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The dilemma in prioritizing chemicals for environmental analysis: known *versus* unknown hazards†

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A major challenge for society is to manage the risks posed by the many chemicals continuously emitted to the environment. All chemicals in production and use cannot be monitored and science-based strategies for prioritization are essential. In this study we review available data to investigate which substances are included in environmental monitoring programs and published research studies reporting analyses of chemicals in Baltic Sea fish between 2000 and 2012. Our aim is to contribute to the discussion of priority settings in environmental chemical monitoring and research, which is closely linked to chemical management. In total, 105 different substances or substance groups were analyzed in Baltic Sea fish. Polychlorinated dibenzo-*p*-dioxins, polychlorinated dibenzofurans (PCDD/Fs) and polychlorinated biphenyls (PCBs) were the most studied substances or substance groups. The majority, 87%, of all analyses comprised 20% of the substances or substance groups, whereas 46 substance groups (44%) were analyzed only once. Almost three quarters of all analyses regarded a POP-substance (persistent organic pollutant). These results demonstrate that the majority of analyses on environmental contaminants in Baltic Sea fish concern a small number of already regulated chemicals. Legacy pollutants such as POPs pose a high risk to the Baltic Sea due to their hazardous properties. Yet, there may be a risk that prioritizations for chemical analyses are biased based on the knowns of the past. Such biases may lead to society failing in identifying risks posed by yet unknown hazardous chemicals. Alternative and complementary ways to identify priority chemicals are needed. More transparent communication between risk assessments performed as part of the risk assessment process within REACH and monitoring programs, and information on chemicals contained in consumer articles, would offer ways to identify chemicals for environmental analysis.

Environmental impact

The use of chemicals is a fundamental part of modern society. New chemicals are continuously introduced to commerce and world chemical sales increase yearly. Environmental analysis of chemicals helps us understand the risks chemicals pose to ecosystems and humans. All chemicals in commerce cannot be analyzed and prioritizations are needed. This is a major challenge. We use bibliographic data to compile a database with chemicals that were analyzed in Baltic Sea fish between the years 2000 and 2012, both within research and monitoring. We use this database as a basis for analysis and discussion of how chemicals are prioritized for environmental analysis and what consequences this might have for environmental chemical risk assessments.

Introduction

The use of chemicals has become a fundamental part of modern society. New chemicals are continuously introduced to commerce and world chemical sales increase yearly. From 2003 to 2013, EU's chemical sales almost doubled, and China's sales increased by 280%.[1] Safeguarding the health of ecosystems and humans has become an important and challenging task for society. The European chemicals regulation REACH (Registration, Evaluation, Authorization and Restriction of Chemical substances) has, so far, registered >12 600 substances.[2] To date these comprise substances produced within, or imported to, the European Union (EU) at ≥100 tons per importer/producer annually, as well as carcinogenic-, mutagenic- and reprotoxic (CMR) substances. Substances produced or imported in lower tonnages (1–100 tonnes per year per producer/importer) have to be registered by the end of May, 2018. Chemicals imported to the EU as constituents in consumer articles are only regulated to a limited extent in REACH,[3] despite growing evidence that emissions of hazardous chemicals from articles reach the environment.[4–6]

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Efforts to manage risks associated with chemicals are often built on decisions to restrict their use and to reduce exposures, in combination with monitoring of both occurrence and effects of chemicals. In the 1970's and 1980's, environmental concentrations and emissions of several persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs) and polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) peaked.[7,8] Since then, emissions of chemicals to the environment have generally emerged from well-defined point sources (such as industrial activities) emitting relatively few chemicals in high amounts, to many small diffuse sources (such as release of chemicals from consumer products we use in our every-day life). Time series of concentrations of known hazardous chemicals in the environment are important for the evaluation of actions taken to reduce emissions, as well as to diagnose any increase in exposure. On the other hand, early detection of chemicals of emerging concern is critical to enable actions to manage future hazards. Chemical analyses are very costly, and resources are limited. Society therefore needs to prioritize among the many chemicals that are in use and identify those of highest concern. This is a great challenge.

The Baltic Sea is polluted.[9] Its low species diversity makes the Baltic Sea particularly vulnerable to external stressors, such as pollution by industrial chemicals, pesticides and biocides.[10] Considerable resources are invested to understand and reduce levels of various pollutants in the Baltic Sea ecosystem. Legacy pollutants such as PCBs and other POPs are still of concern[9] due to their hazardous properties and the fact that they were emitted in high volumes. The densely populated catchment area also makes the Baltic Sea exposed to emerging pollutants, such as pharmaceuticals,[11] siloxanes[12] and perfluorinated chemicals.[13]

The aim of this study was to discuss and contribute to the development of the priority setting in contaminant monitoring and research. We reviewed available data to investigate which chemicals were analyzed in Baltic Sea fish as a part of environmental monitoring or research studies performed between 2000 and 2012. We furthermore determined how many of the analyzed chemicals are regulated by any chemicals legislation. We discuss what causes and consequences the prioritization of chemicals might have for society and initiate a discussion on potential ways forward towards an improved chemical management.

Method

Data collection

Data were compiled from both scientific journals and Swedish regional and national monitoring and screening program reports and databases. Scientific papers were searched for in Web of Science (Science Citation Index Expanded and Book Citation Index-Science) and Scopus using the following combinations of keywords: (i) fish AND Baltic Sea AND chemical, (ii) fish AND Baltic Sea AND contaminant, and (iii) fish AND Baltic Sea AND pollutant, covering the time period January 1st 2000 to December 31st 2012. Only research studies that performed measurements of chemicals in Baltic Sea fish were included, *i.e.* excluding those that only used data from previous reports. Monitoring data were taken from Swedish studies only. Sweden has a well-developed monitoring programme for pollutants in the Baltic Sea, which makes the Swedish data well-suited for the purpose of this study. Monitoring and screening studies included in the study covered the same time period as the research reports (2000–2012). This study was limited to analyses on fish, which means that chemicals with a low bioaccumulation potential most likely will not be present in our dataset.

Data compilation

Each analyzed chemical was identified by its Chemical Abstracts Service (CAS)-number and noted in the database as "detect" or "non-detect". A chemical was notified as "non-detect" if it was reported below its detection limit in all samples analyzed in a specific study. For a specific article/report, every substance was noted as one entry, although a substance might have been analyzed several times in that particular study. There were discrepancies in reporting among the studies, for example regarding whether specific congeners or isotopes or the total sum of all were reported. Therefore, to enable analysis of the data the substances were compiled into substance groups. For example, all PCB congeners were compiled and counted as one substance group, as were the brominated diphenyl ethers and so on. Degradation products were compiled together with their parent compound when this was known, as the emission routes are the same and can be regulated through the parent compound. The degradation products from the biocide tributyltin (TBT), monobutyltin (MBT) and dibutyltin (DBT) are used as stabilisers in plastic production. These two substances were not compiled into the substance group TBT. By grouping the chemicals this way, some substances and degradation products were listed as regulated even though they were not specifically covered by a legislation. This effect is minor and will not have a significant influence on the interpretation of the results. A table with all individual substances and how they are grouped is provided in the ESI (ESI, Table S1†).

International and European regulations

We searched for chemicals detected in Baltic Sea fish in regulations relevant to the Baltic Sea. Both CAS number and chemical name were used to search for the substances in the regulations. The following rules and regulations were searched:

- Regulation EC 1272/2008 on classification, labelling and packaging (CLP) of substances and mixtures, and in particular if the substances were identified as "Hazardous to the aquatic environment" according to the CLP. Both annex VI and industrial classifications were searched (database searched in August, 2014).

- Annex A, B or C in the Stockholm Convention on Persistent Organic Pollutants, updated 2013.

- Annex XIV (*i.e.* candidate list) of the Regulation EC 1907/2006 concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH).

- Annex XVII (*i.e.* restriction list) of the Regulation EC 1907/2006 concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH).

- Annex II of the Directive 2008/105/EC on Environmental Quality Standards.

The EU has adapted the United Nations Global Harmonized System of classification and labelling of chemicals (GHS) into the CLP of substances and mixtures.[14] The aim of CLP is to provide hazard information and thereby contribute to a safer handling of chemicals. The CLP establishes hazard criteria for different properties and end points. Substances that fulfil a criterion are classified accordingly and assigned specified hazard pictograms and hazard phrases for labelling the substance. Classification and labelling are the major communication tools used to convey the chemical hazard information to workers and consumers who may be in contact with the chemical. Only the environmental hazard classification in the CLP was used for this study.

The REACH regulation requires registration of substances produced within or imported to the EU over 1 tonne annually before the chemicals are allowed in the market.[15] Annex XVII of REACH restricts the use for specific chemicals. Candidates for inclusion in REACH annex XVII are added in annex XIV (also called the candidate list; art. 59§10, REACH).

The Directive on Environmental Quality Standards (Directive 2008/105/EC) aims together with the Water Framework Directive (WFD; Directive 2000/60/EC) to protect and promote good quality status in all European waters. In the Directive on Environmental Quality Standards, environmental quality standards of priority substances or substance groups of concern in European waters are identified. The chemical status of waters should be assessed, and further managed if the quality criteria are not met.[16]

The Stockholm convention on POPs is an international agreement with the objective to protect human health and the environment from persistent organic pollutants.[17] It requires its parties to take measures to eliminate or reduce the release of POPs (listed in Annexes A, B and C) into the environment.

Survey

A link to a questionnaire was sent by email to 41 of the corresponding authors of the scientific papers used in the analysis. These were the authors for whom we could find present addresses. Authors of the Swedish monitoring and screening programs were not included in the survey, as the selection of chemicals for monitoring is less flexible and not decided upon by one single author. The questions to the researchers in the survey were:

- What were the main reasons for choosing to analyze the environmental concentrations of the specific chemical(s) in your paper?

- Have you included other emerging chemicals in your research, for which the results were not published? – If yes, why?

- Do you think that focusing your research on known hazardous chemicals, such as POPs, affects the chance to receive funding?

All answers were treated anonymously. All questions and answers can be found in the ESI.†

Results

Chemicals

In total 105 substances or substance groups were analyzed in fish and published in the scientific literature (53 peer-reviewed research articles)[18–74] or in Swedish environmental monitoring reports (22 reports, listed in the ESI†) between 2000 and 2012. The database contains a total of 2070 entries (*i.e.* the number of reports and scientific papers that reported analysis of a certain substance). Of all entries, 88% were detects. Non-detect entries represent several substance groups. Most substance groups were more frequently detected than not detected (Fig. 1). Almost half of the substances or substance groups were reported both within scientific research and in environmental monitoring/screening reports. Monitoring/screening reports covered 55 substances or substance groups that were not investigated in scientific studies, while scientific reports included 19 substances that were not covered by any monitoring/screening study. PCDD/Fs and PCBs were the most studied substance groups with 654 and 381 entries, respectively. The majority, 87%, of all entries correspond to 20% of the substance groups (Fig. 2), whereas 46 substance groups (44%) only had a single entry.

Analyzed chemicals and coverage by legislation

More than two thirds of the substances, 70%, analyzed in Baltic Sea fish between the years 2000 and 2012 are covered by one or more regulations, or were self-classified by industry according to the environmental hazard criteria in the CLP regulation. The non-regulated chemicals analyzed in Baltic Sea fish were analyzed within both scientific and monitoring studies and belonged to the groups "Metals & Elements", "Perfluorinated compounds", "Other flame retardants", "Polychlorinated dibenzothiophenes", "Phenolic substances", "Phthalates" and "Others". Almost three quarters of all entries, 72%, regarded a POP-substance or a POP-related substance (*e.g.* DDE, the degradation product of DDT). In total, 82% of the substances on the POP list, 25% of the substances included in annex XVII (REACH), 58% of the prioritized substances according to the Directive on Environmental Quality Standards and 6% of the substances on the candidate list were analyzed in Baltic Sea fish (Fig. 3). Compared to the number of chemicals hitherto registered within REACH, the number of substances analyzed in fish within both scientific research and environmental monitoring corresponded to 2%.

Survey

In total 54% (22 of 41) of the contacted authors answered the survey. The most commonly stated reason for researching a specific substance was that it was a known hazardous substance (Fig. 4). Five persons answered that they also had analyzed emerging contaminants in Baltic Sea fish without yet publishing the results, although one person had recently submitted a report for publication. The reasons as to why no emerging substances were analyzed included too high uncertainty regarding the analysis, substances not fitting within the scope of the article, and the chemical(s) not being detected. The

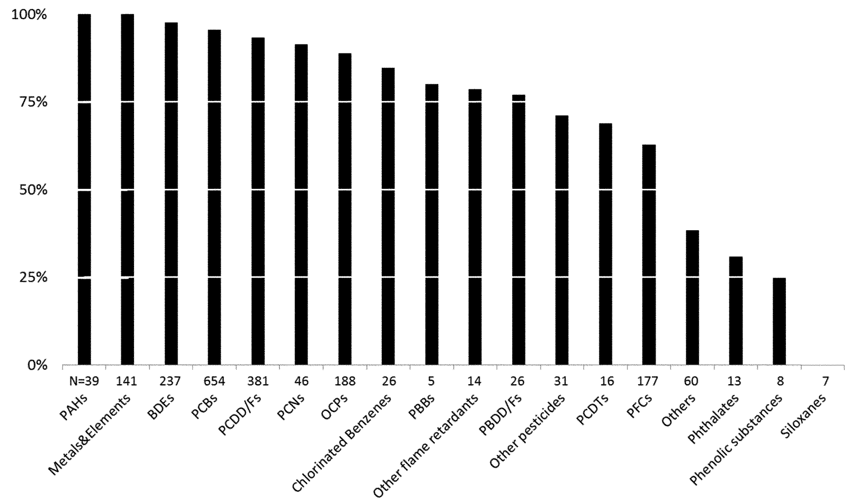

Fig. 1 Detects (%) for pooled substance groups. n = number of entries per pooled substance group.

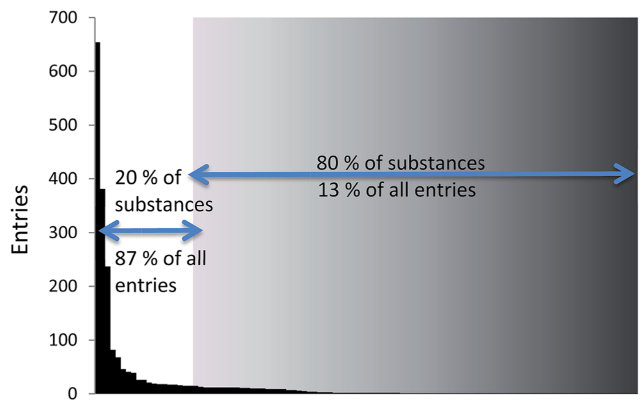

Fig. 2 Number of entries per substance group. Of all entries, 87% corresponded to 20% of the substance groups.

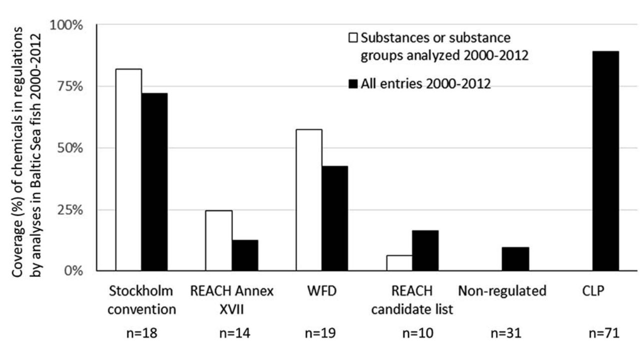

Fig. 3 Coverage (%) of the chemicals included in regulations that were analyzed in Baltic Sea fish 2000–2012 (white bars). Black bars demonstrate the percentage of the total number of entries (*i.e.* all analyses in the database collected for this study) that were covered by a specific regulation. Non-regulated substances imply that these substances were not covered by regulations analyzed in this study. CLP includes only environmental classification.

answer to whether or not focusing research on known hazardous chemicals, such as POPs, affects the chances to receive funding divided the respondents; 4% answered that it decreased the chance, 41% answered that it increased the chance and 41% answered that it did not affect the chance. Furthermore, comments by the authors on the survey pointed out that analytical equipment and standards for enabling emerging contaminant research are needed; non-target screening projects for prioritizing chemicals for large-scale monitoring are warranted in the Baltic region; novel methods to identify new POPs were needed as well as fish as a dietary source of contaminants needs to be further evaluated.

Discussion

To research or monitor all chemicals in commerce is not possible and not even desirable, as many chemicals will not pose a risk to ecosystems or humans. Still, this study illustrates that few, and already regulated chemicals, correspond to the absolute majority of analyses on environmental contaminants in Baltic Sea fish (Fig. 2). These findings are similar to what Grandjean *et al.*[75] observed when they performed a literature review to investigate which chemicals were analyzed in research during 2000–2009. Grandjean and co-workers demonstrated that although their database included 760 056 CAS-numbers, the top 20 chemicals corresponded to 12% of the total number of analyses. Our study focused on the Baltic Sea, but the situation will most likely be similar in other environments. The Baltic Sea is polluted and receives discharge from a catchment area populated by ~85 million people. Hence, for the 9 countries surrounding the Baltic Sea, it "offers" an environment well suited for analyses of emerging pollutants. Still, the majority of investigations have focused on well-known legacy chemicals.

There are many good reasons to analyze regulated chemicals, such as POPs, in the environment. These chemicals are toxic, persistent and bioaccumulative, and are present in the

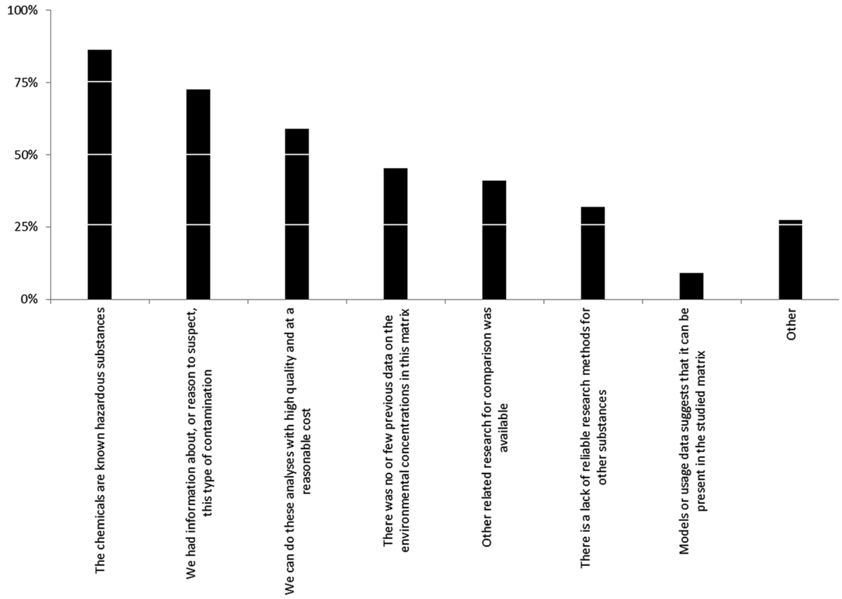

Fig. 4 Main reasons motivating the selection of chemicals. Comments under "Other" mainly concerned the lack of analytical capability and shortage of funding as restrictions of choice; all comments are available in the ESI.†

environment in concentrations that may be hazardous to ecosystems and humans. One such apparent example is the PCDD/Fs and dioxin-like PCBs in Baltic Sea herring, which occasionally exceed the EU limit value for food and feed.[76] Society therefore has a responsibility to monitor these chemicals in the environment and provide advice on how to handle risks associated with chemical pollution. A long and well-resolved time series, as a result of monitoring well-known pollutants, is an important tool in the diagnosis of environmental status and is used for trend analysis; it helps assess how fast a change occurs and whether more actions are needed. Time trends of regulated chemicals such as POPs play an important role in the policy work of organisations such as the OSPAR Commission (protecting and conserving the North-East Atlantic and its Resources), HELCOM (the Baltic Marine Environment Protection Commission) and UNEP (the United Nations Environment Programme) to improve the environmental status of marine environments. Identification of new hazardous chemicals is another important but difficult part of environmental analysis, which needs a different approach from traditional monitoring and target analysis of regulated pollutants. Screening methods utilizing gas chromatography- and liquid chromatography-high resolution mass spectrometry have been developed and significantly improved over the last few years,[77] and offer society a potential way forward to cover many of the unknowns in environmental monitoring programs and research.

Selection of chemicals in research

The chemicals analyzed by scientific studies were almost the same as the chemicals analyzed by monitoring studies, with PCBs, PCDD/Fs and other legacy pollutants as dominating compound groups. The majority of the researchers who responded to the survey stated that knowing the hazardous properties was an argument for choosing the substance in their research, but it was only once stated singly as a reason. The importance of whether it is a well-known hazardous substance might be explained by the context of the research. If the aim of the study is to describe and understand environmental processes of emerging pollutants or even to discover new pollutants, the selection of chemicals would be different from that in many of the reports included in this study. Developing new analytical methods for chemicals is a tedious and costly task. Possibilities of acquiring funding for a research project affect what kind of studies will be performed, and therefore, in the long-run, also whether the focus will be on identifying new chemicals or not in research. Only three scientific research projects with the aim to identify new emerging contaminants were funded by the Swedish Research Council for the Environment (Formas) during the years 2000 to 2012.[78] The choice between analyzing well-known chemicals that will certainly have detects and the risky and often expensive task of looking for unknowns may be dependent on the possibilities of acquiring appropriate funding. The difficulty of reporting "negative data" in terms of non-detects may also play a role in the choice of chemicals. The negative consequences of the lack of non-detects in scientific reporting on risk assessment were recently highlighted.[79]

Potential bias in prioritization of chemicals in environmental analysis

The Matthew effect is a psychological phenomenon, which states that items given much attention in the past are likely to generate more attention in the future.[80] Daughton[81] recently concluded that the Matthew effect may bias the exposure assessment process in the environmental risk assessment of pharmaceuticals. The identified biases included the following:

no available data being interpreted as zero concentration, a lack of holistic approach to assess total chemical exposure, an unclear prioritization process as well as the lack of data and uncertainty not being transparently handled in the risk management of chemicals. These biases together lead to an underestimation of the risk, according to Daughton.[81] Furthermore, Grandjean *et al.*[75] demonstrated that the overwhelming dominance of a few chemicals reported in the scientific literature during 2000–2009 could be due to the Matthew effect; the very reason of having been much researched can be considered enough motivation to research the chemical again. Grandjean and co-authors[75] stated that "such bias detracts from the societal needs for documentation on less well-known environmental hazards, and it may also impact negatively on the potentials for innovation and discovery in research". Hence, although there are strong arguments in support of the selection and prioritization of the chemicals analyzed in Baltic fish, there may still be bias in the selection process. A thorough review of the prioritization criteria used today, and the risks that society aims to monitor and minimize would be valuable for an assessment of the needs for revised strategies for environmental chemical analyses. The concept of planetary boundaries, which delimits a safe operating space for humanity,[82] is yet another example that illustrates the problem of focusing on knowns. One of the conditions identified for chemical pollution to cause a planetary boundary threat is that "the pollution has a disruptive effect on a vital earth system process of which we are ignorant".[83] MacLeod *et al.*[84] describe ways to identify chemicals that are planetary boundary threats and conclude that it is most challenging to prioritize chemicals by their potential to have currently unknown effects on a vital earth system process. Hence, the prioritization is further complicated by the fact that it is not necessarily known what to look for and therefore selection of chemicals is easily biased if it is based mainly on properties and research of known pollutants.

Conclusions

Monitoring and screening programs of today cannot embrace all known pollutants. With an ever increasing number of chemicals produced worldwide it is highly likely that future monitoring and screening programs will include an even smaller fraction of all chemicals in production and use. Adding more chemicals to monitoring and screening lists to keep up with ever increasing production and use is therefore not a realistic option for the future. Instead, we must find alternative ways to identify priority chemicals. The development of non-target and suspect screening techniques offers one complementary way forward, particularly in combination with effect-based tools to identify toxicity drivers.[85] Furthermore, there is a need for more transparent communication between risk assessments performed within REACH and monitoring activities in for instance the WFD and the Directive on Environmental Quality Standards. Parts of the EU member states' monitoring activities could be based on chemical safety assessments. This possibility is limited today by a lack of information and difficulties in getting access to chemical safety assessments performed within REACH. It is widely acknowledged that the management of risks associated with chemicals in articles needs to be improved, not least since chemicals incorporated in consumer articles constitute a significant source of toxic substances to the environment.[86] Still, chemicals in consumer articles are covered by REACH only to a limited extent. Providing environmental agencies with information on chemicals contained in consumer articles and that are imported to the EU would therefore offer an alternative to identify emerging pollutants to include in monitoring or screening activities.[3]

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