Chemosphere 312 (2023) 137175

Contents lists available at ScienceDirect

Chemosphere

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

Safety of recycled plastics and textiles: Review on the detection, identification and safety assessment of contaminants

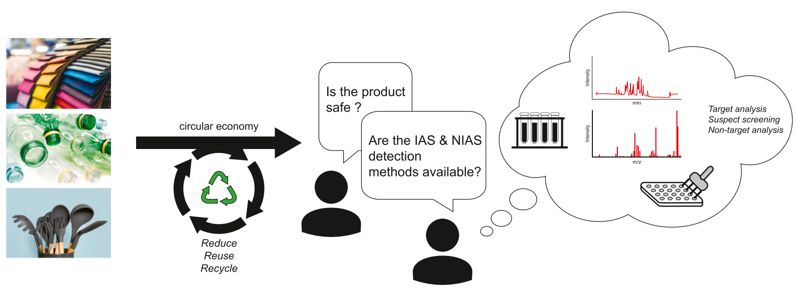
Anna K. Undas, Marc Groenen *, Ruud J.B. Peters, Stefan P.J. van Leeuwen

Wageningen Food Safety Research, Akkermaalsbos 2, 6708, WB, Wageningen, Netherlands

HIGHLIGHTS

- The database on contaminants in recycled plastic FCM is limited.
- Nearly no information on the safety of recycled textiles is available.
- Studies covering potential inorganic contamination in recycled materials are still missing.
- Approaches like TTC and CoMSAS for risk assessment should be used for recycled plastic and textile materials.

GRAPHICAL ABSTRACT



ARTICLE INFO

Handling Editor: Derek Muir

Keywords:
Circular economy
Recycling
Plastic
Textile
Chemical analysis
Safety assessment

ABSTRACT

In 2019, 368 mln tonnes of plastics were produced worldwide. Likewise, the textiles and apparel industry, with an annual revenue of 1.3 trillion USD in 2016, is one of the largest fast-growing industries. Sustainable use of resources forces the development of new plastic and textile recycling methods and implementation of the circular economy (reduce, reuse and recycle) concept. However, circular use of plastics and textiles could lead to the accumulation of a variety of contaminants in the recycled product. This paper first reviewed the origin and nature of potential hazards that arise from recycling processes of plastics and textiles. Next, we reviewed current analytical methods and safety assessment frameworks that could be adapted to detect and identify these contaminants.

Various contaminants can end up in recycled plastic. Phthalates are formed during waste collection while flame retardants and heavy metals are introduced during the recycling process. Contaminants linked to textile recycling include; detergents, resistant coatings, flame retardants, plastics coatings, antibacterial and anti-mould agents, pesticides, dyes, volatile organic compounds and nanomaterials. However, information is limited and further research is required. Various techniques are available that have detected various compounds, However, standards have to be developed in order to identify these compounds. Furthermore, the techniques mentioned in this review cover a wide range of organic chemicals, but studies covering potential inorganic contamination in recycled materials are still missing. Finally, approaches like TTC and CoMSAS for risk assessment should be used for recycled plastic and textile materials.

* Corresponding author.
E-mail address: marc.groenen@wur.nl (M. Groenen).

https://doi.org/10.1016/j.chemosphere.2022.137175
Received 23 December 2021; Received in revised form 30 June 2022; Accepted 5 November 2022
Available online 9 November 2022

1. Introduction

Plastic is a widely used multipurpose commodity. In 2019, 368 mln tonnes of plastics were produced worldwide, of which 57,9 mln tonnes were produced in Europe. Some forecast that the global market for recycled plastics will grow 8.2% between 2021 and 2028 (Fortune Business Insights, 2021). However, increased plastic production will lead to an increase in the energy required to produce the materials, consume more fossil fuels, and more plastic waste will be released to the environment. While the market for plastic products is growing, the amount of plastic that is being recycled is lagging behind. Europeans recycled only 9.4 mln tonnes of plastic in 2018 (Plastics Europe, 2020) even though approaches to slow down the demand for some types of virgin plastic have been developed and waste management and recycling technologies are in place or are being developed.

In Europe, (plastic) food contact materials (FCMs), are regulated in EC regulation October 2011 "on plastics materials and articles intended to come into contact with food" and its amendment (EU, 2020/1245) (European Commission, 2011). In the case of recycled plastics (including packaging and, e.g. kitchen utensils), guidance is provided by Commission Regulation (EC) No 282/2008 "on recycled plastic materials and articles intended to come into contact with foods and amending Regulation (EC) No 2023/2006" (European Commission, 2008). It should be noted that the recycling processes themselves are regulated and that the European Commission keeps a register for validated FCM recycling processes (European Commission, 2014), rather than regulating contaminating substances. More recently, the European commission is planning to revise FCM legislation as part of its Farm to Fork Strategy (European Commission, 2022c).

The textiles and apparel industry produces large amounts of materials, which lead to large amounts of waste. With an annual revenue of 1.3 trillion USD in 2016, the textiles and apparel industry is one of the largest fast-growing global industrial sectors (Footwear, 2016). Annual production has nearly doubled since 2000, surpassing 100 billion units in 2015, with apparel consumption expected to rise 63% by 2030. However, awareness of the industry's linear supply lines, the fast-fashion model, and its environmental impact is increasing. The textiles and apparel industry can thus significantly contribute to the vision of a circular economy if materials and energy can be recovered from used products (Ellen McArthur Foundation and Circular Fibres Initiative, 2017). Salerno-Kochan and Kowalski (2020a, 2020b). The two-part paper from Salerno-Kochan and Kowalski reviewed legal regulations regarding safety requirements for clothing and textile products that are spread over multiple EU regulations. None of them, though, establish a framework for the safety evaluation of recycled materials. More recently though, the EU called for a mandatory minimum use of recycled fibres by 2030 and a consecutive ban on the destruction of many unsold products, stimulating the need for recycling practices of textiles (European Commission, 2022a,b).

From a technical point of view, recycling and reprocessing thermoplastic materials, with the aim of producing new plastic materials, can generally be performed easily. Waste collection strategies are in place and plastic waste then needs to be grinded and might be subjected to an optional washing step. After re-melting, recycled pellets can be used to create new products by injection moulding, extrusion, rotational moulding, or heat pressing. On the other hand, thermoset materials cannot be recycled due to chemical degradation during the melting process. Other materials such as composites and textiles remain challenging due to the heterogeneity of polymers and fabrics (Maris et al., 2018; Post et al., 2020; Soroudi and Jakubowicz, 2013). While several types of fabric are readily recycled through mechanical recycling (e.g., respinning), mixed textiles are hard to separate.

Although technically some recycling processes have been established, and others are developed, the question rises if such recycled materials are safe to use for the same purpose, or even a different purpose. Extending the life cycle of plastics and textiles will also introduce the risk of contaminants accumulating in reusable products (Leslie et al., 2016). There are a variety of contaminants that can occur in recycled plastics and textiles. These include intentionally added substances (IAS) like pigments and additives or unknown non-intentionally added substances (NIAS) and contaminants like per- and polyfluoroalkyl substances (PFAS), bisphenol-A (BPA) and brominated flame retardants (BFRs). A framework for the safety (risk) evaluation of potential contaminants in recycled plastics and textiles is needed to facilitate increased recycling while ensuring consumer safety.

To identify potential hazardous substances and associated risks for consumers, state-of-the-art chemical analyses need to be implemented. Especially new strategies are needed for NIAS as only a few were reported in plastics (Geueke, 2018; Horodytska et al., 2020). In this paper, our aim is to first review the origin and nature of potential hazards that arise from the recycling processes of plastics and textiles. This will support best monitoring and investigation practices by offering an overview of contaminants that should be observed. Next, we review current analytical methods and safety assessment frameworks that could be adapted to detect and identify these contaminants and thus improve the safety of recycled products and the acceptance of circular plastics and textiles by consumers.

2. IAS, NIAS and contaminants in recycled materials

Plastics and textile materials can be recovered through various forms of recycling (Geyer et al., 2016). Of these, mechanical recycling is the most common method (Ignatyev et al., 2014). Recently, several publications have emerged that give an overview of substances associated with plastic, plastic packaging or textiles.

2.1. Plastics

The group of potential contaminants that may end up in products containing recycled plastics is diverse. During the life cycle of plastic (Fig. 1), many substances from different sources can contaminate a recycled product: polymeric impurities (monomers, oligomers, polymeric fractions) from a different polymer than the intended product, additives (e.g. pigments, stabilisers, catalysts, fillers), chemical contaminants originating from previous use (e.g. odours and flavours, residues), newly formed chemicals generated during the recycling process, volatile organic compounds (VOCs) formed during the degradation of polymers, and contaminants coming from the mixed collection of waste polymers.

2.1.1. Contaminants formed during production

During the production of plastics, several substances are blended to produce the intended product. In Europe, around 600 substances are authorised as additives and polymer production aids for Food Contact Materials (FCM) (European Commission, 2011). However, residual additives and their breakdown products may remain in the plastic material. These IAS in plastic may migrate into food, cosmetics, or the environment. A report from the Norwegian Environment Agency from 2013 outlined the presence of 43 substances used in the production of plastics that are on the country's priority list for contaminants and may limit the possibilities for plastic recycling (NEA, 2013). However, the report does not discuss recycled materials. Therefore, the list of indicated substances can potentially be longer. Nevertheless, identified substances in the report include phthalates, toxic metals, BFRs and poly-aromatic hydrocarbons (PAHs). Recycling and reuse could thus lead to the accumulation of these contaminants in recycled plastics (Leslie et al., 2016).

2.1.2. Contaminants arising from previous use and waste collection

Recycling FCM, a diverse group of plastics commonly used for kitchen utensils and packaging foodstuffs, may lead to incidental contaminants arising from previous use or cross-contamination during

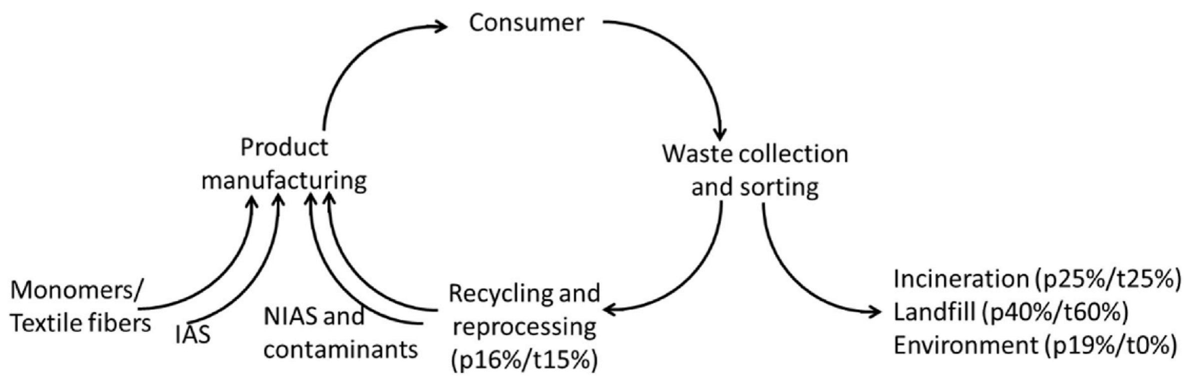


Fig. 1. The plastic and textile recycling process. NIAS and contaminants are introduced by recycling and reprocessing techniques. The percentages which are recycled or go to incineration, landfill or the environment are indicated for plastics (p) and textiles (t). (The percentages for the plastic cycle were extracted from (Geyer et al., 2017). The percentages for textiles were extracted from: US-EPA, Advancing Sustainable Materials Management: Footwear, 2016, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management).

disposal. Contamination by previous use has been reported in recycled plastics (Dutra et al., 2011; Geueke et al., 2018). 11 esters and 6 alcohols were identified in recycled but not in virgin HDPE; their origin was assigned to previous use of the packaging, e.g., personal hygiene products or cleaning agents. Furthermore, flavour, odour, and aroma substances are common contaminants in post-consumer plastic packaging. The presence of limonene and citrus-based essential oils has been attributed to soft drinks stored in PET bottles. Additionally, Dreolin et al. (2019) showed the presence of BPA originating from printing inks or other materials in the recycled-PET (rPET) samples. Other substances from food-grade PET used in non-food applications such as mouthwash, personal hygiene and household cleaners also contribute to the contamination of post-consumer PET (Ubeda et al., 2018). Similar substances were also measured in recycled HDPE (Geueke et al., 2018).

One class of contaminants originating from previous use and waste collection are phthalates. Keresztes et al. (2013) detected several phthalates in water samples from PET bottles with 20–30% recycled content. In contrast, these phthalates were not found or detected only in low concentrations in water samples from bottles composed of virgin PET. The results of Pivnenko et al. (2016), who analysed the levels of phthalates in plastic waste samples, suggest that these phthalates were introduced into post-consumer PET as irregular external contaminants derived from other polymer types during the collection stage. The systematic statistical assessment of the evaluated PET samples could indicate that phthalates are added in later stages of plastic manufacturing (labelling, glueing, etc.) and are not removed in the re-processing of plastics, making recycling a potential source of phthalates in rPET.

2.1.3. *Contaminants formed during the recycling process*

During recycling, materials are treated with washing agents and solvents and are heated above 125 °C. These processes potentially contribute to a wide range of residual contaminants and *de novo* chemical reaction products. Information on the nature of these contaminants is limited and are also often not known to the manufacturer. During mechanical recycling, plastic polymers are partially degraded by shredding and heating, resulting in lower molecular weight distribution and changed mechanical and optical properties. By-products of oligomers may form during the recycling of polymers. Linear and cyclic oligomers have been measured in recycled PET, with di- and trimers being the predominant species (Ares Pernas et al., 2014). Acetophenone and benzaldehyde are oxygenated derivatives of styrene, which have been found in higher relative abundances in recycled compared to virgin polystyrene (PS) samples (Geueke et al., 2018). Song et al. (2019) measured thermal degradation of PS after recycling and found increased levels of volatile NIAS migration into vegetable oils at high temperatures. While the formation of a variety of unintentional by-products during recycling is known, the knowledge on their migration into food seems to be limited.

Additionally, plasticisers, antioxidants and stabilisers may form unintended reaction products during recycling. These compounds cause undesirable changes to the plastics' characteristics. To compensate for these changes, virgin polymers and additives are added. Dutra et al. (2014) measured the migration of non-volatile and inorganic residual substances from post-consumer recycled PET and multilayer packaging material containing post-consumer recycled High-Density Polyethene HDPE. Using food simulants, several authorised plastic additives were measured in recycled PET. Among these were the plasticisers di-isononyl adipate (DINA) and di-isononyl phthalate (DINP), the optical brightening agent Uvitex OP and the slip agent oleamide. Several inorganic contaminants were found, determined by inductively coupled plasma mass spectrometry (ICP-MS). All were below acceptable levels.

Metals can also contaminate recycled plastic products. Metal-containing additives directly impact the recyclability of plastics or even support the degradation of plastics (Pivnenko et al., 2016). In particular, metal salts or oxides such as Fe_2O_3, CuO, ZnO and TiO_2 have been found to act as pro-oxidants and photo-oxidation catalysts (Nikolaivits et al., 2021). Plastic samples, including plastic household waste, recycled plastic waste from households and industry, and virgin plastics, were analysed for 15 selected metals. Samples of reprocessed household waste contained the overall highest concentrations of metals, potentially related to the use of metal-containing additives (e.g., fillers) to enhance the mechanical properties of plastic during recycling. While the elevated metal concentrations in recycled plastic did not exceed legal limits, it is important to be aware that metal concentrations are higher in recycled plastic from household plastic waste. A continuous increase in plastic recycling rates may lead to higher metal concentrations in the future (Eriksen et al., 2018).

Cross-contamination can also originate from non-food grade plastics by transference of certain groups of additives into new recycled products. For instance, brominated and phosphorous flame retardants, brominated dioxins and phthalates have been found in children's toys containing recycled material (Budin et al., 2020; Hahladakis et al., 2018; Ionas et al., 2014; Lee et al., 2014). Flame retardants have also been measured in samples of black plastic FCMs and household products within the European market (Puype et al., 2015, 2017; Samsonek and Puype, 2013). Flame retardants are commonly divided into four groups based on the main chemical constituent: halogenated, phosphorus-containing, nitrogen-containing and inorganic (Delva et al., 2018). A subgroup of halogenated organic flame retardants, the BFRs, are present the most. Hexabromocyclododecane (HBCD) and tetrabromobisphenol A (TBBPA) are well-established BFRs, while there are also emerging phenol-containing BFRs such as 2,4-dibromophenol (2,4-DBP) and 2,4,6-tribromophenol (2,4,6-TBP). HDPE contained the lowest concentrations of HBCD and TBBPA, while packaging waste

HDPE (both source segregated and residual) contained the highest concentrations of 2,4-DBP and 2,6-dibromophenol (2,6-DBP). In addition to the direct use of selected BFRs, relatively high concentrations of 2,4-DBP (240 ng/g), 2,6-DBP (250 ng/g) and TBBPA (7000 ng/g) in a sample could be attributed to thermal degradation of TBBPA and production of dibromophenols as by-products in recycling. Puype et al. (2015) analysed 10 selected food contact utensils (produced from recycled materials), of which seven contained a bromine level ranging from 57 to 5975 mg kg-1. BFRs that were present were TBBPA decabromodiphenylether (decaBDE), decabromodiphenylethane (DBDPE) and 1,2-bis(2,4,6tribromophenoxy)ethane (BTBPE). All cases in which bromine was detected at higher concentrations, antimony was also detected. This observation confirms the synergetic use of antimony in combination with BFRs. Finally, the plastic recycling process may also influence the transformation of contaminants contained in waste material. For example, among the three isomers of HBCD measured, α-HBCD was found in relatively higher concentrations compared to β– or γ-HBCD (Pivnenko et al., 2017). This contradicts the common composition of commercial HBCD mixtures where γ-HBCD is the dominant isomer. Exposing HBCD to temperatures higher than 100 °C promotes the transformation of γ-HBCD to α-HBCD. These temperatures are commonly applied in thermoplastics re-processing (135–245 °C) and can alter the diastereomeric ratio of a HBCD mixture and explain the prevalence of the α-HBCD in samples of recycled plastics.

Many substances can be used to produce plastic. This process may lead to accumulation of phthalates, toxic metals, BFRs and polyaromatic hydrocarbons in plastic when it is continuously recycled. Previous use and waste collection may cause flavour, odour and aroma compounds to build up in HDPE while limonene and phtalates may form a risk in rPET. Furthermore, the recycling process itself can cause metals, especially metal salts, and BFRs to end up in the recycled product. The wide variety of contaminants in recycled materials (Table 1) emphasizes the need for a detailed assessment strategy for contaminants associated with plastic packaging.

2.2. Textiles

An overview of the life cycle of textiles is presented in Fig. 1. Like plastics, many substances are used during the production or recycling of textiles. Six broad substance groups have been identified: amines, dyes and residuals, halogenated substances, metals, monomers and solvents, and process aids (Safer Made, 2018). All these groups are represented by a broad spectrum of chemicals. For example, over 8000 substances may be used to provide colour or impart function to textile (Safer Made, 2018). The number of additives used can comprise 5–15% of a garment's weight (Safer Made, 2018). However, various products have been identified to be toxic to human health and produce a multitude of environmental effects, most notably water pollution. Risk assessment of many substances, especially those classified as NIAS still needs to be performed. An overview of papers on contaminants in textiles can be found in Table 2. We aimed to indicate important papers and briefly summarise the type of contamination.

The current composition of textile materials (e.g., cotton mixed with other polymers) impedes its recycling since they are hard to separate. Additionally, specific substances increase the difficulty of recycling. Consequently, the knowledge base surrounding substances problematic for recycling of textiles is limited and specific impacts have not been characterised. In the current system, information regarding substances and quantities present in textile materials are not generally passed on to recycling companies. It would be beneficial to fill the knowledge gaps in this area by improving traceability and the identification of substances in textile materials and the examination and identification of substances that have been found to interfere with recycling technologies. In addition to known substances of concern, there are emerging concerns related to plastic pollution caused by the textile and apparel industry. Synthetic textile fibres like polyester and nylon are abundant in apparel. Synthetic polymers tend to persist in the environment and can end up acting as chemical contaminants as well as substrates that magnify the accumulation of other harmful substances in the ecosystem. A study by Browne et al. (2011) connects plastic microfiber pollution in the marine environment with wastewater disposal from washing apparel made from synthetic fibres. Since (mechanically) recycled textile is expected to contain less strong bound textile fibre, this problem may increase with increasing textile recycling. A wide range of contaminants was reported in several studies, as shown in Table 2. The study by van der Veen et al. (2020) included one recycled fabric, but it is unclear if the PFAS found in that product resulted from the recycling of PFAS contaminated fabric, or from postproduction treatment with PFAS to improve water and dirt repellence. To the best of our knowledge, no further reports on contaminants in recycled textiles are available and further research is required.

3. Analytical approaches for chemical analysis of recycled plastics and textiles

There are a variety of techniques to detect and identify the contaminants mentioned previously (see Tables 1 and 2). Selecting suitable techniques depends on the physical and chemical properties of the compounds of interest, e.g., volatile versus non-volatile compounds and polar versus non-polar compounds. Techniques like headspace trapping or solid phase microextraction (SPME) are often used to analyse volatile contaminants. Potential non-volatile contaminants can be extracted from plastics or textile material using organic solvents, often microwave-assisted or using an ultrasonic bath. For materials intended as FCM, migration studies are performed using relevant food simulants. 10% and 20% ethanol or 3% acetic acid are used as polar food simulants, while 50% ethanol and vegetable oil are used as non-polar food simulants (European Commission, 2011).

Regarding the scope of the analysis, techniques can be classified into target, non-target and suspect screening. Targeted analytical approaches use dedicated analytical and data processing approaches to investigate specific chemicals or a group of chemicals of which the identity is known prior to analysis. In contrast, suspect screening uses generic analytical methods for detection, while data evaluation uses a list of suspects (Schymanski et al., 2015). A list of suspects usually concentrates on IAS, while non-target approaches concentrate on detecting NIAS. Non-target approaches simultaneously generate data on hundreds or thousands of molecules, representing unknown compounds characterised by their monoisotopic masses, retention times and isotope patterns, sometimes accompanied by fragmentation spectra when MS/MS analysis is performed (Sobus et al., 2018). Identification of NIAS uses the "identification levels" concept provided by Schymanski et al. (2014), where five confidence levels are determined. The ultimate identification is achieved at level 1, where the confirmation is obtained through measuring pure standards. In the case of the analysis of recycled materials, identification will finish at level 2 (list of probable structure(s)) or 3 (list of tentative candidate(s)) for many contaminants due to the lack of a pure standard.

Currently used analytical approaches were discussed by Martínez-Bueno et al. (2019), Wrona and Nerín (2020), Kato and Conte-Junior (2021), and Curran and Strlič (2015). The techniques and data processing approaches for analysing migrants from FCM are discussed in the first review, while the second and third summarise the analytical approaches used to assess the safety of FCM via IAS and NIAS analysis. The last-mentioned review concentrates on analysing volatile organic compounds (VOCs) emitted from plastics and rubber objects. Nerín et al. (2022) not only summarises the state-of-art techniques but also provide the guidelines that need to be taken into consideration when analysing NIAS.

The current state of the art, especially HRMS techniques, allow us to detect a wide range of chemicals. However, we lack the harmonised methods, databases and tools for better identification. The existing

Table 1
Overview of recent inventories and research papers on the substances in plastic or plastic packaging.

No. Of chemicals	Material	Classes of chemicals (examples of chemicals)	IAS/ NIAS[a]	Identification level			Citation
				Literature study	Tentative identification	Identified with standards	
not specified	virgin and recycled HIPS	# VOCs # styrene dimers # compounds originating styrene trimers # different aliphatic compounds	NIAS		x		Vilaplana et al. (2007)
approx. 2600 detected peaks analysed; not specified	virgin and recycled plastics LDPE, PP, PS	#VOCs: - chlorinated hydrocarbons - phthalates - other compounds i.e. aliphatic hydrocarbons, aromatic hydrocarbons, alcohols, aldehydes, ketones, carboxylic acids, esters, ethers	NIAS		x		Yamashita et al. (2009)
85	PET post-consumer flakes and pellets HDPE multilayer packaging containing recycled HDPE	# VOCs: aliphatic and aromatic aldehydes, ethers, esters, aliphatic acids, aromatic compounds, alkanes, alkenes, ketones and alcohols	NIAS		x	- benzaldehyde, - 2,4-di-*tert*-butylphenol, - BHT, - limonene	Dutra et al. (2011)
6	PET bottles	# phthalates: DEP, DMP, DiBP, DBP, BBP, DEHP	NIAS		x	- DEP - DMP - DiBP - DBP - BBP - DEHP	Keresztes et al. (2013)
7	PET post-consumer flakes and pellets HDPE multilayer packaging containing recycled HDPE	A. organic compounds – plasticisers: diisononyl adipate (bis(7-methyloctyl) hexanedioate), diisononyl phthalate (diisononyl ester 1,2-benzene-dicarboxylic acid) – optical brightening agents: Uvitex OB (2,5-bis(5-*tert*-butyl-2-benzoxazolyl thiophene) – slip agents: oleamide ((Z)-octadec9-enamide), diethyl toluamide (*N*,*N*-diethyl-3-methyl-benzamide) – UV stabilizers: Tinuvin 328 (2-(benzotriazol-2-yl)4,6-bis(2-methylbutan-2-yl)phenol); and the slip agent – monomers: - PET monomer: diethylene glycol (DEG) B. inorganic: Al, Cr, Mn, Fe, Ni, Se, Ba, Pb, Sb			x		Dutra et al. (2014)
not specified	virgin and recycled PET	linear and cyclic oligomers, di- and trimers	NIAS		x		Ares Pernas et al. (2014)
144 groups of- or- single substances	plastic materials, products and waste	e.g. - antimicrobial substances (e.g. organic tin and triclosan) - blowing agents (e.g. fluorinated greenhouse gases) - heavy metal based colorants, stabilisers and catalysts (e.g. cadmium and lead and their compounds - flame retardants (e.g. BFRs and organo phosphates) - monomers, cross linkers, hardeners, chain modifiers and catalysts (e.g. Bisphenol A and formaldehyde) - organic based colorants (e.g. azo dyes) - UV stabilisers, antioxidants and other stabilisers (e.g. dibutyltin dichloride) - plasticisers (e.g. short chain chlorinated paraffins and many different phthalates) - solvents- neutral and reactive (e.g. dimethylformamide) - others (e.g. nonylphenol and PFOs).	IAS	x			Stenmarck et al. (2017)
40	34 packaged foodstuffs (corn snacks, potato snacks, cookies, cakes) and packaging materials	organic compounds: alkanes, aldehydes, alcohols, phthalates, citrates, adipates, phosphates, phenolic compounds, diisocyanates, fatty acids	IAS		x	- diethyl phthalate (DEP),- dibutyl phthalate (DBP), - diisobutyl phthalate (DIBP), - bis(2-ethylhexyl) phthalate (DEHP), - acetyltributyl citrate	García Ibarra et al. (2018)

(*continued on next page*)

Table 1 (*continued*)

No. Of chemicals	Material	Classes of chemicals (examples of chemicals)	IAS/ NIAS[a]	Identification level			Citation
				Literature study	Tentative identification	Identified with standards	
						(ATBC), - benzophenone (BP), - butylated hydroxytoluene (BHT)	
not specified	commonly used FCMs from virgin and recycled plastics	# flavour, aroma and odour compounds # oligomers, monomers and derivatives: linear and cyclic PET oligomers # additives and their degradation products: UV absorbers, antioxidants, plasticisers, phthalates # contaminants from non-food grade plastic and consumer products: brominated flame retardants, sulfuric compounds # inorganic elements	IAS/ NIAS	x			Geueke et al. (2018)
not specified	plastics	# functional additives: stabilisers, antistatic agents, flame retardants, plasticisers, lubricants, slip agents, curing agents, foaming agents, biocides etc. # colorants: pigments, soluble azo-colorants etc. # fillers: mica, talk, kaolin, clay, calcium carbonate, bohrium sulphate # reinforcements: e.g glass fibres, carbon fibres	IAS/ NIAS	x			Hahladakis et al. (2018)
not specified	virgin and recycled PET	cyclic and lineal oligomers	NIAS		x		Ubeda et al. (2018)
80	12 samples of plastic films with and without printing ink (PE/PET, PP/PP, PE/PA, PE/PP, PE/EVA, PP/PET)	A. VOCs: (30) alkanes, cycloalkanes, alkenes, aldehydes, alcohols, aromatic compounds, cyclic amides, phenolic compounds and phthalate esters B. semi-volatile compounds: (50) citrates, phthalates, adipates, phosphates, alkanes, aldehydes, carboxylic acids, alcohols, phenolic compounds, diisocyanates, fatty acids, cyclic amides	IAS/ NIAS		x	21 compounds confirmed with standards: - dodecane - caprolactam - tridecane - tripropylene Glycol - 2,6-Toluene diisocyanate - 2,4-Toluene diisocuanate - tetradecane - butylated hydroxytoluene - diethyl phtalate - hexadecane - benzophenone - heptadecane - octadecane - diisobutyl phtalate - eicosane - docosane - tributyl acetylcitrate - bis(2-ethylhexyl) adipate - tetracosane - bis(2-ethylhexyl) phthalate - erucamide - squalene	García Ibarra et al. (2019)
99	virgin and recycled EPS containers	# volatile and semi-volatile compounds including hydrocarbons, aldehydes, ketones, alcohols and ester	NIAS		x		Song et al. (2019)
148	plastics FCMs	# accelerators: dithiocarbamates, thiazoles, thiurams # biocides: carbamates, phenolic compounds, metal-containing compounds, parabens # colorants: dyes, azo-dyes and pigments # fire retardants: borons, organophosphates # plasticisers: chlorin-d paraffins, phthalates # foaming agents: alkanes # monomers or intermediate	IAS/ NIAS	x			Groh et al. (2019)

(*continued on next page*)

Table 1 (*continued*)

No. Of chemicals	Material	Classes of chemicals (examples of chemicals)	IAS/ NIAS[a]	Identification level			Citation
				Literature study	Tentative identification	Identified with standards	
		compounds: acrylic, amines, bisphenols, zinc containing compounds # solvents: limonenes. Naphtha-related compounds, other hydrocarbons # stabilizers: tins, organophosphites, hindered phenols, benzophenones, benzotriazols # surfactants or its degradation products: nonyl-, octylphenol and nonyl-phenol derivatives, amine on nitrogen containing compounds, PFAS					
23	food samples that were packed in FCMs (glass, plastic, metal, paper, cardboard)		NIAS			- BPA - BADGE and chlorohydrin derivatives - phthalates (DEHP, DBP, DIBP, BBP, DIDP, DINP, DEP, DCHP, DOP, DBS, DEHA) - photo initiators (BP, 4-MBP, 4-HBP, PBZ, ITX)	Sirot et al. (2021)
53	postconsumer recycled polyolefin pellets	different types of low molecular weight compounds e.g. octocrylene, 1-tetradecene, 1-dodecene, and dodecyl acrylate, 2,4-di-*tert*-butylphenol and 1,4-benzenedicarboxylic acid, diethyl ester, benzenamine, 2,4-dichloro- and diethyl phthalate	NIAS		x		Su et al. (2021)

[a] Author's interpretation.

databases, although comprehensive, still concentrate on IAS that are possibly used (Groh et al., 2021). Additionally, the number of studies dealing with the analysis of contamination in recycled plastics or textiles is limited. A few studies focus on methods for detecting contaminants in recycled thermoplastic polymers while most studies on textile-derived contaminants focus on the environmental effects of textile production and its effluents (Hu et al., 2019). Only a few studies report the development of methods to analyse contaminants in textile material itself. At the same time, a framework for the evaluation of potential contaminants and associated risks for the consumer is absent. These examples, together with studies that focus on analysing volatile NIAS, an important group of potential contaminants of recycled materials, are presented in Table 3.

4. Safety assessment framework

Recycled plastics and textiles may contain unknown chemicals that can be identified but not quantified by analytical approaches described in the previous section and summarised in Table 3. Consequently, compound-specific toxicity cannot be assessed. One of the options to assess if those products contain contaminants that could pose a health risk is to test overall migrant toxicity using bioassays. Combining bioassays with chemical analysis has shown to be very effective, although chemical identification is still necessary before toxicity can be linked to a specific substance. The threshold of toxicological concern (TTC) concept has been adopted within the European Union legislation as a tool to deal with unknown chemical substances (European Food Safety Authority and World Health Organization, 2016). The TTC concept uses tentative exposure data to determine whether intake of a substance is below an acceptable threshold of no concern, defined by assigning a Cramer class based on the chemical structure or so-called structural alerts.

TTC is a preliminary assessment tool that is applied to detect and evaluate NIAS, as described by Koster et al. (2014) and Pieke et al. (2018a). Koster et al. published an extensive report on a safety assessment strategy to detect unknown NIAS in FCMs. This strategy facilitates the distinction between toxicologically relevant and less relevant substances through several toxicological assessments. The method is described as a Complex Mixture Safety Assessment Strategy (CoMSAS), and uses several analytical and biological screening procedures that allow the exposure to NIAS to be estimated (Koster et al., 2015). CoMSAS is a decision tree method based on the TTC concept and was applied by Koster et al. to 3 carton FCMs. The LOD of 10 μg/kg food that is generally required and used for the detection of migrants in FCMs, has been replaced by an exposure threshold of 90 μg/day, based on the TTC of Cramer toxicity class III substances. The new threshold is increased by nine times, which substantially reduces the group of components that must be identified. The identification of unknown substances then focussed exclusively on those substances exceeding the threshold.

One model that incorporates the TTC approach is the Complex Mixture Safety Assessment Strategy (CoMSAS). This screening combines four different analytical techniques to ensure as many NIAS as possible are detected. The evaluation of Koster et al. (2014) includes (1) headspace GC-MS (EI) for volatile substances, (2) GC-MS (EI) for semi-volatile substances, (3) derivatisation of non-volatiles followed by GC-MS (EI) analysis, and (4) LC coupled to an evaporative light scattering detector (UV/ELSD) for analysis of non-volatiles. These detectors are used to give a uniform response so a semi-quantitative estimate of the migration rate can be made since incorporating chemical standards is almost impossible due to the large number of potentially present substances. Whenever a substance exceeded the threshold of 90 μg/day, it was identified by GC- and LC-MS. Secondly, during the analytical screening, known highly toxic substances and substances that are not relevant for the TTC concept were excluded. The presence of the following substances was examined: aflatoxin-like substances, *N*-nitroso substances, azoxy substances, polyhalogenated dibenzo-p-dioxins, -dibenzofurans and -biphenyls, steroids, non-essential metals, high molecular weight substances, and organophosphates and carbamates. The third step included a genotoxicity assessment of the migration extract by means of a bioassay. The BlueScreen HC assay was chosen because of its

Table 2
Overview of recent inventories and research papers on the substances in textiles.

No. Of chemicals	Material	Classes of chemicals (examples of chemicals)	Chemicals identified with standards	Citation
not specified		A. Detergents and auxiliaries (e.g. nonphenol ethoxylates) B. water-, oil-, stain-, and wind resistant coatings C. Flame retardants (polybrominated compounds, organophosphoric compounds) D. Plastics coatings E. Antibacterial, anti-mould agents and pesticides (e.g. DMF, triclosan, poly (dimethylaminomethyl) styrene, organic tin compounds, permethrin) F. Dyes and colours G. VOCs H. Nanomaterials		Wijnhoven and Kooi (2010)
400-600 auxiliaries 4000 dyes	textiles	A. Auxiliaries and finishing agents - Agents for improving crumpling and wrinkling behavior: *N*-methylol derivatives (e.g. formaldehyde) - Catalysts for crumpling and wrinkling finish: dialkylated tin derivatives - Gripping agents (e,g, polymers) - Flame retardants (e.g. organophosphates) - *Anti*-microbially active agents: biocides - Phagodeterrents: Permethrin - Waterproofing agents: paraffins, fluoropolymers - Anti-felting finish: polymers - Conditioning agents: oils, greases - Lustering finishing agents: waxes, paraffins - Coating agents: polymers B. Dyes C. Nano finishes		BfR (2012)
22	colored or black clothing	aromatic amines	2,6-Xylidine 3,4-Dichloroaniline 2,5-Diaminotoluene 2,4-Xylidine 2-Methoxy-4-nitroaniline 2-Amino-4-nitroanisol 4-Aminophenol 4-Nitroaniline 4-Ethoxyaniline 2-Amino-6-methoxybenzothiazol *N*,*N*-Dimethyl-1,4-phenylenediamine 1,3-Phenylenediamine-4-sulfonic acid 4-Aminodiphenylamine *p*-Phenylenediamine Sulfanilic acid 1,4-Diamino-2-methoxybenzol 2-Amino-5-chloro-*p*-toluenesulfonic acid 2-Chloroaniline p-Toluidine *m*-Phenylenediamine Aniline 2,20-Dimethylbenzidine	Brüschweiler et al. (2014)
11	26 clothing samples diverse in material and colour	benzothiazoles and benzotriazoles	Benzothiazole (BT) 2-Methylthio benzothiazole (MTBT) 2,2′-Dithiobisbenzothiazole (MBTS) *N*-cyclohexyl-2-benzothiazolesulfenamide (CBS) 1-H-benzotriazole (BTri) 5,6-Dimethylbenzotriazole (XTri) 5-Methyl-benzotriazole (5-TTri) 2-(Benzotriazol-2-yl)-4-methylphenol (UV–P) 2-(2H-benzotriazol-2-yl)-4,6-di-*tert*-pentylphenol (UV-328) 2-(2H-benzotriazol-2-yl)-4,6-bis(1-methyl-1-phenylethyl) phenol (UV-234) 2,4-Di-*tert*-butyl-6-(5-chlorobenzotriazol-2-yl) phenol (UV-327)	Avagyan et al. (2015)
21	clothes	quinolines and nitro anilines	A. Quinolines (involved in manufacture of dyes) - Quinoline - Iso-Quinoline - 2-methylquinoline - 3-methylquinolin - 4-methylquinoline -6-methylquinoline - 8-methylquinoline - 1-methyisoquinoline - 2,6-dimethylquinoline - 2,4-dimethylquinoline	Luongo et al. (2016)

(*continued on next page*)

Table 2 (*continued*)

No. Of chemicals	Material	Classes of chemicals (examples of chemicals)	Chemicals identified with standards	Citation
			B. Anilines (aromatic amines) - *p*-chloroaniline - *o*-nitroaniline - *m*-nitroaniline - *p*-nitroaniline - 5-chloro-2-nitroanilin - 2-chloro-5-nitroaniline - 2-chloro-4-nitroaniline - 2,6-dichloro-4-nitroaniline - 6-chloro-2,4-dinitroaniline - 2,4-dinitroaniline - 2-bromo-4,6-dinitroaniline	
6	waste plastic, poly-styrene and textile including: - construction and demolition materials - waste electrical and electronic equipment - end of life vehicle - soft furnishing	BFRs (brominated flame retardants)	- PBDEs - HBCDDs	Abdallah et al. (2017)
not specified, expected >8000	textiles	A. Amines - amines - aryl amines - quaternary ammonium compounds (DTDMAC, DSDMAC, DHTDMAC) B. Dyes and residuals - azo-dyes (aryl-amine releasers) - hypochlorite - naphthalene - poly aromatic hydrocarbons (PAHsand) - sensitizing disperse dyes (ZDHC for subset of known sensitizers, or GHS codes H317, H334, R43, R42) - TiO2 C. Halogenated chemicals - chlorinated and non-chlorinated (MIT/CMIT) - chlorinated benzenes - chlorophenols - halogenated flame retardants - per- and polyfluorinated compounds - short chain chlorinated paraffin - triclosan and triclocarban D. Metals As, Sb, Cr, Pb, Hg, nano Ag, Organotin compounds E. Monomers - acrylamides - acrylonitrile, acrylates and methacrylates - bisphenols including BPA, halogenated bisphenols, epoxy resins - butadiene and styrene - epoxide and epoxide precursors like ethylene oxide, propylene oxide, epichlorohydrin - formaldehyde and other shortchain aldehydes - isocyanates - *ortho*-phthalates - vinyl chloride and vinylidene chloride F. Solvents and process aids - alkyl-phenol Ethoxylates - aromatic solvents - benzene and o-, p-, or m- cresol - carbon disulfide - chlorinated cleaning solvents - DMF - glycols - N, Ndimethylacetamide (DMAC)		Safer Made (2018) [a]
29	outdoor clothing	ionic and volatile PFASs	A. Ionic PFASs PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTrDA, PFTeDA, PFBS, PFHxS, PFHpS, PFOS, FOSA, 4:2 FTSA, 6:2 FTSA, 8:2 FTSA B. Volatile PFASs 4:2 FTOH, 6:2 FTOH, 8:2 FTOH, 10:2 FTOH, 6:2 FTAC, 8:2 FTAC, 10:2 FTAC, 6:2 FTMAC, 8:2 FTMAC, 10:2 FTMAC	Van der Veen et al. (2020)

[a] Including recycled plastic or textile materials.

Table 3
Overview of the methods used for the analysis of virgin or recycled plastics and textile.

Recycled	Tested material	Migration simulant used							Compounds of interest	Type of analysis[a]			Extraction method	Detection method	Reference
		A	B	C	D1	D2	E	other		Target	Suspect	Non-Target			
x	HIPS								VOCs, styrene dimers and trimers, aliphatic compounds			x	microwave-assisted extraction, *n*-hexane/ isopropanol (50% v/v)	GC-TOF-MS (column: DB-5, *m/z* 33–500)	Vilaplana et al. (2007)
x	LDPE, PP, PS, waste plastic pellets (PE, PP, PS)								VOCs			x	automatic thermal desorption (ATD)	(TD)-GC-MS (column: HP-1)	Yamashita et al. (2009)
x	HIPS								NIAS			x	microwave-assisted extraction in *n*-hexane/ isopropanol (50% v/v)	GC-MS (column: *C*P-sil 5CB, *m/z* 35–500)	Vilaplana et al. (2010)
x	post-consumer PET flakes, PET (amorphous) pellets, HDPE pellets, HDPE multilayer packaging								VOCs			x	headspace-solid phase microextraction (HS-SPME)	GC-(EI)-MS (column: BPX5, *m/z* 40–650) GC-(EI)-MS (column: HP-5, *m/z* 45–650)	Dutra et al. (2011)
	poluamide (virgin material and textile)							artificial sweat solution	total inorganic contaminants (Sb, As, Pb, Cd, Cr, Co, Cu, Ni, Hg)	x			microwave assisted digestion in nitric acid	ICP-OES	Matoso and Cadore (2012)
	clothing garments								22 aromatic amines	x			citrate buffer/sodium dithionite solution/ methanol	LC-MS/MS (column: hermo-Dionex Acclaim Polar Advantage II), ammonium formate buffer 5% acetonitrile	Brüschweiler et al. (2014)
x	post-consumer PET and HDPE	x	x					95% EtOH	NIAS			x		LC-(ESI+)-MS/MS (column: C18, Mobile phase A: water, Mobile phase B: methanol, *m/z* 100–1450)	Dutra et al. (2014)
	EPS								VOCs				solid phase microextraction (SPME)	GC-(EI)-MS (column HP-5, *m/z* 45–400)	Pajaro-Castro et al. (2014)
	rubber tire, common clothing textile (PE, EL, CT, PA, OCT)								benzothiazole and benzotriazole derivatives	x			ultrasonic assisted dichloromethane extraction	LC-(ESI+)-MS/MS (column: C8, Mobile phase A: water/0.1% (v/v) FA, Mobile phase B: ACN/0.1% (v/v) FA)	Avagyan et al. (2013, 2015)
	textile								10 quinolines, 11 aromatic amines	x			dichloromethane extraction	GC-(EI)-MS (column: DB5-MS)	Luongo et al. (2016)
	textile								Diisopropyl fluorophosphate (DFP), tributyl phosphate (TBP), and 3-hepten-2-one (heptenone)	x	x		solid phase microextraction (SPME)	GC-(EI)-MS (*m/z* 55–270)	Salter et al. (2016)
	waste plastics (PS) and textile								POP-BFRs, DecaBDE (HBCDDs & PBDEs)	x			ultrasonic assisted dichloromethane extraction	GC-(EI)-MS (column: Rxi-5 Sil MS) LC-QQQ-MS (column: C18, Mobile phase A: MeOH: 2 mM ammonium acetate in ultrapure water (1:1), Mobile phase B: MeOH)	Abdallah et al. (2017)
	antimicrobial nanocomposites (PLA, PL, ZnO NPs)	x	x						NIAS			x		LC-(HESI-Orbitrap)-HRMS (column: C8, Mobile phase A: 5 mM ammonium formate, 0.1% FA, 2% MeOH in water, Mobile phase B: 5 mM ammonium formate, 0.1% FA 98% MeOH in water, *m/z* 80–800)	Martínez-Bueno et al. (2017)

(*continued on next page*)

Table 3 (*continued*)

Recycled	Tested material	Migration simulant used A	B	C	D1	D2	E	other	Compounds of interest	Type of analysis[a] Target	Suspect	Non-Target	Extraction method	Detection method	Reference
	textiles (infant clothing and diapers)								bisphenols, benzophenones, BADGEs and NOGEs	x			extraction in acetone and dichloromethane (v/v 1/4)	GC-(EI-Orbitrap)-HRMS (column TG-OCP I, m/z 50–550) LC-(ESI-)-MS/MS (column: C18, Mobile phase A: MeOH, Mobile phase B: 1% ammonium hydroxide in ultrapure water	Xue et al. (2017)
	34 packaged foodstuffs (corn snacks, potato snacks, cookies, cakes) and packaging materials								(1) NIAS (2) DEP, DBP, DIBP, DEHP, ATBC, BP, BHT	x[(2)]		x[(1)]	acetonitrile extraction	GC-(EI)-MS (column: ZB-5MS m/z 40–400)	García et al. (2018)
x	post-consumption PET flakes		x	x					NIAS	x				ICP-OES	Masmoudi et al. (2018)
	12 samples of plastics films (PE, PP, PET, PA, EVA)								volatile and semi-volatile IAS and NIAS			x	(1) purge & trap followed by thermal desorption (2) acetonitrile extraction	(1) GC-(EI)-MS (column: ZB-624) m/z 20-400 (2) GC-(EI)-MS (column: ZB-5MS) m/z 40–500	(García Ibarra et al., 2019)
x	EPS containers	x	x						VOCs			x	solid phase microextraction (SPME)	GC-MS (column: HP-5MS, m/z 45–400)	Song et al. (2019)
	PP							95% EtOH	NIAS			x		GC-(EI)-MS (column: HP-5MS, m/z 45–350) UPLC-(ESI)-IMS/QTOF (column C18, Mobile phase A: water, Mobile phase B: MeOH, m/z 50–1000)	Canellas et al. (2019)
	LDPE, HDPE used as food contact materials	x	x		x		x	95% EtOH	NIAS			x		UPLC-(ESI)-IMS/QTOF (column C18, Mobile phase A: water, Mobile phase B: 0.1% FA MeOH, m/z 50–1200)	Vera et al. (2019)
	PE, LDPE plus nylon used as food packaging		x	x					NIAS			+		LC-(qTOF)-HRMS (column: C8, Mobile phase A: 5 mM ammonium formate, 0.1% FA, 2% MeOH in water, Mobile phase B: 5 mM ammonium formate, 0.1% FA 98% MeOH in water	Gómez Ramos et al. (2019)
x	PET	x	x	x					acrylate compounds	x				UPLC-(ESI)-MS/MS (column: C18, Mobile phase A: MeOH 0.1% FA, Mobile phase B: ultrapure water)	Otoukesh et al. (2019)
x	multilayered films LLDPE and LDPE, PCW							95% EtOH	IAS and NIAS		x	x		HPLC-UV (column: C18) GC-MS (column: ZB-5MSPlus)	Radusin et al. (2020)
x	PE pellets								VOCs			x	headspace-solid phase microextraction (HS-SPME)	GC-(EI)-MS (column: HP-5MS, m/z 45–400)	Chen et al. (2020)
x	PET								volatile: acetaldehyde, benzene, limonene, 2-methyl-1,3-dioxolane, ethylene glycol non-volatile: anthranilamide, oligomers and their degradation products	x			(1) headspace (2) dichloromethane extraction	HS-GC-FID (column: DB 1) GC-MS (column: ZB1MS, ZB WAXplus)	Pinter et al. (2021)
x	PE (HDPE, LDPE)							95% EtOH	(semi-)VOCs			x			Chen et al. (2021)

(*continued on next page*)

Table 3 (*continued*)

Recycled	Tested material	Migration simulant used							Compounds of interest	Type of analysis[a]			Extraction method	Detection method	Reference
		A	B	C	D1	D2	E	other		Target	Suspect	Non-Target			
x	PP								NIAS			x	headspace-solid phase microextraction (HS-SPME)	GC-(EI)-MS (column: HP-5MS, m/z 50–550) GC-(Olifactory)-MS (column: HP-5MS, m/z 45–350)	Paiva et al. (2021)
x	post-consumer HDPE milk bottles		x					95% EtOH	VOCs, NIAS			x	ultrasonic assisted dichloromethane extraction	GC-(EI)-MS (column: DB-5MS, m/z 40–700)	Su et al. (2021)
	clothing garments								(1) inclusion list: 149 masses from SVHCslisted by Swedish Chemicals Agency (2) NIAS		x	x	dichloromethane extraction	LC-(ESI+ & -)-Orbitrap-MS (column C18, Mobile phase A: 10 mM ammonium acetate in ultrapure water, Mobile phase B: ACN), m/z 66.7–1000 120,000 (@400)	Carlsson et al. (2022)
	biodegradable multi-layered material from teacups (40% polyester, 60% PLA)							tea	VOCs, NIAS			x	headspace-solid phase microextraction (HS-SPME)	UPLC-(ESI+)-IMS-Q/TOF (column: C18, Mobile phase A: water 0.1% FA, Mobile phase B: methanol 0.1% FA, m/z 50–1000) GC-(EI)-MS (column: HP-5MS, m/z 45–350)	Canellas et al. (2022)
	ethylene-vinyl acetate corks		x	x					VOCs, NIAS			x		UPLC-(ESI)-IMS-Q/TOF (column: C18, Mobile phase A: water 0.1% FA, Mobile phase B: methanol 0.1% FA, m/z 50–1000) GC-(EI)-MS (column: HP-5MS, m/z 45–350)	Vera et al. (2022)

Migration simulants: A: 10% EtOH, B: 3% acetic acid, C: 20% EtOH, D1: 50% EtOH, D2: vegetable oil and E: poly (2, 6-diphenyl-*p*-phenylene oxide), particle size 60–80 mesh, pore size 200 nm.
HIPS: high-impact polystyrene; (L)LDPE: (linear) low-density polyethylene; PP: polypropylene; PS: polystyrene; PET: polyethylene terephthalate; HDPE: high-density polyethylene; EPS: expanded polystyrene; CT: cotton; EL: elastane/lycra; OCT: organic cotton; PLA: polylactic acid; PL: polylimonene; ZnO NPs: zinc oxide nanoparticles; PE: polyethylene; PA: polyamide; EVA: ethylene vinyl acetate; PCW: post-consumer waste.
GC-TOF-MS: gas chromatography time of flight mass spectrometry; (TD)-GC-MS: (thermal desorption) gas chromatography mass spectrometry; GC-(EI)-MS: gas chromatography (electron impact ionisation) mass spectrometry; ICP-OES: inductively coupled plasma optimal emission spectroscopy; LC-MS/MS: liquid chromatography tandem mass spectrometry; LC-(ESI +/−)-MS/MS: liquid chromatography (with positive or negative electrospray ionisation) tandem mass spectrometry; LC-(HESI-Orbitrap)-HRMS: liquid chromatography with heated electrospray ionisation orbitrap high resolution mass spectrometry, GC-(EI-Orbitrap)-HRMS gas chromatography with electron impact Orbitrap mass spectrometry; UPLC-(ESI)-IMS/QTOF: ultra-high performance liquid chromatography with electrospray ionisation ion mobility quadrupole time-of-flight mass spectrometry; LC-(qTOF)-HRMS: liquid chromatography with quadrupole time-of-flight high resolution mass spectrometry; HPLC-UV: high performance liquid chromatography with ultraviolet detection; HS-GC-FID headspace gas chromatography flame ionisation.
[a] Author's interpretation.

sensitivity for gene mutations, clastogenicity and aneugenicity. When the bioassay gives a positive response for genotoxicity, it is further analysed. Lastly, screening for non-volatile substances that might have been missed during the previous experiments was run. These might be non-volatile apolar substances that are difficult to analyse with GC. According to Leeman and Krul (2015), the CoMSAS approach is the only one of its kind to assess unidentifiable NIAS. The introduction of an exposure threshold provides a pragmatic way for efficient screening for toxicological relevant NIAS and increases the efficiency of the whole process.

Another approach is proposed by Pieke et al. (2018a). They realised that a risk assessment of NIAS in a traditional way is in most cases not feasible since crucial information is missing. This was also concluded by Muncke et al. (2017). Most NIAS do not have assigned chemical structures, concentration data or characterisation of hazards. Studies by Pieke et al. (2017; 2018a,b), described the use of explorative methods to determine NIAS in FCM and concluded that untargeted analytical strategies are useful to estimate the concentration and chemical structure of NIAS. However, a comprehensive analysis of all substances found via exploration is not realistic and therefore a risk prioritisation is required to identify the substances that most likely have adverse health effects (Pieke et al., 2017, 2018a,b).

During the last years, *in silico* methods have received substantial attention, stimulating their development. As a result these methods are becoming more interesting for the assessment of chemical hazards. *In silico* tools are essentially computer models able to make predictions for non-evaluated substances. These models are based on knowledge extracted from a collection of structurally related substances with experimental toxicity data. Quantitative structure-activity relationship (QSAR) modelling of chemical hazard may provide substitute toxicity data if testing is not possible. Van Bossuyt et al. (2017) and Pieke et al. (2018a) successfully applied QSAR to FCM for hazard-based assessment and prioritisation. The widespread use of *in silico* tools, however, remains limited due to the non-flexibility of the current regulatory framework and the fact that uncertainty exists as to which *in silico* model is most suitable to assess a given substance for a particular endpoint. Therefore, the most promising application of *in silico* tools will be its use in priority setting while screening many substances. A detailed characterisation of the complete toxicological profile of all substances in a non-targeted chemical analysis is not feasible from an economic and ethical (animal testing) point of view. By identifying substances of highest concern, available resources for experimental testing can be attributed more efficiently.

5. Conclusions

We aimed to review the origin and nature of potential hazards that arise from the recycling processes of plastics and textiles. Also, we reviewed current analytical methods and safety assessment frameworks that could be adapted to detect and identify these contaminants. The origin of contamination in recycled products is mainly attributed to previous use and the recycling process itself. Contaminants include phthalates and odour, flavour and aroma compounds formed during waste collection, but also BFRs and metals introduced during the recycling process. Contaminants linked to textile recycling include; detergents, resistant coatings, flame retardants, plastics coatings, antibacterial and anti-mould agents, pesticides, dyes, volatile organic compounds and nanomaterials. However, information is limited on contaminants in textile during recycling and recycled end-products.

From the analytical point of view, various techniques are available to analyse (hazardous) substances in recycled plastics or textiles. Further research is required to improve the identification of detected compounds since identification is still impossible in many cases due to the lack of standards. Furthermore, the techniques mentioned in this review cover a wide range of organic chemicals, but studies covering potential inorganic contaminants in recycled materials are still missing. Finally, risk prioritisation schemes and techniques such as TTC and CoMSAS for risk assessment have not been used for recycled plastic and textile materials Therefore, developing these schemes and techniques for this field is strongly advised.

Author contributions

A. K. Undas: Writing- Original draft preparation M. Groenen: Writing- Original draft preparation R. J. B. Peters: Writing- Reviewing and Editing, Conceptualization, S·P.J. van Leeuwen: Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This research was funded by the Wageningen University and Research Knowledge Base Program Towards a circular and climate neutral society (KB34), project Recycling and end-of-life strategies for sustainability and climate (KB-34-011-001).

References

Abdallah, M.A.-E., Drage, D.S., Sharkey, M., Berresheim, H., Harrad, S., 2017. A rapid method for the determination of brominated flame retardant concentrations in plastics and textiles entering the waste stream. J. Separ. Sci. 40, 3873–3881.

Ares Pernas, A.I., Abad López, M.J., Latorre, A.L., López Vilariño, J.M., González Rodríguez, M.V., 2014. Assessing changes on poly(ethylene terephthalate) properties after recycling: mechanical recycling in laboratory versus postconsumer recycled material. Mater. Chem. Phys. 147, 884–894.

Avagyan, Rozanna, Sadiktsis, Ioannis, Thorsén, Gunnar, Östman, Conny, Westerholm, Roger, 2013. Determination of benzothiazole and benzotriazole derivates in tire and clothing textile samples by high performance liquid chromatography–electrospray ionization tandem mass spectrometry. J. Chromatogr. A. https://doi.org/10.1016/j.chroma.2013.07.087.

Avagyan, R., Luongo, G., Thorsén, G., Östman, C., 2015. Benzothiazole, benzotriazole, and their derivates in clothing textilesa potential source of environmental pollutants and human exposure. Environ. Sci. Pollut. Control Ser. 22, 5842–5849.

BfR, 2012. Introduction to the Problems Surrounding Garment Textiles. Updated BfR Opinion (041/2012). https://www.bfr.bund.de/cm/349/introduction-to-the-problems-surrounding-garment-textiles.pdf.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179.

Brüschweiler, B.J., Küng, S., Bürgi, D., Muralt, L., Nyfeler, E., 2014. Identification of non-regulated aromatic amines of toxicological concern which can be cleaved from azo dyes used in clothing textiles. Regul. Toxicol. Pharmacol.: RTP (Regul. Toxicol. Pharmacol.) 69, 263–272.

Budin, Clémence, Petrlik, Jindrich, Strakova, Jitka, Hamm, Stephan, Beeler, Bjorn, Behnisch, Peter, Besselink, Harrie, van der Burg, Bart, Abraham Brouwer, 2020. Detection of high PBDD/fs levels and dioxin-like activity in toys using a combination of GC-HRMS, rat-based and human-based DR CALUX reporter gene assays. Chemosphere. https://doi.org/10.1016/j.chemosphere.2020.126.

Canellas, E., Vera, P., Nerín, C., 2019. Ion mobility quadrupole time-of-flight mass spectrometry for the identification of non-intentionally added substances in UV varnishes applied on food contact materials. A safety by design study. Talanta 205, 120103.

Canellas, E., Vera, P., Nerin, C., Dreolin, N., Goshawk, J., 2022. The detection and elucidation of oligomers migrating from biodegradable multilayer teacups using liquid chromatography coupled to ion mobility time-of-flight mass spectrometry and gas chromatography–mass spectrometry. Food Chem. 374, 131777 https://doi.org/10.1016/j.foodchem.2021.131777.

Carlsson, Josefine, Iadaresta, Francesco, Eklund, Jonas, Avagyan, Rozanna, Östman, Conny, Nilsson, Ulrika, 2022. Suspect and non-target screening of chemicals in clothing textiles by reversed-phase liquid chromatography/hybrid quadrupole-orbitrap mass spectrometry. Anal. Bioanal. Chem. 414 (3), 1403–1413. https://doi.org/10.1007/s00216-021-03766-x.

Chen, Z.-F., Lin, Q.-B., Song, X.-C., Chen, S., Zhong, H.-N., Nerin, C., 2020. Discrimination of virgin and recycled polyethylene based on volatile organic

compounds using a headspace GC-MS coupled with chemometrics approach. Food Packag. Shelf Life 26, 100553. https://doi.org/10.1016/j.fpsl.2020.100553.
Chen, Z.-F., Lin, Q.-B., Su, Q.-Z., Zhong, H.-N., Nerin, C., 2021. Identification of recycled polyethylene and virgin polyethylene based on untargeted migrants. Food Packag. Shelf Life 30, 100762. https://doi.org/10.1016/j.fpsl.2021.100762.
Curran, K., Strlič, M., 2015. Polymers and volatiles: using VOC analysis for the conservation of plastic and rubber objects. Stud. Conserv. 60, 1–14.
Delva, L., Hubo, S., Cardon, L., Ragaert, K., 2018. On the role of flame retardants in mechanical recycling of solid plastic waste. Waste management 82, 198–206.
Dreolin, N., Aznar, M., Moret, S., Nerin, C., 2019. Development and validation of a LC–MS/MS method for the analysis of bisphenol a in polyethylene terephthalate. Food Chem. 274, 246–253. https://linkinghub.elsevier.com/retrieve/pii/S0308814618315206.
Dutra, C., Pezo, D., Freire, M.T. de A., Nerín, C., Reyes, F.G.R., 2011. Determination of volatile organic compounds in recycled polyethylene terephthalate and high-density polyethylene by headspace solid phase microextraction gas chromatography mass spectrometry to evaluate the efficiency of recycling processes. J. Chromatogr. 1218, 1319–1330.
Dutra, C., Freire, M.T. de A., Nerín, C., Bentayeb, K., Rodriguez-Lafuente, A., Aznar, M., Reyes, F.G.R., 2014. Migration of residual nonvolatile and inorganic compounds from recycled post-consumer PET and HDPE. J. Braz. Chem. Soc. 25, 686–696.
Ellen McArthur Foundation, Circular Fibres Initiative, 2017. A New Textiles Economy: Redesigning Fashion's Future.
Eriksen, M.K., Pivnenko, K., Olsson, M.E., Astrup, T.F., 2018. Contamination in plastic recycling: influence of metals on the quality of reprocessed plastic. Waste Manag. 79, 595–606.
European Commission, 2008. Commission Regulation (EC) No 282/2008 of 27 March 2008 on Recycled Plastic Materials and Articles Intended to Come into Contact with Foods and Amending Regulation (EC) No 2023/2006 (Text with EEA Relevance). Publications Office of the European Union.
European Commission, 2011. Commission Regulation (EU) No 10/2011 of 14 January 2011 on Plastic Materials and Articles Intended to Come into Contact with Food.
European Commission, 2014. Register of Valid Applications for Authorisation of Recycling Processes to Produce Recycled Plastic Materials and Articles Intended to Come into Contact with Foods submitted under article 13 of regulation (ec) no 282/2008.
European Commission, 2022a. Revision of EU rules (europa.eu). available at: https://ec.europa.eu/food/safety/chemical-safety/food-contact-materials/policy-initiatives/revision-eu-rules_en.
European Commission, 2022b. EU Strategy for Sustainable and Circular Textiles. COM, p. 141, 2022.
European Commission, 2022. Farm to Fork strategy. https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en.
European Food Safety Authority and World Health Organization, 2016. Review of the Threshold of Toxicological Concern (TTC) approach and development of new TTC decision tree. EFSA Supporting Publications 13, 1006E.
Footwear, E.I.A., 2016. Global Fashion Industry Statistics - International Apparel. Fashion United.
Fortune Business Insights, 2021. Recycled Plastic Market Size, Share & COVID-19 Impact Analysis, By Type (Polyethylene Terephthalate, High-density Polyethylene, Polypropylene, Low-density Polyethylene, and Others), By Application (Non-food Packaging, Food Packaging, Construction, Automotive and Others), and Regional Forecast, 2021-2028. https://www.fortunebusinessinsights.com/recycled-plastic-market-102568. (Accessed 14 December 2021).
García, Carlos J., Gil, María I., Tomas-Barberan, Francisco A., 2018. LC–MS untargeted metabolomics reveals early biomarkers to predict browning of fresh-cut lettuce. Postharvest Biol. Technol. 146, 9–17. https://doi.org/10.1016/j.postharvbio.2018.07.011. December.
García Ibarra, V., Rodríguez Bernaldo de Quirós, A., Paseiro Losada, P., Sendón, R., 2018. Identification of intentionally and non-intentionally added substances in plastic packaging materials and their migration into food products. Anal. Bioanal. Chem. 410, 3789–3803.
García Ibarra, V., Rodríguez Bernaldo de Quirós, A., Paseiro Losada, P., Sendón, R., 2019. Non-target analysis of intentionally and non-intentionally added substances from plastic packaging materials and their migration into food simulants. Food Packag. Shelf Life 21. https://doi.org/10.1016/j.fpsl.2019.100325.
Geueke, B., Food Packaging Forum Foundation, 2018. Non-intentionally added substances (NIAS). Food Packaging Forum FPF Dossier. https://www.foodpackagingforum.org/food-packaging-health/non-intentionally-added-substances-niase.
Geueke, B., Groh, K, Muncke, J., 2018. Food packaging in the circular economy: overview of chemical safety aspects for commonly used materials. J. Cleaner Prod. 193, 491–505.
Geyer, R, Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), 1207–1221. https://doi.org/10.1126/sciadv.1700782.
Geyer, B., Lorenz, G., Kandelbauer, A., 2016. Recycling of poly (ethylene terephthalate)-A review focusing on chemical methods. Express Polym. Lett. 10, 559–586.
Gómez Ramos, M.J., Lozano, A., Fernández-Alba, A.R., 2019. High-resolution mass spectrometry with data independent acquisition for the comprehensive non-targeted analysis of migrating chemicals coming from multilayer plastic packaging materials used for fruit purée and juice. Talanta 191, 180–192.
Groh, K.J., Backhaus, T., Carney-Almroth, B., Geueke, B., Inostroza, P.A., Lennquist, A., Leslie, H.A., Maffini, M., Slunge, D., Trasande, L., Warhurst, A.M., Muncke, J., 2019. Overview of known plastic packaging-associated chemicals and their hazards. Sci. Total Environ. 651, 3253–3268.
Groh, K.J., Geueke, B., Martin, O., Maffini, M., Muncke, J., 2021. Overview of intentionally used food contact chemicals and their hazards. Environ. Int. 150, 106225. https://linkinghub.elsevier.com/retrieve/pii/S0160412020321802.
Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard Mater. 344, 179–199.
Horodytska, O., Cabanes, A., Fullana, A., 2020. Non-intentionally added substances (NIAS) in recycled plastics. Chemosphere 251.
Hu, E., Shang, S., Chiu, K.-L., 2019. Removal of reactive dyes in textile effluents by catalytic ozonation pursuing on-site effluent recycling. Molecules 24, 2755.
Ignatyev, I.A., Thielemans, W., Vander Beke, B., 2014. Recycling of polymers: a review. ChemSusChem 7, 1579–1593.
Ionas, A.C., Dirtu, A.C., Anthonissen, T., Neels, H., Covaci, A., 2014. Downsides of the recycling process: harmful organic chemicals in children's toys. Environ. Int. 65, 54–62.
Kato, L.S., Conte-Junior, C.A., 2021. Safety of plastic food packaging: the challenges about non-intentionally added substances (NIAS) discovery, identification and risk assessment. Polymers 13, 2077.
Keresztes, S., Tatár, E., Czégény, Z., Záray, G., Mihucz, V.G., 2013. Study on the leaching of phthalates from polyethylene terephthalate bottles into mineral water. Sci. Total Environ. 458–460, 451–458.
Koster, S., Rennen, M., Leeman, W., Houben, G., Muilwijk, B., van Acker, F., Krul, L., 2014. A novel safety assessment strategy for non-intentionally added substances (NIAS) in carton food contact materials. Food Addit. Contam. Part A, Chemistry, Analysis, Control, Exposure & Risk Assessment 31, 422–443. https://doi.org/10.1080/19440049.2013.866718.
Koster, S., Bani-Estivals, M.-H., Bonuomo, M., Bradley, E., Chagnon, M.-C., Garcia, M.L., Godts, F., Gude, T., Helling, R., Paseiro-Losada, P., Pieper, G., Rennen, M., Simat, T., Spack, L., 2015. GUIDANCE ON BEST PRACTICES ON THE RISK ASSESSMENT OF NON-INTENTIONALLY ADDED SUBSTANCES (NIAS) IN FOOD CONTACT MATERIALS AND ARTICLES (No. D/2015/10.996/39. LSI Europe, Belgium.
Lee, J., Pedersen, A.B., Thomsen, M., 2014. The influence of resource strategies on childhood phthalate exposure role of REACH in a zero waste society. Environ. Int. 73, 312–322.
Leeman, W., Krul, L., 2015. Non-intentionally added substances in food contact materials: how to ensure consumer safety. Current Opinion in Food Science, Food Toxicology Food Safety 6, 33–37. https://doi.org/10.1016/j.cofs.2015.11.003.
Leslie, H.A., Leonards, P.E.G., Brandsma, S.H., de Boer, J., Jonkers, N., 2016. Propelling plastics into the circular economy weeding out the toxics first. Environ. Int. https://doi.org/10.1016/j.envint.2016.05.012.López, M. del M.C.
Luongo, G., Iadaresta, F., Moccia, E., Östman, C., Crescenzi, C., 2016. Determination of aniline and quinoline compounds in textiles. J. Chromatogr. 1471, 11–18.
Maris, J., Bourdon, S., Brossard, J.-M., Cauret, L., Fontaine, L., Montembault, V., 2018. Mechanical recycling: compatibilization of mixed thermoplastic wastes. Polym. Degrad. Stabil. 147, 245–266.
Martínez-Bueno, M.J., Hernando, M.D., Uclés, S., Rajski, L., Cimmino, S., Fernández-Alba, A.R., 2017. Identification of non-intentionally added substances in food packaging nano films by gas and liquid chromatography coupled to orbitrap mass spectrometry. Talanta 172, 68–77. https://doi.org/10.1016/j.talanta.2017.05.023.
Martínez-Bueno, M.J., Gómez Ramos, M.J., Bauer, A., Fernández-Alba, A.R., 2019. An overview of non-targeted screening strategies based on high resolution accurate mass spectrometry for the identification of migrants coming from plastic food packaging materials. TrAC, Trends Anal. Chem. 110, 191–203. https://doi.org/10.1016/j.trac.2018.10.035.
Masmoudi, F., Fenouillot, F., Mehri, A., Jaziri, M., Ammar, E., 2018. Characterization and quality assessment of recycled post-consumption poly(ethylene terephthalate) (PET). Environ. Sci. Pollut. Control Ser. 25, 23307–23314.
Matoso, E., Cadore, S., 2012. Determination of inorganic contaminants in polyamide textiles used for manufacturing sport T-shirts. Talanta 88, 496–501.
Muncke, J., Backhaus, T., Geueke, B., Maffini, M.V., Martin, O.V., Myers, J.P., Soto, A.M., Trasande, L., Trier, X., Scheringer, M., 2017. Scientific challenges in the risk assessment of food contact materials. Environ. Health Perspect. 125, 095001.
(NEA), N.E.A., 2013. Hazardous Substances in Plastic Materials (No. TA-3017/2013). Oslo, Norway.
Nerín, C., Bourdoux, S., Faust, B., Gude, T., Lesueur, C., Simat, Th, Stoermer, A., Van Hoek, E., Oldring, P., 2022. Guidance in selecting analytical techniques for identification and quantification of non-intentionally added substances (NIAS) in food contact materials (FCMS). Food Addit. Contam. 39 (3), 620–643. https://doi.org/10.1080/19440049.2021.2012599.
Nikolaivits, E., Pantelic, B., Azeem, M., Taxeidis, G., Babu, R., Topakas, E., Brennan Fournet, M., Nikodinovic-Runic, J., 2021. Progressing plastics circularity: A review of mechano-biocatalytic approaches for waste plastic (re) valorization. Frontiers in Bioengineering and Biotechnology 9, 535.
Otoukesh, M., Nerín, C., Aznar, M., Kabir, A., Furton, K.G., Es'haghi, Z., 2019. Determination of adhesive acrylates in recycled polyethylene terephthalate by fabric phase sorptive extraction coupled to ultra performance liquid chromatography - mass spectrometry. J. Chromatogr. A 1602, 56–63. https://doi.org/10.1016/j.chroma.2019.05.044.
Paiva, R., Wrona, M., Nerín, C., Bertochi Veroneze, I., Gavril, G.-L., Andrea Cruz, S., 2021. Importance of profile of volatile and off-odors compounds from different recycled polypropylene used for food applications. Food Chem. 350, 129250 https://doi.org/10.1016/j.foodchem.2021.129250.
Pajaro-Castro, N., Caballero-Gallardo, K., Olivero-Verbel, J., 2014. Identification of volatile organic compounds (VOCs) in plastic products using gas chromatography and mass spectrometry (GC/MS). Ambiente Água - An Interdiscip. J. Appl. Sci. 9, 610–620.

Pieke, E.N., Granby, K., Teste, B., Smedsgaard, J., Rivière, G., 2018a. Prioritization before risk assessment: the viability of uncertain data on food contact materials. Regul. Toxicol. Pharmacol. 97, 134–143. https://doi.org/10.1016/j.yrtph.2018.06.012.

Pieke, E.N., Granby, K., Trier, X., Smedsgaard, J., 2017. A framework to estimate concentrations of potentially unknown substances by semi-quantification in liquid chromatography electrospray ionization mass spectrometry. Anal. Chim. Acta 975, 30–41.

Pieke, E.N., Smedsgaard, J., Granby, K., 2018b. Exploring the chemistry of complex samples by tentative identification and semiquantification: a food contact material case. J. Mass Spectrom.: JMS 53, 323–335.

Pinter, E., Welle, F., Mayrhofer, E., Pechhacker, A., Motloch, L., Lahme, V., Grant, A., Tacker, M., 2021. Circularity study on PET bottle-to-bottle recycling. Sustainability 13, 7370.

Pivnenko, K., Eriksen, M.K., Martín-Fernández, J.A., Eriksson, E., Astrup, T.F., 2016. Recycling of plastic waste: presence of phthalates in plastics from households and industry. Waste Manag. 54, 44–52.

Pivnenko, K., Granby, K., Eriksson, E., Astrup, T.F., 2017. Recycling of plastic waste: screening for brominated flame retardants (BFRs). Waste Manag. 69, 101–109.

Plastics Europe, 2020. Plastics – the Facts 2020. https://plasticseurope.org/knowledge-hub/plastics-the-facts-2020/. (Accessed 22 November 2021).

Post, W., Susa, A., Blaauw, R., Molenveld, K., Knoop, R.J., 2020. A review on the potential and limitations of recyclable thermosets for structural applications. Polymer Reviews 60 (2), 359–388.

Puype, F., Samsonek, J., Knoop, J., Egelkraut-Holtus, M., Ortlieb, M., 2015. Evidence of waste electrical and electronic equipment (WEEE) relevant substances in polymeric food-contact articles sold on the European market. Food Addit. Contam. Part A, Chemistry, Analysis, Control, Exposure & Risk Assessment 32, 410–426. https://doi.org/10.1080/19440049.2015.1009499.

Puype, F., Samsonek, J., Vilímková, V., Kopečková, Š., Ratiborská, A., Knoop, J., Egelkraut-Holtus, M., Ortlieb, M., Oppermann, U., 2017. Towards a generic procedure for the detection of relevant contaminants from waste electric and electronic equipment (WEEE) in plastic food-contact materials: a review and selection of key parameters. Food Addit. Contam. 34, 1767–1783.

Radusin, T., Nilsen, J., Larsen, S., Annfinsen, S., Waag, C., Eikeland, M.S., Pettersen, M.K., Fredriksen, S.B., 2020. Use of recycled materials as mid layer in three layered structures-new possibility in design for recycling. J. Clean. Prod. 259, 120876.

Safer Made, 2018. Safer Chemistry Innovation in the Textile and Apparel Industry. https://refashion.fr/eco-design/sites/default/files/fichiers/Safer%20Chemistry%20Innovation%20in%20the%20Textile%20and%20Apparel%20Industry.pdf. (Accessed 28 September 2021).

Salerno-Kochan, R., Kowalski, M., 2020a. Safety management of textile products in the European union and estimation of its efficiency. Part 1. FIBRES & TEXTILES in eastern. Fibres Text. East. Eur. 140, 8–14. https://doi.org/10.5604/01.3001.0013.7307.

Salerno-Kochan, R., Kowalski, M., 2020b. Safety Management of Textile Products in the European Union and Estimation of its Efficiency. Part 2. Fibres and Textiles in Eastern Europe 141, 12–17.

Salter, W.B., Lovingood, D.D., Creasy, W., Owens, J.R., 2016. Analysis of vaporous contaminants including low-volatility analytes permeating textiles at room temperature using headspace solid-phase microextraction GC. Surf. Interface Anal. 48, 47–50.

Samsonek, J., Puype, F., 2013. Occurrence of brominated flame retardants in black thermo cups and selected kitchen utensils purchased on the European market. Food Addit. Contam. Part A, Chemistry, Analysis, Control, Exposure & Risk Assessment 30, 1976–1986.

Schymanski, E.L., Jeon, J., Gulde, R., Fenner, K., Ruff, M., Singer, H.P., Hollender, J., 2014. Identifying small molecules via high resolution mass spectrometry: communicating confidence. Environ. Sci. Technol. 48, 2097–2098. https://doi.org/10.1021/es5002105.

Schymanski, E.L., Singer, H.P., Slobodnik, J., Ipolyi, I.M., Oswald, P., Krauss, M., Schulze, T., Haglund, P., Letzel, T., Grosse, S., Thomaidis, N.S., Bletsou, A., Zwiener, C., Ibáñez, M., Portolés, T., de Boer, R., Reid, M.J., Onghena, M., Kunkel, U., Schulz, W., Guillon, A., Noyon, N., Leroy, G., Bados, P., Bogialli, S., Stipaničev, D., Rostkowski, P., Hollender, J., 2015. Non-target screening with high-resolution mass spectrometry: critical review using a collaborative trial on water analysis. Anal. Bioanal. Chem. 407, 6237–6255. https://doi.org/10.1007/s00216-015-8681-7.

Sirot, V., Rivière, G., Leconte, S., Leblanc, J.C., Kolf-Clauw, M., Vasseur, P., Cravedi, J., Hulin, M., et al., 2021. Infant total diet study in France: Exposure to substances migrating from food contact materials. Environ. Int. 149.

Sobus, J.R., Wambaugh, J.F., Isaacs, K.K., Williams, A.J., McEachran, A.D., Richard, A.M., Grulke, C.M., Ulrich, E.M., Rager, J.E., Strynar, M.J., Newton, S.R., 2018. Integrating tools for non-targeted analysis research and chemical safety evaluations at the US EPA. J. Expo. Sci. Environ. Epidemiol. 28, 411–426.

Song, X.-C., Wrona, M., Nerin, C., Lin, Q.-B., Zhong, H.-N., 2019. Volatile non-intentionally added substances (NIAS) identified in recycled expanded polystyrene containers and their migration into food simulants. Food Packag. Shelf Life 20, 100318.

Soroudi, A., Jakubowicz, I., 2013. Recycling of bioplastics, their blends and biocomposites: a review. Eur. Polym. J. 49, 2839–2858. https://doi.org/10.1016/j.eurpolymj.2013.07.025.

Stenmarck, Å., Belleza, E.L., Fråne, A., Busch, N., Larsen, Å., Wahlström, M., 2017. Hazardous substances in plastics, 2017:505 ed, TemaNord. Nordic Council of Ministers. https://doi.org/10.6027/TN2017-505. Copenhagen.

Su, Q.Z., Vera, P, Nerín, C., Lin, Q.B., Zhong, H.N., 2021. Safety concerns of recycling postconsumer polyolefins for food contact uses: regarding (Semi-)Volatile migrants untargetedly screened. Resources, Conservation and Recycling 167.

Ubeda, S., Aznar, M., Nerín, C., 2018. Determination of oligomers in virgin and recycled polyethylene terephthalate (PET) samples by UPLC-MS-QTOF. Analytical and bioanalytical chemistry 410 (9), 2377-2364.

Van Bossuyt, M., Van Hoeck, E., Raitano, G., Manganelli, S., Braeken, E., Ates, G., Vanhaecke, T., Van Miert, S., Benfenati, E., Mertens, B., Rogiers, V., 2017. (Q)SAR tools for priority setting: a case study with printed paper and board food contact material substances. Food Chem. Toxicol. 102, 109–119. https://doi.org/10.1016/j.fct.2017.02.002.

Van der Veen, I., Hanning, A.C., Stare, A., Leonards, P.E., de Boer, J., Weiss, J.M., 2020. The effect of weathering on per-and polyfluoroalkyl substances (PFASs) from durable water repellent (DWR) clothing. Chemosphere 249.

Vera, P., Canellas, E., Barknowitz, G., Goshawk, J., Nerín, C., 2019. Ion-mobility quadrupole time-of-flight mass spectrometry: a novel technique applied to migration of nonintentionally added substances from polyethylene films intended for use as food packaging. Anal. Chem. 91, 12741–12751.

Vera, Paula, Canellas, Elena, Nerín, Cristina, Nicola Dreolin, Goshawk, Jeff, 2022. The migration of NIAS from ethylene-vinyl acetate corks and their identification using gas chromatography mass spectrometry and liquid chromatography ion mobility quadrupole time-of-flight mass spectrometry. Food Chem. 366, 130592 https://doi.org/10.1016/j.foodchem.2021.130592. January.

Vilaplana, F., Ribes-Greus, A., Karlsson, S., 2007. Analytical strategies for the quality assessment of recycled high-impact polystyrene: a combination of thermal analysis, vibrational spectroscopy, and chromatography. Anal. Chim. Acta 604, 18–28.

Vilaplana, F., Ribes-Greus, A., Karlsson, S., 2010. Chromatographic pattern in recycled high-impact polystyrene (HIPS) Occurrence of low molecular weight compounds during the life cycle. Polym. Degrad. Stabil. 95, 172–186.

Wijnhoven, S.W.P., Kooi, M.W., National Institute for Public Health and the Environment (RIVM), 2010. Consumer Exposure to Chemicals in the Indoor Environment; A specific focus on chemicals from textile products. Letter report 320104010/2010. https://www.rivm.nl/bibliotheek/rapporten/320104010.pdf.

Wrona, M., Nerín, C., 2020. Analytical approaches for analysis of safety of modern food packaging: a review. Molecules 25, 725. https://doi.org/10.3390/molecules25030752.

Xue, J., Liu, W., Kannan, K., 2017. Bisphenols, benzophenones, and bisphenol A diglycidyl ethers in textiles and infant clothing. Environ. Sci. Technol. 51, 5279–5286.

Yamashita, K., Yamamoto, N., Mizukoshi, A., Noguchi, M., Ni, Y., Yanagisawa, Y., 2009. Compositions of volatile organic compounds emitted from melted virgin and waste plastic pellets. J. Air Waste Manag. Assoc. 59, 273–278. https://doi.org/10.3155/1047-3289.59.3.273.