs for chemical recycling techniques in comparison to mechanical techniques could be determined during the review.

Being a relatively new field, the techniques involved in pilot projects of chemical recycling were often not described in detail. Although it is often claimed that chemical recycling has the potential to remove a number of hazardous substances and contaminations, it was difficult to assess which substances could be removed in which processes, and to what extent. A parallel can be drawn to the often mentioned advantage of chemical recycling of dealing with heterogeneous waste streams, as identified during the initial literature study for this project. During the subsequent interview study it appeared, however, that, as in mechanical recycling, the chemical recycling techniques work better with homogeneous waste streams of known content.

Urging of policy action and testing standards

Representatives from the recycling industry pointed out that although technical developments results in improved sorting and recycling, a question remains regarding what to do with separated fractions that contain hazardous substances and SVHCs.

Several of the interviewed representatives pointed out the need for legislative changes, such as stricter limit values for hazardous substances in articles and mixtures in general, to enforce a shift towards less hazardous substances in virgin material, as this is the source of hazardous substances in waste.

A general improvement that several of the interviewed representatives asked for was, however, standards for sampling routines and testing frequency. As some techniques and options for detection, sorting and removal of certain hazardous substances already exist, available guidelines on how and when to sample and analyse for unwanted substances in the recycling streams could facilitate the process and significantly improve overall control.

Future potential for control of SVHC in recycling processes

This review shows that there is potential to control SVHCs in present-day recycling techniques, but also that several available techniques control for similar substances and that it is difficult to use available techniques for efficient removal of SVHCs and simultaneous efficient recycling of valuable materials.

Several of the interviewed representatives pointed out that future recycling will most probably have to combine different techniques during the entire recycling process, from sorting to detection and removal, to better control SVHCs and other hazardous substances in recycled materials.

A final conclusion from both literature and interview studies is that the future in recycling seems to lie in neither mechanical nor chemical recycling techniques, but in combinations of the two. Chemical recycling has the potential to increase recycling of waste streams and materials that are difficult to recycle with present-day mechanical techniques. In combination with established mechanical techniques, the options for increased control of SVHCs as well as increased recycling using both mechanical and chemical techniques offer promising potential.

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Appendix 1. Technical summaries

This document is an appendix to the report 'Control of Substances of Very High Concern in Recycling', describing present and future techniques for detection, quantification and/or removal of Substances of Very High Concern (SVHC) during recycling processes.

Contents

Introduction

The major findings of the literature and interview studies are presented in technical summaries, Appendix 1, as well as being summarised in Table 2 of the report.

The concept of the technical sheets is intended to be a user-friendly guide, an accessible review of the topic. Present-day techniques in the recycling industry are generally not specific to intended identification or removal of SVHCs, and control of SVHCs is often a result for example of ‘co-removal’ during sorting processes aimed at producing homogeneous material streams. The technical summaries are nonetheless intended to be a review of present-day techniques with the potential to control for SVHCs in different material types and waste streams, as well as assessments of when new techniques might be in commercial and industrial use. The intention has not been to provide in-depth insight into each technique, but to provide a summary, a stand-alone guide of the technical prerequisites for recycling of different material types and waste streams.

A few techniques have been organised into general groups (dissolution-based chemical recycling, thermal recycling, extractive metallurgy and laboratory analysis techniques), while all other techniques are presented in separate summaries.

Reading guide to the technical summaries

All the techniques are described with a brief summary at the top headed “At a Glimpse”, including the main properties of the techniques concerned. The collected information from the literature and interview studies has been organised under different headings, similarly for all techniques. The type of information of each heading is described below.

RECYCLING STREAM

‘Recycling stream’ refers to examples of both waste and materials streams that the technique can be applied to, for example plastics and/or ELV.

HAZARDOUS SUBSTANCE*S*

‘Hazardous substances’ refers to examples of which types of SVHC can be controlled by the technique. It also includes materials or other hazardous substances that can be indications of SVHCs and controlled by the technique.

APPLICATION

‘Application’ refers to what the technique is used for in the recycling industry. Some techniques can be used for several purposes, and the terminology used during the literature and interview review regarding these was sometimes ambiguous. Some techniques that are used for detection are often referred to as sorting techniques, while some techniques for sorting indirectly can be used for removal of material with SVHCs. Several techniques have therefore been classified for multiple applications.

The following applications were used:

- Detection techniques: techniques that can detect certain substances, including SVHCs, in material streams, but are reliant on other techniques, such as air jets, for the actual sorting.

- Quantification techniques: techniques that can quantify the level of certain substances, including SVHCs, in material streams.
- Sorting techniques: i) techniques that sort incoming waste materials into more homogeneous fractions, based on different material properties, and therefore also indirectly can identify or detect materials with SVHCs; and ii) techniques that can detect certain substances, including SVHCs, but are reliant on other techniques for the actual sorting, often referred to as sorting techniques.
- Removal techniques: i) techniques that have the potential to eliminate SVHCs from material streams; and ii) techniques that can separate (sort) material fractions with possible SVHC content and therefore potentially can be used to remove these fractions from re-circulation.

TECHNICAL READINESS
'Technical readiness' refers to whether the identified technique is in commercial use today ('in use'), or whether it is estimated to be in commercial use within a short period of time ('within 5 – 10 years').

DESCRIPTION
This section provides a short description of the technique, its areas of use in the recycling industry, what materials and waste streams the technique is applicable to, and which SVHCs, materials or hazardous substances indicating presence of SVHCs can be either detected, quantified, sorted or removed using the technique.

FUTURE POTENTIAL
'Future potential' refers to an assessment of the technique's potential to be a technique in industrial use, potential for development and/or potential for control of SVHCs.

ACCURACY
'Accuracy' refers to assessments of the technique's accuracy in controlling SVHCs, including the precision with which the technique can identify or indicate the presence of an SVHC (as an element, as a group, or as a specific regulated compound), as well as precision in quantification, such as detection limits.

ADVANTAGES AND LIMITATIONS
'Advantages and limitations' refers to different aspects of the techniques that were identified during the review, for example costs, risks associated with handling of the equipment and difficulties associated with the technique.

MANUAL SORTING

AT A GLIMPSE

Recycling stream:	e.g. plastics, textiles, tyres and glass from several waste streams
Hazardous substances:	Parts and materials with known presence of SVHCs

Application	Technical readiness
☐ Detection	☒ In use
☐ Quantification	☐ In use within 5 – 10 years
☒ Material sorting	Main advantages: Sort out materials that cannot be separated by automatic processes, high accuracy.
☒ Removal	Main limitations: Labour-intensive and costly. Requires available information on the content of hazardous substances.

DESCRIPTION

Manual sorting, also referred to as manual disassembly or ocular assessment, includes material sorting and removal of parts as a preparatory treatment prior to further separation or recycling[1 2]. It is also used as a sorting technique for parts that cannot be separated by automatic processes[3]. Manual sorting is mainly performed to form more homogeneous material streams[4 5] but is also a means of removing contaminations such as foreign materials or problematic materials from the incoming waste stream, such as TV covers and computer screens in waste electrical and electronic equipment (WEEE)[6 7] and dismantling of specific parts in end-of-life vehicles (ELVs)[8]. The technique can include application of hand-held tools or larger aids such as excavators or cranes[9 10]. Directions on where to find parts that should be removed can sometimes be found in staff guidance documents[11], but this is often acquired knowledge on the part of the operator[12]. It is normally followed by further separation techniques such as density separation and screening techniques[13]. Manual sorting is used, for example, to remove parts with heavy metals such as cadmium, chromium and lead, as well as phthalates and BFRs[14].

TECHNICAL READINESS

Manual sorting is in commercial use in several recycling industries but is used to a varying extent depending on the waste and material streams[15 16 17]. It is used, for example, for removal of parts and items containing batteries in small domestic appliances and for sorting of refrigerators based on coolant and plays an important role in identifying and separating plastic components containing SVHCs or other hazardous substances[18 19]. The present-day textile recycling industry is reliant on manual sorting to single out textiles of certain materials suitable for the recycling processes concerned[20 21].

FUTURE POTENTIAL

On the one hand manual sorting is expected to be replaced by automatic sorting techniques in the near future using, for example, image recognition, infrared techniques and fast-picking robot arms[22]. On the other hand, plastics from ELVs and rubber from tyres, for example, could be recycled to a greater extent and in more homogeneous material streams, if manually dismantled or manually sorted to a greater degree before shredding[23 24].

ACCURACY

Manual sorting has high reliability and produces a larger fraction of material of high quality, and a lower fraction destined for incineration, than automatic screening techniques. Manual sorting can, for example, classify incoming plastic material into more fractions than automatic separation techniques[25].

ADVANTAGES AND LIMITATIONS

Manual sorting enables the recycling industry to sort out materials that cannot be separated by automatic processes, and to sort out a larger fraction of each material type, i.e. it results in a higher yield[26]. By removing specific parts with known hazardous substances before initiating shredding and grinding processes, the industry can avoid hazardous substances being mixed with other waste fractions, as these can be more difficult to remove at a later stage[27]. Manual sorting can also handle black plastics, which is not possible to the same extent with automatic processes[28]. Manual processes cannot, however, separate small pieces, and are labour intensive and costly. They might also be problematic from an occupational health perspective[29].

DENSITY SEPARATION

AT A GLIMPSE

Recycling stream:	Plastics and other materials from complex waste streams, for example WEEE, ELV, C&D
Hazardous substances:	e.g. heavy metals, plasticisers, PVC, BPA, BFRs
Application	Technical readiness
☐ Detection	☒ In use
☐ Quantification	☐ In use within 5 – 10 years
☒ Material sorting	
☒ Removal	Main advantages: Quick, effective and non-expensive.
	Main limitations: Limitations in precision, requires pre-removal of material that absorbs water.

DESCRIPTION

Also known as floatation, sink-float or bulk separation, density separation is a wet process that separates materials based on their density, as heavier materials sink in a bath medium, while lighter materials float[30]. The technique can separate different materials such as plastics, metals, rubber and glass but can also separate different plastic polymer types and different polymer grades from each other, such as HDPE, PP and PE (which float) from PET, PVC and impurities (which sink) [31] [32] [33] [34] [35]. The technique is used to remove undesired fractions for further separation[36] or destruction by incineration[37]. By separating different materials by density separation, materials with hazardous substances can be removed in the process, such as plastics containing brominated flame retardants, phthalates, lead, PVC and bisphenol A (BPA).[38]

TECHNICAL READINESS

The technique is in industrial and commercial use for complex waste streams, including waste electrical and electronic equipment (WEEE), end-of-life vehicles (ELVs), municipal scrap and construction and demolition (C&D) waste. The technique is widely used to separate brominated plastics from non-brominated plastics[39] [40].

FUTURE POTENTIAL

The technique is already well developed, but there is ongoing research regarding the potential to extract the remaining part of pure plastic from the contaminated fractions sorted out by density separation, with a test-bed built in Sweden in 2019.[41]

ACCURACY

By adjusting the density of the bath medium, for example by adding magnesium sulphate to the water and applying the technique in several steps, additional fractions can be separated and sorted[42] [43]. Series of tanks can be used for example for WEEE flake separation (PS, ABS, PP, PE) and to separate PVC from PET, which have close densities[44]. However, the technique has limitations in precision as it sorts out all fractions with higher density, which results in difficulties in separating plastic types with large density intervals (for example PVC, which can have both large and small amounts of plasticisers affecting the density)[45], plastics with similar density intervals (such as PA and PC) and fractions containing bromine[46] [47]. Both static and centrifugal density separation systems are available, and although centrifugal systems are thought to be more effective, static ones are more commonly used industrially today[48].

ADVANTAGES AND LIMITATIONS

The main advantages of the technique are that it is quick, effective and very efficient in combination with the X-ray technique XRF[49]. It can separate and remove materials that contain hazardous additives, including SVHCs. It is efficient in sorting large volumes and assessed as being quite inexpensive in comparison to other methods[50]. However, the limitations in precision lead to a risk of larger fractions being sorted out than is needed from a regulatory perspective (for example sorting out all fractions with bromine and not only fractions with restricted BFRs)[51]. There is also a need to remove all materials that can absorb water, such as paper, foam and textiles, before the process[52].

MAGNETIC SEPARATION

AT A GLIMPSE

Recycling stream:	Mixed streams with metal content, shredded or ground material for example from ELV, WEEE and C&D
Hazardous substances:	Metals, possibly cobalt and chromium

<u>Application</u>

☐ Detection

☐ Quantification

☒ Material sorting

☒ Removal

<u>Technical readiness</u>

☒ In use

☐ In use within 5 – 10 years

<u>Main advantages:</u> Easy and straightforward.

<u>Main limitations:</u> Non-specific with regard to hazardous substances.

DESCRIPTION

Magnetic separation is a commonly available sorting technique for mixed waste streams where ferromagnetic metals are separated from other materials like plastic and non-ferrous metals[53] [54] [55]. It can be applied both as an over-belt magnetic separation technique, i.e. mounted over shredded or ground material, on a conveyor belt or vibration feeder or as a magnetic repulsion belt[56] [57] [58]. The technique is commonly used as permanent magnets for removal of iron in initial sorting processes and the use of electromagnetic magnets further enables sorting of the collected ferromagnetic materials [59].

The technique can be considered not only as a method for sorting, but indirectly also for detection and removal. The technique is applied for mixed streams with ferromagnetic metals, such as shredded or ground material from End-of-Life Vehicles (ELVs) and Waste Electrical and Electronic Equipment (WEEE)[60]. Magnetic separation can, for example, be used to separate ferrous parts from non-ferrous parts in PVC window frames[61]. As the technique separates ferromagnetic metals, predominantly iron but also other metals and materials, it could potentially also be used to separate and remove, for example, cobalt, which has hazardous properties, from waste streams. It could possibly also be used for direct or indirect detection or removal of ferrous or non-ferrous materials with hazardous properties, including the presence of SVHCs.

TECHNICAL READINESS

The technique is in industrial and commercial use with the intention of sorting and separating ferrous fractions from the waste material stream[62] [63].

FUTURE POTENTIAL

Limited information available.

ACCURACY

The accuracy of magnetic separation is high, although the technique has higher performance if the ingoing material has been shredded or ground prior to the treatment[64]. It is not clear whether the technique is a preferable method for removing hazardous ferromagnetic metals, but it has potential for this.

ADVANTAGES AND LIMITATIONS

The advantage of using magnetic separation is that it can easily separate certain fractions[65]. It would, however, be a rather non-specific technique with regard to control of SVHCs or other hazardous substances or materials in the recycling process.

MELT FILTRATION

AT A GLIMPSE

Recycling stream:	Plastics, for example from most post-consumer waste streams, including ELV and WEEE
Hazardous substances:	Solid contaminations such as phenol formaldehyde and epoxy plastics

<u>Application</u>

☐ Detection

☐ Quantification

☒ Material sorting

☒ Removal

<u>Technical readiness</u>

☒ In use

☐ In use within 5 – 10 years

<u>Main advantages:</u> Simultaneous removal of hazardous substances and odours.

<u>Main limitations:</u> Non-specific technique for removal of SVHCs.

DESCRIPTION

Melt filtration is a mechanical separation technique used in recycling of plastics, where melted plastics are forced through a filter of woven metal fibres to remove solid contaminations that were not melted with the plastic in the incoming material stream[66 67].

Contaminations that can be removed in melt filtrations are materials such as paper, wood, textile fibres, rubber, silicone, pieces of thermosetting polymer (such as phenol formaldehyde or epoxy), PUR foam, glass, metal pieces, parts of circuit boards and rocks[68 69 70]. The melt filtration is executed in an extruder with a melt filtration unit and can handle approximately 10% of impurities[71]. After filtration the material is formed into pellets that can be used in production of new plastic products[72].

TECHNICAL READINESS

Melt filtration is in industrial use within the recycling industry to create homogenous plastic fractions where the material is mixed on a molecular level[73]. The technique is used to remove solid contaminants and homogenize the material for most plastic post consumer waste, including plastics from ELV and WEEE[74].

Although the purpose of the technique is to remove solid contaminations, it could possibly be applicable as an indirect technique to control SVHCs in recycling processes.

FUTURE POTENTIAL

Limited information available.

ACCURACY

The filter in the equipment is available in different mesh sizes which determine the degree of filtration, where the pore size of the filter normally range between 80-250µm[75].

ADVANTAGES AND LIMITATIONS

Plastic recycling has been associated with odour issues[76], and melt filtration is a common technique to remove such odours[77].

The major advantages of melt filtration in this context is, however, the possibility of removing hazardous substances, including SVHCs, with the simultaneous removal of non-melted contaminations, although it would be a rather non-specific technique with regard to control of SVHCs in the recycling process.

ED-XRF
ENERGY-DISPERSIVE XRF

AT A GLIMPSE

Recycling stream: Plastics, metals and textiles for example from WEEE, ELV and C&D waste,

Hazardous substances: Heavy metals, bromine, chlorine

Application	Technical readiness
☒ Detection	☒ In use
☒ Quantification	☐ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	Main advantages: Non-destructive, quick, hand-held and industrial versions.
	Main limitations: Only provides information regarding material surfaces. Emits radiation and requires training and permits.

DESCRIPTION

X-ray fluorescence is a commonly deployed technique for sensor-based detection and quantification, often used for screening in automatic sorting processes[78 79]. In ED-XRF spectrometers, the fluorescence from an irradiated sample is measured with an energy dispersive detector[80]. XRF is often used by recyclers focused on plastics, WEEE and ELV, but has also been used for other metals, textiles, paper, paints, aqueous liquids, wood and leather[81 82 83 84]. It is efficient in combination with density sorting techniques such as sink-float[85 86]. The XRF technique can detect the total content of pure metals and elements such as bromine, lead, chlorine, cadmium, mercury and chromium[87 88]. It is often used to screen for total bromine content or chlorine content and used for indirect identification of materials (often plastics) containing BFRs, for determination of whether a plastic type is PVC or as an indication of the presence of dioxins and furans[89 90]. Significant concentrations of chlorine can also be an indication SCCP and MCCP[91].

TECHNICAL READINESS

ED-XRF is in industrial use in both stationary and hand-held versions[92].

FUTURE POTENTIAL

There is great potential for online analysis with the ED-XRF technique in the recycling industry with regard to elements that indicate presence of SVHC, especially at relatively high concentrations[93].

ACCURACY

XRF can detect bromine and chlorine < 1% and but has difficulties in determining very low concentrations[94 95 96]. ED-XRF has been shown to have good correspondence of measurements of bromine with analyses done with destructive chemical analysis and can measure bromine in a wide concentration range in consumer plastics and WEEE[97].

ADVANTAGES AND LIMITATIONS

ED-XRF is a non-destructive and quick technique, with readings within seconds or minutes. It can have in-built software for comparison between detected values and regulated limit values, such as RoHS. It enables simultaneous elemental analysis, has a small, compact instrument design, low electrical consumption and portable versions require no cables[98 99].

However, XRF can only measure material surfaces and dirt and coatings can affect the measurement[100]. It may require post-measurement analyses and cannot be used on for example rubber foam[101]. XRF is often used for screening, but there is a lack of standards and regulations concerning how often random sampling and screening should be performed[102]. XRF provides information on atomic composition and not on substances which the atom is part of. The technique can therefore not distinguish, for example, between regulated and unregulated BFRs[103].

ED-XRF is assessed as being a relatively inexpensive and cost-efficient technique for smaller volumes[104]. A hand-held ED-XRF costs around 28 000 euros[105], while the cost of a stationary ED-XRF is >57 000 euros[106].

WD-XRF
WAVELENGTH-DISPERSIVE FLUORESCENCE

AT A GLIMPSE

Recycling stream: Plastics, metals, textiles for example from WEEE, ELV and C&D waste

Hazardous substances: Heavy metals, bromine, chlorine, fluorine

Application	Technical readiness
☒ Detection	☒ In use
☒ Quantification	☐ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	Main advantages: Non-destructive, quick, can detect fluorine.
	Main limitations: Only provides information regarding material surfaces. No hand-held version, requires vacuum.

DESCRIPTION

X-ray fluorescence is a commonly deployed technique for sensor-based detection and quantification, often used for screening in automatic sorting processes[107 108]. In WD-XRF spectrometers, the fluorescence from an irradiated sample is measured with a wavelength-dispersive detection system[109]. XRF is often used by recyclers focused on plastics, WEEE and ELV, but has also been used for other metals, textiles, paper, paints, aqueous liquids, wood and leather[110 111 112 113]. It is efficient in combination with density sorting techniques such as sink-float[114 115]. The XRF technique can detect the total content of pure metals and elements such as bromine, lead, chlorine, cadmium, mercury and chromium[116 117]. It is often used to screen for total bromine content or chlorine content and used for indirect identification of materials (often plastics) containing BFRs, for determination of whether a plastic type is PVC or as an indication of the presence of dioxins and furans[118 119]. Significant concentrations of chlorine can also be an indication SCCP and MCCP[120]. WD-XRF requires vacuum for measurement and is therefore not available as hand-held instruments[121].

TECHNICAL READINESS

WD-XRF is in industrial use in both stationary and hand-held versions[122].

FUTURE POTENTIAL

There is great potential for online analysis with WD-XRF technique within the recycling industry with regard to elements that indicate the presence of SVHCs, especially at relatively high concentrations[123].

ACCURACY

Different XRF-tools have different accuracy. XRF can detect bromine and chlorine < 1% and but has difficulties in determining very low concentrations[124 125 126].

ADVANTAGES AND LIMITATIONS

WD-XRF is a non-destructive and quick technique, with readings within seconds or minutes. It can have in-built software for comparison between detected values and regulated limit values, such as RoHS. Some WD-XRF tools can detect the presence of fluorine and hence indicate the presence of perfluorinated substances[127 128]. It has high resolution and low detection limits for lighter elements[129].

However, XRF can only measure material surfaces, dirt and coatings can affect the measurement. It may require post-measurement analyses and cannot be used on for example rubber foam[130 131]. XRF is often used for screening, but there is a lack of standards and regulations concerning how often random sampling and screening should be performed[132]. XRF provides information on atomic composition and not on substances which the atom is a part of. The technique can therefore not distinguish, for example, between regulated and unregulated BFRs[133]. The cost of WD-XRF is > 95 000 euros[134].

XRT
X-RAY TRANSMISSION

AT A GLIMPSE

Recycling stream: Plastics, metals

Hazardous substances: Heavy metals, bromine

Application	Technical readiness
☒ Detection	☒ In use
☒ Quantification	☐ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	Main advantage: Non-destructive.
	Main limitation: Only provides information regarding material surfaces.

DESCRIPTION

X-ray transmission is used for automatic sorting of shredded waste[135]. The XRT technique can detect metals and elements such as heavy metals, as well as bromine[136]. It is a non-mobile technique that monitors the atomic density of materials in a waste stream where it is used, for example, to separate heavy metals from aluminium to produce clean aluminium fractions[137] [138].

TECHNICAL READINESS

XRT is in industrial use to sort fragmented waste like scarp plastic and metals based on the materials content of heavy metals and bromine[139] [140] and also within the mining industry to detect non-ferrous metals, ferrous metals, slag metals, industrial minerals, gemstones, coal and other fuels[141].

FUTURE POTENTIAL

Based on its properties, there is a potential for XRT, as for other X-ray techniques in the recycling industry, to be used for detection and sorting of materials, based on measurements of elements that indicate the presence of SVHCs[142]. XRT would then have the potential to detect SVHCs like heavy metals or to be used for indirect identification of materials containing SVHCs, such as BFRs.

ACCURACY

Limited information available.

ADVANTAGES AND LIMITATIONS

XRT is a non-destructive technique that could be used for detection, indication and sorting of hazardous substances and SVHCs such as heavy metals and bromine. However, XRT has been assessed as unpractical and unsuitable to use as a simple screening technique for bromine in consumer products, as it is not mobile and sorts on atomic density[143]. Using an X-ray source, it emits radiation and should therefore also require special operator training. XRT has been associated with high costs[144].

NIR
NEAR-INFRARED SPECTROSCOPY

AT A GLIMPSE

Recycling stream: Plastics from e.g. WEEE, soft PVC, textiles, paper, single stream C&D waste

Hazardous substances: e.g. BFRs and plastic types such as HDPE

Application	Technical readiness
☒ Detection	☒ In use
☒ Quantification	☐ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	Main advantage: Non-destructive.
	Main limitations: Cannot detect black plastics.

DESCRIPTION

NIR is a sensor-based detection technique using the near-infrared region of the electromagnetic spectrum for molecular characterisation[145][146]. It is a common technique used in automatic online sorting processes[147] [148]. NIR can be used on several different waste streams and materials, such as plastics, paper and electronic waste like circuit boards, construction and demolition (C&D) waste and textiles[149] [150] [151]. It is often used to sort plastic packaging, to detect and sort plastic materials like PP, PE and PET and HDPE[152] [153]. NIR can be used to detect and sort materials containing chemical compounds such as BFRs and soft PVC[154] [155]. The technique could theoretically be used to detect SVHCs in textiles. In plastic sorting, NIR, like FT-IR, only works on non-black plastics, and is in principle applicable to transparent thermoplastics only[156].

TECHNICAL READINESS

NIR is in industrial and commercial use in the recycling industry, mainly for sorting of different plastic types[157]. Other typical applications in use include medical and physiological diagnostics and research, as well as applications in other areas such as health care and food and agrochemical quality control[158].

FUTURE POTENTIAL

Visual light sensors, cameras and metal sensors can be integrated alongside or inside NIR appliances, to increase the quality or purity of material flake processing[159]. The textile recycling industry today relies on manual sorting, but NIR and FT-IR are considered suitable candidates for automatic sorting of textiles and fibres and methods for this are being developed in projects around Europe[160]. These projects could also open up potential for identification or removal of SVHCs and other hazardous substances using NIR and FT-IR, although there is no consensus regarding whether FT-IR and NIR could be useful and cost-efficient for purposes other than sorting of fibres in textile materials[161] [162] [163]. Developments in the NIR technique may enable recognition of black plastics in the recycling industry[164].

ACCURACY

The technique is used on a large scale with good accuracy in sorting plastic polymers[165], but with possibly limited applications in control of low concentrations of SVHCs in recycling processes[166] [167].

ADVANTAGES AND LIMITATIONS

NIR is a non-destructive, quick and relatively inexpensive technique with a relatively long history in the recycling industry[168]. Future use of NIR in textile recycling would not require tagging of the textile item, as the RFID and QR techniques would[169]. A limitation with NIR is the difficulty of recognising black plastic as plastic/polymer[170]. It is also unable to detect mixtures of different material and as analysis is performed only on the surface of the material, possible substances or materials beneath the surface are not revealed by the technique[171].

FT-IR FOURIER TRANSFORM INFRARED SPECTROSCOPY

AT A GLIMPSE

Recycling stream: Plastics, textiles

Hazardous substances: e.g. BFRs

Application	Technical readiness
☒ Detection	☒ In use
☒ Quantification	☐ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	Main advantage: Non-destructive.
	Main limitation: Cannot detect black plastics.

DESCRIPTION

FT-IR is a sensor-based detection technique using the infrared spectrum of light. It is a common technique used in automatic online sorting processes[172]. Depending on the sample, the spectrum can be measured in either reflection or transmission. The term *Fourier transform* relates to the mathematical operations needed to analyse the raw data collected by the sensor[173]. FT-IR is used industrially to sort different plastic types and can be used for detection, quantification and sorting of plastics containing chemical compounds such as BFRs[174]. The technique can also potentially be used to sort other materials, such as textiles[175 176].

TECHNICAL READINESS

The FT-IR technique is in industrial and commercial use in the recycling industry, mainly for sorting of different plastic types and for detection of BFRs[177].

FUTURE POTENTIAL

The textile recycling industry today relies on manual sorting[178], but FT-IR and NIR are considered suitable candidates for automatic sorting of textiles and fibres, and methods for both techniques are being developed in projects around Europe[179 180]. These projects could also open up potential for identification or removal of SVHCs and other hazardous substances using FT-IR and NIR, although there is no consensus regarding whether FT-IR and NIR could be useful and cost-efficient for purposes other than sorting of fibres in textile materials[181 182 183].

ACCURACY

Low concentrations of SVHCs might be problematic for FT-IR to detect, as the signal from these substances could be concealed in the shadow of other substances on the material surface[184].

ADVANTAGES AND LIMITATIONS

FT-IR is a non-destructive technique[185] that can detect a wide range of polymers and substances from samples of for example plastics, rubbers, metallic surfaces, with paint and varnish surfaces[186].

A limitation with FT-IR is the difficulty of recognising black plastic as plastic or polymer[187]. In addition, analysis is performed only on the surface of the material, and possible substances or materials beneath the surface are not revealed by the technique. Like NIR, FT-IR cannot detect mixtures of different materials[188].

As for many other techniques, the costs of FT-IR are related to the intended use. Applications for quantification of substances in low concentrations are more expensive than applications for sorting of polymers[189].

SLIDING SPARK SPECTROSCOPY

AT A GLIMPSE

Recycling stream: Plastics

Hazardous substances: Halogens like bromine, chlorine, fluorine, BFRs, PFOS, PVC

Application	Technical readiness
☒ Detection	☒ In use
☒ Quantification	☐ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	Main advantages: Easy to use, available as hand-held version, quick analysis.
	Main limitation: Only provides information regarding material surfaces.

DESCRIPTION

Sliding spark spectroscopy is a screening technique used to identify the element composition of a material. A small amount of the sample area is evaporated with heavy current. The evaporated material is atomised and activated to emit radiation, which is used to identify the material[190]. Sliding spark spectroscopy is available as hand-held instruments and allows for in-situ measurements. The measured material should be compact and non-conductive but needs no preparation prior to measurement. The hand-held versions deliver results from measurements within seconds[191].

The technique has mainly been used to identify and quantify bromine, chlorine and fluorine in plastic materials[192]. It can detect bromine-containing materials and inorganic additives such as BFRs, fillers and stabilisers, as well as chlorine-containing plastics such as PVC or chlorinated flame retardants, perfluorinated substances such as PFOS[193] [194].

TECHNICAL READINESS

The technique is in industrial and commercial use for detection, quantification and sorting of plastic materials in recycling processes[195].

FUTURE POTENTIAL

Limited information.

ACCURACY

The sliding spark technique can quantify bromine and chlorine concentrations down to approximately 1%, with good repeatability and reliability. It provides more uncertain measurements around 0-1%. The technique can detect concentrations of organofluorine (such as PFOS) and inorganic additives down to approximately 0.1%[196].

The sliding spark spectroscopy technique has a detection limit close to the current permitted threshold for PBDEs (1000 ppm) and has therefore been questioned for such analyses. Others have showed that it can still be suitable for verification of efficient density separation (i.e. removal of fractions containing bromine in sorting processes)[197].

ADVANTAGES AND LIMITATIONS

Sliding spark spectroscopy is easy to apply to materials and is available as a hand-held instrument. It is a quick method, giving measurement results within seconds[198]. It does, however, require mains power and is therefore less flexible than XRF, for example, which has no need for electrical cords. The technique requires the measured material to have a clean surface and flat area for good spark contact. It will leave a burn spot from the spark at the point of measurement[199]. In addition, it only provides information on the surface of the tested material[200].

Sliding spark spectroscopy is assessed as being relatively inexpensive as the cost of a sliding spark instrument is approximately 5 000 - 6 000 euros[201].

LIBS LASER-INDUCED BREAKDOWN SPECTROSCOPY

AT A GLIMPSE

Recycling stream: Plastics and metals for example from WEEE

Hazardous substances: Can potentially detect all elements

Application	Technical readiness
☒ Detection	☒ In use
☒ Quantification	☐ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	Main advantages: Hand-held versions, requires no training, no radiation.
	Main limitation: Time consuming technique.

DESCRIPTION

In LIBS (Laser-Induced Breakdown Spectroscopy) techniques, a laser pulse is focused on a small point of the measured material surface and generates a plasma plume. Emitted light from the plasma is transmitted through optical fibres, dispersed in spectrometers and detected by an image sensor[202]. It is a versatile technique that could potentially measure all elements in the periodic table, and potentially measure elements in gas, solids and liquids[203]. LIBS has predominantly been used to detect lighter elements. It can detect small amounts of elements in alloys, known as tramp elements, such as lithium and beryllium, and has been used to separate close aluminium alloys and, for example, to discriminate lithium in aluminium[204]. It has been used increasingly in metal recycling applications, but could also be used to screen for bromine in plastics[205].

TECHNICAL READINESS

The technique is readily available for sorting for example copper alloys such as brass and bronze, in metal recycling industries[206 207], in the steel industry for detection of alloys[208], as well as to some extent for sorting of plastics in some facilities in Sweden and Europe[209 210]. It is in the research phase for other materials and uses, where it could be in industrial use within 5-10 years[211].

FUTURE POTENTIAL

LIBS possibly offers good potential as a future technique for plastic recycling as it is not limited by black colour[212]. It is, however, limited by difficulty in quantifying detected substances[213]. It is not in specific use for detection or quantification of SVHCs or other hazardous substances in recycling today but has future potential and promising development[214].

ACCURACY

Some versions of LIBS have very low detection limits, as low as 1 ppm, while others are less specific[215].

ADVANTAGES AND LIMITATIONS

LIBS is available in hand-held versions[216] and is not limited by black or transparent plastics[217]. It is assessed as being superior to X-ray techniques such as XRF in detecting and separating lighter metals and to provide both more accurate and faster separation of aluminium alloys. It has comparatively low energy requirements and as it does not emit radiation (such as XRF) no protective gear is needed, nor are there regulatory requirements or specific operator training[218].

While some versions provide readings within seconds, other versions have longer data acquisition times making them unsuitable for automatic sorting processes[219].

LIBS measure surfaces and measurements can therefore be sensitive to moisture and surface contamination[220]. LIBS is assessed as being a more expensive technique than XRF[221].

RAMAN SPECTROSCOPY

AT A GLIMPSE

Recycling stream: Plastics, textiles

Hazardous substances: e.g. BFRs

Application
- ☒ Detection
- ☒ Quantification
- ☒ Material sorting
- ☐ Removal

Technical readiness
- ☐ In use
- ☒ In use within 5 – 10 years

Main advantage: Non-destructive.

Main limitation: Complicated.

DESCRIPTION

Like FT-IR and NIR, Raman spectroscopy is a sensor-based detection method that can be used for automatic sorting in the recycling industry, giving a ‘fingerprint’ of the measured material[222]. Raman spectroscopy is a molecular spectroscopic technique with laser where the information is obtained from a light scattering process, in contrast to IR techniques that use the absorption of light for identification of illuminated substances[223]. Raman can provide additional information to IR techniques, but can also be used in conjunction with NIR[224]. The bonds in laser-illuminated molecules result in information and identification using different wavelengths than, for example, NIR[225], typically wavelengths of 532 nm, 785 nm, 830 nm and 1064 nm[226].

TECHNICAL READINESS

The technique is readily available in various applications to identify molecules and bonds but is normally not used in the recycling industry[227] [228].

FUTURE POTENTIAL

Raman spectroscopy could possibly be a technique of future potential for control of SVHCs in recycling processes[229], especially in combination with NIR, measuring at other wave lengths[230], but limited information available is.

ACCURACY

Raman absorbance and scattering works well on plastic polymers[231].

ADVANTAGES AND LIMITATIONS

Raman spectroscopy is a non-destructive technique using laser, which allows use of long optical cords, if necessary[232].

The technique works in water and through a window, which could be used to eliminate sample stream contamination[233].

The Raman technique has previously been more complicated to use than other spectroscopic techniques[234].

Raman spectroscopy is thought to be more costly than the more traditional spectroscopic and screening techniques NIR, FT-IR and XRF[235].

RFID
RADIO FREQUENCY IDENTIFICATION

AT A GLIMPSE

Recycling stream: Textiles

Hazardous substances: Any, known at the time of manufacturing

Application	Technical readiness
☒ Detection	☐ In use
☒ Quantification	☒ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	

Main advantages: Can store/read any information. Works with small labels. Can be positioned discreetly.

Main limitations: Only applicable to intact textiles, does not work if the material is shredded/cut into pieces. Requires known chemical content.

DESCRIPTION

RFID is a technique with electronic reading of tagged materials using electromagnetic fields[236]. The tags contain electronically stored information which can include any type of information[237]. RFID is increasingly discussed as an alternative to tagging of textile materials[238], where the tags could contain details for example on fibre type, but also information on chemicals used in the manufacturing process such as colours, added coatings such as flame retardants, perfluorinated substances or antibacterial substances[239]. The stored information on the RFID tag could be used in a sorting process in future recycling of the tagged item and it would be possible to sort on a variety of different levels, based on the information programmed in the tag[240]. The technique could potentially be used for both detection of SVHCs, and indirect quantification of, or information on, the content of the same substances, and potentially used in an automatic sorting system[241].

TECHNICAL READINESS

RFID is not in commercial use in the textile recycling industry, although it is used in other sectors, such as laundry operation services to monitor individual textiles[242], surveillance of production and manufacturing processes, in bus cards, for road tolls, in libraries and so on[243].

FUTURE POTENTIAL

RFID code is a possible future technique with ongoing research, which could be implemented commercially in the relatively short term[244 245 246]. It has possibly the greatest future potential if used in combination with QR, where the information on the QR code is aimed at consumers and the RFID tagged information is aimed at the industry, from manufacturing to recycling[247]. Possible techniques for detecting, quantifying, sorting and removal of SVHC and other hazardous substances are assessed as being of great value to the textile recycling industry, as textiles can be burdened by several hazardous substances from all manufacturing steps, such as flame retardants, fluorinated polymers, biocides and hazardous colourants[248].

ACCURACY

The accuracy of the information is high, as long as no significant alterations have been made to the fabric before recycling[249].

ADVANTAGES AND LIMITATIONS

The major advantage of RFID is that it can store any type of information and that all textile articled could be programmed with information from all parts of the production chain[250]. RFID works with small labels, which can be positioned discreetly, for instance in seams[251] and is considered an option for faster sorting than techniques such as NIR[252].

On the other hand, the technique would only be applicable to intact textiles, and would not work if the material was shredded or modified in other ways[253]. RFID is considered more expensive than spectrophotometric methods and X-ray-techniques[254] and there are yet no RFID labelling systems developed for textiles at reasonable cost[255]. It has also been argued that the cost for a system based on items being tagged in the production chain could accrue to the producer/manufacturer or retailer while profiting the recycling industry[256].

QR CODE
QUICK RESPONSE CODE

AT A GLIMPSE

Recycling stream:	Textiles
Hazardous substances:	Any, known at the time of manufacturing

Application	Technical readiness
☒ Detection	☐ In use
☒ Quantification	☒ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	Main advantage: Can store any type of information.
	Main limitations: Only applicable to intact textiles, does not work if the material is shredded, requires large label in visible area. Requires known chemical content

DESCRIPTION

QR codes are a type of matrix codes, or two-dimensional bar codes, for storing information that can be acquired by optical reading. The QR technique is based on a tag, or label, that is attached to products and articles such as textiles. The technique could be used for both detection and information on percentage of hazardous substances, as well as in automatic sorting systems in recycling processes. The stored information on the QR tag could be used in a sorting process in future recycling of the tagged item and it would be possible to sort on a variety of different levels, based on the information programmed in the tag[257].

TECHNICAL READINESS

QR codes are not in commercial use for control of hazardous substances in the recycling industry in the textile recycling industry. However, it is used in other sectors, such as in libraries, education, advertising and so on[258].

FUTURE POTENTIAL

The textile industry is burdened by hazardous substances in several of the different manufacturing steps[259], the greatest problems from a recycling perspective being added substances such as BFRs, fluorinated polymers, biocides and colourants, as these to a large extent remain in the fabric[260]. Possible techniques for detecting, quantifying, sorting and removal of hazardous substances are therefore of great value.

QR code is a possible future technique with ongoing research that could be implemented commercially in the relatively short term[261]. It has possibly the greatest future potential if used in combination with RFID, where the information on the QR code is aimed at consumers and the RFID tagged information is aimed at the industry[262].

ACCURACY

The accuracy of the information is high, as long as no significant alterations have been made to the fabric[263].

ADVANTAGES AND LIMITATIONS

The major advantage of QR code is that it can store any information[264]. QR codes can contain larger amounts of data than traditional bar codes and every single textile article could potentially have a unique QR code. It would make it possible to log information from all parts of the production chain (such as fibre content, colour, chemical content, manufacturing process and details on accurate sorting and waste management). QR codes could make faster sorting possible than techniques such as NIR[265]. QR codes are less expensive than RFID tags, could more easily be implemented commercially, and the added cost per textile item is assessed as being relatively small[266] [267].

However, the technique requires relatively large labels that need to be positioned visibly to enable optical reading[268]. Labels with QR codes face the same problems as other labels on textiles, and there is a risk of them being cut off[269]. In addition, QR codes would require manual handling before optic reading during the sorting process[270]. In addition, the technique would only be applicable to intact textiles, and would not work if the material was shredded or modified in other ways[271]. It has also been argued that the cost for a system based on items being tagged in the production chain could accrue to the producer/manufacturer or retailer while profiting the recycling industry[272].

DROPLET TEST

AT A GLIMPSE

Recycling stream: Textiles

Hazardous substances: Perfluorinated substances

Application	Technical readiness
☒ Detection	☐ In use
☐ Quantification	☒ In use within 5 – 10 years
☒ Material sorting	
☐ Removal	Main advantages: Easy, quick, requires no chemicals or equipment.
	Main limitations: Unspecific, manual performance.

DESCRIPTION

The droplet test is a possible future screening method, a simple and quick evaluation of the likelihood that a textile material has been treated with perfluorinated substances (e.g. stain-resistant, water-repellent and anti-grease substances)[273]. It is also referred to as the water drop test or measurement of contact angle[274]. The test is based on the fact that few substances have the ability to be both hydrophilic and hydrophobic[275]. If drops of water and oil are placed on the surface of a material, and both drops remain intact by forming 'pellets' on top of the textile material, it is likely that the material is coated or treated with perfluorinated substances[276]. If the oil droplet flattens out on the tested surface, the surface is more likely to be treated with a non-fluorinated chemical[277] such as a hydrocarbon surfactant or a silicone coating[278]. The technique is applicable to high-performing materials, i.e. small amounts of perfluorinated substances will not be detected[279] [280].

TECHNICAL READINESS

No available information regarding whether the droplet test is in industrial or commercial use.

FUTURE POTENTIAL

The droplet test could possibly be implemented within a short period of time, but only as a somewhat 'quick-and-dirty' first screening method prior to other sorting and recycling steps[281].

ACCURACY

The droplet test is fast, but only indicative. The absence of the two drops does not prove the absence of smaller amounts of fluorinated substances. It also cannot specify which perfluorinated substance the textile is coated with[282]. For assurance and details concerning whether the substance is, for example, PFOS or another substance, complementary laboratory analyses are required[283].

ADVANTAGES AND LIMITATIONS

The major advantages of the water and oil drop test is its simplicity, the quick reading of the result (instantaneous) and the fact that it requires no chemicals or equipment. However, the method is not very specific and is more an indication than an actual detection methodology, possibly suitable as a screening and pre-sorting method[284].

The technique only gives information of substances on the material surface[285]. As it is not a method for automatic detection and sorting, it would require manual performance and would therefore be labour-intensive.

LABORATORY ANALYSES

AT A GLIMPSE

Recycling stream: Most materials, such as plastics, textiles, rubber, paper/paperboard and C&D waste

Hazardous substances: A large number of organic and inorganic substances

Application	Technical readiness
☒ Detection	☒ In use
☒ Quantification	☐ In use within 5 – 10 years
☐ Material sorting	
☐ Removal	Main advantages: Specific, high accuracy.
	Main limitations: Costly, time consuming.

DESCRIPTION

There are a number of different laboratory analyses used in the recycling industry, such as the chromatographic methods high-performance liquid chromatography (HPLC) and gas chromatography (GC), coupled to spectrophotometric detection methods such as mass spectroscopy (MS)[286]. HPLC can be used to detect substances that can be dissolved, while GC can be used to detect substances that can be gasified in certain conditions. The techniques can further be performed in different conditions, such as pyro-GC/MS, which is performed at elevated temperature and can characterise polymers and composites that traditional GC-MS cannot[287], HPLC-UV which can be used for detection for example of benzo(a)pyrene, polyaromatic hydrocarbons (PAHs) and phenol[288], HPLC-FLD which can detect, for example, DNOP[289], and TED GC/MS which can be used for analysis of microscale plastic particles[290]. Laboratory analyses are often performed for random sampling or when on-line technologies cannot determine how to sort certain incoming material streams[291]. Laboratory analyses are often used as a complement for detection and quantification of BFRs in plastics, and can also determine, for example, PBDEs, decaBDE, DINP and DIDP[292] [293] [294].

TECHNICAL READINESS

Various laboratory techniques are available and in industrial use for analyses of chemical substances, including detection and quantification of hazardous substances. The techniques are often used for analysis of random sampling or for regular measurements, for example in monthly samplings to check efficiency of sorting processes[295] [296] [297].

FUTURE POTENTIAL

Laboratory analyses are the only available techniques today for detection and quantification of a large number of hazardous substances, including SVHCs, and therefore have great future potential for control of SVHCs in recycling processes[298] [299].

ACCURACY

Laboratory analyses generally have high accuracy and are more specific than online screening techniques. The large number of different laboratory techniques are suitable for analysis of different substances. An example is the common technique GC-MS, which is validated for example for the determination of PBDEs in electrotechnical products[300].

ADVANTAGES AND LIMITATIONS

Laboratory techniques can often simultaneously detect and quantify several substances[301]. They are specific and of high accuracy. Laboratory techniques are, however, limited by high costs and time-consuming methods[302]. A laboratory analysis of a particular substance or substance group in one sample is assessed to cost approximately 400 euros[303].

Due to the methods being time-consuming, they are not applicable for online measurements, but useful tools for occasional sampling and verifications[304]. The techniques require advanced equipment and trained personnel, for both performance and interpretation of results[305].

CITRIC ACID / ACETIC ACID

AT A GLIMPSE

Recycling stream: Glass

Hazardous substances: Heavy metals such as mercury, lead, chromium and cadmium

Application	Technical readiness
☐ Detection	☐ In use – n.d.
☐ Quantification	☐ In use within 5 – 10 years – n.d.
☐ Material sorting	
☒ Removal	Main advantage: Removal of hazardous substances.
	Main limitations: Limited information available regarding the technique.

DESCRIPTION

Cleaning recycled glass with citric acid or acetic acid has been suggested as a technique to remove hazardous substances and SVHC such as heavy metals from the surface of the glass. The technique removes metal ions from the glass surface and is used, for example, in cleaning of glass containers that are to be reused and/or refilled. Heavy metals such as mercury, lead, chromium and cadmium can occur in the ingoing material when producing the glass but can also be incorporated into glass products for certain specific uses, such as fluorescent lamps and luminaires which may contain mercury, TV screens and crystal glass which may contain lead and colourants which may contain chromium and cadmium[306].

TECHNICAL READINESS

Use of the described acids is a comparatively simple and possibly inexpensive technique, however it is uncertain to what extent it is applicable in the recycling industry today or will be in the future due to limited available information.

The technique would probably not be applicable to crushed glass fractions (such as household packaging of glass which is collected from recycling station containers), but would be possible for other glass waste streams, such as light bulbs, luminaires and flat glass[307].

FUTURE POTENTIAL

Limited information available.

ACCURACY

Limited information available.

ADVANTAGES AND LIMITATIONS

Limited information available.

DEINKING PROCESSES

AT A GLIMPSE

Recycling stream: Paper and paperboard

Hazardous substances: Heavy metals and contaminants such as BPA, DEHP

<u>Application</u>

☐ Detection

☐ Quantification

☐ Material sorting

☒ Removal

<u>Technical readiness</u>

☒ In use

☐ In use within 5 – 10 years

<u>Main advantage:</u> Removal of contaminants in the process.

<u>Main limitations:</u> Loss of paper fibre.

DESCRIPTION

A large number of chemicals are used in producing paper and paperboard, which can be transferred to recycled papers[308].

Deinking is a step in the recycling process of paper and paperboard, where the paper pulp is washed and deinked, and contaminants can simultaneously be removed. The process includes paper pulp washing, floatation deinking and bleaching[309].

In floatation deinking, ink is removed from the paper by adding surface-active substances and air. Ink and other hydrophobic substances are then aggregated in a layer of foam which can be removed. In bleaching processes, bleaching substances such as sodium dithionite and hydrogen peroxide are added[310].

By removing ink and other pigments, the decolouring processes has the potential to also remove SVHCs such as heavy metals from the processed material. Deinking also significantly increases removal of contaminants such as bisphenol A and the plasticiser DEHP during the processes[311].

TECHNICAL READINESS

Different techniques of decolouration are in industrial use in paper and carton recycling[312].

FUTURE POTENTIAL

Limited information available.

ACCURACY

The efficiency in removing hazardous substances can vary between the deinking processes[313].

ADVANTAGES AND LIMITATIONS

The main advantage of the different deinking processes is the simultaneous removal of contaminants, including SVHCs and other hazardous substances.

However, the processes do result in loss of paper fibre and it has been assessed that increased removal of contaminants in the recycling process of paper and paperboard would also result in an additional loss of paper fibre[314].

THERMAL DEGRADATION

AT A GLIMPSE

Recycling stream:	Organic materials such as plastics, textiles, rubber, paper/paperboard and wood
Hazardous substances:	Potentially destroys SVHCs such as certain flame retardants and plasticisers
<u>Application</u>	<u>Technical readiness</u>
☐ Detection	☐ In use
☐ Quantification	☒ In use within 5 – 10 years
☐ Material sorting	
☒ Removal	<u>Main advantage:</u> Potential to recycle unutilised waste streams.
	<u>Main limitations:</u> Immature techniques, high energy consumption.

DESCRIPTION

With thermal degradation processes such as pyrolysis and gasification, sometimes referred to as types of chemical recycling, organic materials are combusted at high temperature and in the absence or scarcity of oxygen to form small chemical building blocks (such as syngas) that can be used as feedstock for production of new polymers of chemicals[315 316]. A mixture of chemical building blocks is formed and needs to be separated into pure streams. Separation processes known in the petrochemical industry can often be utilised for separation. Most organic waste can be processed but some mixed plastic wastes have been difficult to manage in the process, and more homogeneous fractions make separation and utilisation simpler[317 318]. Organic hazardous substances are also decomposed in the processes and some may lose their hazardous properties[319]. There is also potential for remaining hazardous fractions (such as bromine rich fractions) to be removed in the refining processes[320 321]. Thermal degradation processes have been demonstrated for several different plastics, such as PET, PVC, PMMA, PS, PE and PP[322 323].

TECHNICAL READINESS

Thermal degradation processes are not in industrial use for the purpose of detecting, quantifying or separating SVHC in waste materials in recycling processes[324]. However, a few commercial pyrolysis facilities and pilots for plastic waste (i.e. PMMA, PS, PE, PP) exist globally[325]. In Europe there is a facility in Rotterdam[326]. Present-day facilities have focused on production of fuels for incineration[327 328]. The output from the thermal degradation processes can be used for fuels and incineration, sometimes considered a contradictive type of recycling[329 330]. Carbon black, which is an output from pyrolysis of tyre rubber, can be used in the production of new rubber products[331]. Techniques for recycling into new plastics are still technically immature[332].

FUTURE POTENTIAL

These techniques are comparably expensive and with the high accessibility of virgin petrochemical feedstocks for plastics production they are not assessed as being economically viable for recycling today[333]. With a shift in feedstock accessibility, the processes are promising for recycling unutilised waste streams[334 335].

ACCURACY

For hazardous substances that are degraded, including SVHCs, the accuracy may prove to be high[336 337].

ADVANTAGES AND LIMITATIONS

The major advantages are the potential to recycle heterogeneous waste and unutilised waste streams and simultaneously clean out additives, contaminants and hazardous substances as part of the process[338 339 340]. However, other hazardous substances may be formed in the pyrolysis process, such as polycyclic aromatic hydrocarbons (PAHs), dioxins, implying a need for further purification steps[341 342]. Flame retardants in the initial product in a pyrolysis process may result in the formation of brominated dioxins and chlorinated dioxins[343]. Thermal degradation includes energy demanding processes and is expensive in relation to incineration of the waste, the normal procedure for mixed or difficult materials today[344].

DISSOLUTION-BASED CHEMICAL RECYCLING

AT A GLIMPSE

Recycling stream: Plastics (incl. laminates and composites) and textiles (cotton, regenerated fibres, plastic fibres)

Hazardous substances: Potential to remove SVHCs and other hazardous substances

Application	Technical readiness
☐ Detection	☒ In use
☐ Quantification	☒ In use within 5 – 10 years
☐ Material sorting	
☒ Removal	

Main advantages: Potential to recycle unutilised waste streams, potential removal of SVHCs.

Main limitations: Immature techniques, require solvents/catalysts.

DESCRIPTION

Chemical recycling includes several dissolution-based techniques for separation of specific polymers from other materials, such as solvent-based extraction, chemical depolymerisation and solvolysis[345 346 347]. By adding a solvent, specific polymers are disintegrated and sometimes depolymerised to monomers, and then separated from undissolved components[348]. Since different hazardous substances and SVHCs will dissolve or remain undissolved in a specific solvent, there is potential for their removal from either the dissolved or the undissolved fraction with these techniques. Different dissolution methods (different solvents, supercritical solvents, catalysts, temperatures and pressures) are suitable for selective solubilisation of different plastics (such as PET, PU, PLA, PA, PC, PHA, PEF) or textile fibres. The hazardous substances present in the waste stream and the solvent system used will determine what hazardous substances can be removed[349 350 351].

TECHNICAL READINESS

For some applications (e.g. cotton, viscose and rayon) the dissolution techniques are similar to the techniques for production of regenerated textile fibre. These processes are already in industrial use[352]. There are several pilot plants for the plastic types PET, PA and PU in Europe[353]. Several of the pilot plants aim for industrial scale within 5 years[354 355].

FUTURE POTENTIAL

Chemical recycling with dissolution-based techniques is expensive compared to present-day mechanical recycling techniques and with the high accessibility of virgin petrochemical feedstocks for plastics production they are not economically feasible for recycling[356 357]. The techniques are, however, considered to have large future potential, but are still limited by small available waste streams[358]. Chemical recycling holds potential to remove some SVHCs by dissolving them in the solvent, although available information regarding which substances could be removed and to what extent is limited[359].

ACCURACY

The accuracy for removing SVHC will depend on each application.

ADVANTAGES AND LIMITATIONS

The major advantage is that complex and unutilised waste, such as mixed plastic and textiles (i.e. composites, plastic laminates, shredded material from ELVs, polycotton), can be recycled[360 361]. The potential to remove hazardous substances and other contaminants is also advantageous[362]. Nevertheless, a more complex or varying waste stream will require more separation steps and be more expensive[363].

The costs of each chemical recycling process will depend on each application[364]. These techniques require larger volumes of unutilised waste streams than the industry has access to today and are therefore not yet a cost-efficient alternative[365].

EXTRACTIVE METALLURGY

AT A GLIMPSE

Recycling stream: Metals, batteries, WEEE

Hazardous substances: Heavy metals

Application	Technical readiness
☐ Detection	☒ In use
☐ Quantification	☒ In use within 5 – 10 years
☐ Material sorting	
☒ Removal	Main advantage: Extract valuable metals.
	Main limitations: Limited available waste material.

Description

There are two kinds of extractive metallurgy, pyrometallurgy and hydrometallurgy, that could be used in recycling of for example batteries and fluorescent lamps, which can contain a number of hazardous substances such as heavy metals, including SVHCs[366 367]. Pyrometallurgy is based on thermal treatment, where metals in waste material are heated and distributed among a flue gas and dust fraction, slag and a metal melt. The metal melt is then further purified in an electrolytic process. The process is used to recover metals from waste material and is suitable for separation of bulk metals, such as copper, aluminium, iron, chromium, tin and manganese. Hydrometallurgy is based on leaching with acid and alkaline solutions to transform metals from a solid to an aqueous solution[368].

Although a combination of the two techniques would be suitable for extraction of different metals in batteries, there is not enough waste material to sustain facilities with both pyro- and hydrometallurgical processes, or enough material for industrial facilities[369].

There are only a few industries on the European market who recycle lithium-ion batteries, although there are some pilot plants, for example in Belgium, France and Germany.

Technical readiness

In the present recycling industry, pyrometallurgy is in commercial use, while there are no hydrometallurgical processes in commercial use. The commercial processes for example for batteries are hence based on melting down the material to extract and recycle the metals[370].

Pyrometallurgy is also used for other purposes, such as the production of copper in Europe. For this application, hydrometallurgy is in commercial use outside of Europe[371].

Future potential

There is future potential for both pyrometallurgical and hydrometallurgical processes for recycling of metals for example from batteries and WEEE, and therefore for control of SVHCs in such recycling processes[372].

Accuracy

The extractive metallurgical techniques can be used to remove metals such as mercury, cadmium and lead in battery recycling[373].

Advantages and Limitations

Pyrometallurgical processes in battery recycling require the use of high temperatures. Pyrometallurgy can be performed at relatively low cost but do not produce as clean an output as hydrometallurgy, which is a more complex method[374].

Pyrometallurgic processes are assessed as being less expensive than hydrometallurgical processes[375].

Abbreviations

ABS	Acrylonitrile-Butadiene-Styrene
BFR	Brominated Flame Retardant
BPA	Bisphenol A
C&D	Construction and Demolition
decaBDE	Decabromodiphenyl ether
DINP	Diisononyl phthalate
DIDP	Diisodecyl phthalate
DNOP	Di-n-octyl phthalate
ED-XRF	Energy dispersive X-ray fluorescence
ELV	End-of-Life Vehicles
GC	Gas Chromatography
GC/MS	Gas Chromatography – Mass Spectrometry
HDPE	High Density Polyethylene
HPLC	High-performance liquid chromatography
HPLC-FLD	High Performance Liquid Chromatography with Fluorescence Detection
LIBS	Laser induced breakdown spectroscopy
MCCP	Medium-Chained Chlorinated Paraffin
MS	Mass sprectrometry
NIR	Near-Infrared spectroscopy
IR-techniques	Infrared light techniques
PA	Polyamide
PAH	Polycyclic Aromatic Hydrocarbons
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PBDE	Polybrominated diphenyl ethers
PVC	Polyvinyl chloride
Pyro-GC/MS	Pyrolysis Gas Chromatography/Mass Spectrometry
RoHS	Restriction of Hazardous Substances
SCCP	Short-Chain Chlorinated Paraffin
TED GC/MS	Thermal extraction desorption gas chromatography mass spectrometry
WEEE	Waste Electrical and Electronic Equipment
XRF	X-ray fluorescence

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Categories of techniques

Techniques for detection
Magnetic separation
ED-XRF
WD-XRF
XRT
NIR
FT-IR
Sliding spark spectroscopy
LIBS
Raman spectroscopy
RFID
QR
Droplet test
Laboratory analyses

Techniques for quantification
ED-XRF
WD-XRF
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Manual sorting
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Appendix 2 Excluded techniques

Table 1. Techniques identified during the review but not included as technical summaries in the report. Techniques were excluded from further investigation based on their limited potential to control for SVHC, limited commercial potential today or in a near future, limited information to assess potential, or use/development of techniques outside of Europe.

Function	Category	Technology	Comment
Sorting	Mechanical recycling	Air jet	A technique for sorting, used in combination with techniques that could control for SVHC. Not included as it does not identify substances itself, but only sort materials.
Sorting	Mechanical recycling	Eddy current	Potential removal of hazardous substances but limited applicability to SVHC
Sorting	Mechanical recycling	Visual Light sensor/Camera	Potential removal, but limited applicability to SVHC
Sorting	Mechanical recycling and chemical recycling	Digital watermarks	Potential detection pf SVHC but not assessed to be a commercial technique within a near future
Sorting	Mechanical recycling and chemical recycling	Micro structure on surface	Potential detection pf SVHC but limited applicability to SVHC
Sorting	Mechanical recycling	Electrolysis	Limited information
Sorting	Mechanical recycling	Vibrating table	A technique for sorting, used in combination with techniques that could control for SVHC. Not included as it does not identify substances itself,

			but only sort materials.
Sorting	Mechanical recycling	Electrostatic separation	Limited information
Sorting and removal	Mechanical recycling	Aspiration / flake sorting	Limited information
Detection and quantification	Mechanical recycling	ICP- Inductively Coupled Plasma techniques like ICP-AES and ICP-OES	Limited information
Detection	Mechanical recycling and chemical recycling	Burning of material, visual analysis of flame	Potential detection of SVHC. Limited information and not assessed to be a commercial technique within a near future.
Detection	Mechanical recycling	^{19}F NMR - nuclear magnetic resonance spectroscopy (fluorine)	Limited information and not assessed to be a commercial technique within a near future.
Detection	Mechanical recycling	Combustion chromatography	Limited information
Control of hazardous substances	Mechanical recycling and chemical recycling	Closed loop recycling	Potential control of SVHC, mentioned in the report.
Control of hazardous substances	Chemical recycling	Polymer design for improved degradation	Limited information and not assessed to be a commercial technique within a near future.
Removal	Mechanical recycling	Sand blasting of wood for removal of wood preservation treatments like creosote or chromated copper arsenate	Potential removal of SVHC but limited information.
Removal	Mechanical recycling	Saw top layer of wood for removal of wood preservation treatments like creosote or chromated copper arsenate	Potential removal of SVHC but limited information.
Removal	Mechanical recycling	Cleaning wood with rotating brushes for removal of wood preservation treatments like creosote or chromated copper arsenate	Potential removal of SVHC but limited information.
Removal	Mechanical recycling	UV-fluorescence used for glass recycling	Limited information
Removal	Chemical recycling	Econyl process – chemical depolymerisation	Potential removal of SVHC. The type of technique is described in the technical summary for

			Dissolution based chemical recycling.
Removal	Chemical recycling	Solvent-based purification	Potential removal of SVHC. The type of technique is described in the technical summary for Dissolution based chemical recycling.
Removal	Chemical recycling	Urea salt + NaCl	Limited information
Removal	Chemical recycling	re:newcell method for cleaning of process water	Limited information
Removal	Chemical recycling?	Supercritical fluids, enzymes, reduction reactions or metathesis	Limited information
Removal	Mechanical recycling	Thermic process – vaporization of coatings on metal cans	Limited information
Removal	Mechanical recycling	Ozone	Limited information
Removal	Mechanical recycling	pH, temperature, solvents	Limited information
Removal	Chemical recycling	Enzymatic degradation / cascading event	Limited information
Removal	Chemical recycling	Devulcanization	No removal of SVHC Not a commercial technique
Removal	Mechanical recycling	Fuming (fuming facility)	Potential removal Limited information
Removal	Energy recycling	Cleaning of ashes from energy recycling, e.g. ash wash with zinc retrieval = fuming??	Potential removal Limited information
Removal	Leachate from mechanical recycling	Carbon filters + chemical cleaning step	Not removal during recycling process
Removal		Surface treatment with chemicals	Limited information
Removal		Extraction with super critical carbon dioxide	Limited information
Removal		Ultra sound extraction	Limited information
Removal	Chemical recycling	MIPAN	Potential removal of SVHC. The type of technique is described in the technical summary for Dissolution based chemical recycling.

Removal	Chemical recycling	Ecocircle	Potential removal of SVHC. The type of technique is described in the technical summary for Dissolution based chemical recycling.
Removal	Chemical recycling	Ioncell F	Potential removal of SVHC. The type of technique is described in the technical summary for Dissolution based chemical recycling.
Removal	Chemical recycling	Sax-Cell process	Potential removal of SVHC. The type of technique is described in the technical summary for Dissolution based chemical recycling.
Removal	Chemical recycling	CCA, carbamate process	Potential removal of SVHC. The type of technique is described in the technical summary for Dissolution based chemical recycling.
Removal	Chemical recycling	Hydrothermal condensation	Limited information
Removal	Chemical recycling of PVC	Dehydrochlorination	Limited information
Removal	Energy recycling	Incineration /Combustion	Not included as recycling
Recycling step	Mechanical recycling	Friction washing	Limited information on potential to control SVHC
Recycling step	Mechanical recycling	Hammer mill	Performs size reduction of waste streams, limited potential to control SVHC.
Recycling step	Mechanical recycling	Shredding	Performs size reduction of waste streams, limited potential to control SVHC.
Recycling step	Mechanical recycling	Grinding	Performs size reduction of waste streams,

			limited potential to control SVHC.
Textile production	n.a.	Solvent spinning	Limited information on potential to control SVHC
Textile production	n.a.	Melt spinning	Limited information on potential to control SVHC
Textile production	n.a.	Lyocell process	Production technology
Textile production	n.a.	Viscose process	Production technology
n.a.	n.a.	Incubation at high temperature	Limited information
n.a.	n.a.	Vacuum- or inert gas treatment	Limited information
n.a.	n.a.	Neutron activation	Limited information

Control of Substances of Very High Concern in Recycling

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Review of techniques for detection, quantification and removal

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Chemical substances with hazardous properties can enter recycling processes through articles and mixtures that become waste. Some substances have such hazardous properties that they should, as far as possible, be phased out. Of special interest are Substances of Very High Concern (SVHCs).

The aim of this report is to provide an accessible review of techniques that can be used to control SVHCs in recycling processes and prevent recirculation of SVHCs into new products. This includes techniques that can detect, quantify and remove hazardous substances in any of the different steps during a recycling process. The review showed that there are a number of available techniques that control different hazardous substances, although sometimes as a valuable side effect from sorting material streams into more homogeneous fractions. Mechanical recycling is the predominant type of recycling today, although several initiatives are developing techniques for chemical recycling.

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