UC Santa Barbara

UC Santa Barbara Previously Published Works

Title

OrganoRelease - A framework for modeling the release of organic chemicals from the use and post-use of consumer products.

Permalink

<https://escholarship.org/uc/item/9n62d421>

Authors

Tao, Mengya
Li, Dingsheng
Song, Runsheng
[et al.](#)

Publication Date

2018-03-01

DOI

10.1016/j.envpol.2017.11.058

Peer reviewed

Contents lists available at ScienceDirect

Environmental Pollution

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

OrganoRelease – A framework for modeling the release of organic chemicals from the use and post-use of consumer products[☆]

Mengya Tao¹, Dingsheng Li¹, Runsheng Song, Sangwon Suh, Arturo A. Keller^{*}

Bren School of Environmental Science and Management, University of California Santa Barbara, Santa Barbara, CA, 93106, United States

ARTICLE INFO

Article history:

Received 10 May 2017

Received in revised form

15 November 2017

Accepted 16 November 2017

Keywords:

Chemical release

Functional use

Consumer products

Use phase

Post-use phase

ABSTRACT

Chemicals in consumer products have become the focus of recent regulatory developments including California's Safer Consumer Products Act. However, quantifying the amount of chemicals released during the use and post-use phases of consumer products is challenging, limiting the ability to understand their impacts. Here we present a comprehensive framework, OrganoRelease, for estimating the release of organic chemicals from the use and post-use of consumer products given limited information. First, a novel Chemical Functional Use Classifier estimates functional uses based on chemical structure. Second, the quantity of chemicals entering different product streams is estimated based on market share data of the chemical functional uses. Third, chemical releases are estimated based on either chemical product categories or functional uses by using the Specific Environmental Release Categories and EU Technological Guidance Documents. OrganoRelease connects 19 unique functional uses and 14 product categories across 4 data sources and provides multiple pathways for chemical release estimation. Available user information can be incorporated in the framework at various stages. The Chemical Functional Use Classifier achieved an average accuracy above 84% for nine functional uses, which enables the OrganoRelease to provide release estimates for the chemical, mostly using only the molecular structure. The results can be used as input for methods estimating environmental fate and exposure.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Concern over health risks of chemicals in consumer products has been increasing due to human exposure to chemicals released both indoors and outdoors (Trudel et al., 2008, 2011; Zota et al., 2014). Release of chemicals to the general environment from consumer products is also a concern for the health of the ecosystem especially for chemicals that are persistent and induce ecotoxicity, such as perfluorinated compounds, flame retardants, and certain antibiotics (Clarke and Smith, 2011; Ezechias et al., 2014; Janecko et al., 2016; Kunhikrishnan et al., 2015; Ortiz de Garcia et al., 2014; Rosal et al., 2010). As a result, chemicals contained in consumer products have become the focus of recent regulatory developments including the Safer Consumer Products Act of

California, the Safe Chemical Act of the U.S., and the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) program of the European Union.

A major challenge to minimizing the human and ecological health risk of chemicals in consumer products is the lack of available release information on the vast majority of chemicals and the economical infeasibility of obtaining relevant information for all chemicals through traditional experimental testing. To determine release estimates of chemicals from consumer products, one must first determine the plausible uses of a given chemical. Recently, Phillips et al. (2017) proposed a methodology to screen out candidate chemical alternatives based on functional use similarities and hazard information by combining quantitative structure-use relationship models and high-throughput toxicity screening. However, to assess the human and ecological health risk chemicals may pose, exposure as well as the fate and transport of the chemicals must be characterized, which requires estimates of the amount of chemical released from different products and applications. Traditional exposure assessments have been done for chemicals in consumer products (Aronson et al., 2007; Dann and Hontela, 2011; Goebel et al., 2012; Kienhuis et al., 2015). However, these methods rely

[☆] This paper has been recommended for acceptance by Eddy Y. Zeng.

^{*} Corresponding author.

E-mail addresses: mengya@umail.ucsb.edu (M. Tao), dli@ucsb.edu (D. Li), runsheng@umail.ucsb.edu (R. Song), suh@bren.ucsb.edu (S. Suh), keller@bren.ucsb.edu (A.A. Keller).

¹ Authors with equal contribution.

on measuring the concentrations of chemicals in different environmental media, which would be cost prohibitive for evaluating thousands of chemicals in consumer products. Fate and transport models for both indoor and outdoor environments can be used to estimate the concentrations of the chemicals of interest (Garner et al., 2017; Hollander et al., 2016; Liagkouridis et al., 2015; Rosenbaum et al., 2011). However, a vital input for these models is the release information of the chemical(s) to different environmental compartments during and after the use of products that contain the chemical(s).

Holmgren et al. (2012) presented a generic emission model for organic chemicals embedded in solid materials but this model is rather mathematically complex with dozens of parameters for each chemical, the shape of the consumer product, and the room characteristics. A less complicated and parsimonious model was recently developed for the release of volatile organic compounds encapsulated in products (Huang and Jolliet, 2016) but is limited to volatile organic compounds. Furthermore, both models (Holmgren et al., 2012; Huang and Jolliet, 2016) provide release estimates only for indoor air. Various models to estimate the release of different types of nanoparticles to multiple environmental compartments during the life cycle of various products have been published (Gottschalk et al., 2010; Gottschalk and Nowack, 2011; Keller et al., 2013, 2014; Keller and Lazareva, 2013; Sun et al., 2016). However, such studies do not address the release of organic chemicals, which make up the majority of both existing and new chemicals.

Given the current status of research, a systematic methodology for quantitatively estimating the release of organic chemicals contained in a wide range of consumer products is needed as input to models used to characterize potential human and ecosystem exposure to chemicals. Here we present the OrganoRelease framework, a methodology to estimate the distribution (as a fraction of the total amount used) of the release of a chemical to different environmental compartments during the use and post-use phases of consumer products, when product-specific chemical release measurements are lacking. Post-use phase is when chemicals are being transported to wastewater or waste treatment plants after the direct use of consumer products. OrganoRelease was designed to accommodate different levels of data availability for any given organic chemical, with the minimum required input being the chemical structure alone. To achieve this goal, in OrganoRelease we connect the chemical's structure (e.g., topological, physicochemical properties, etc.), possible functional uses which are grouped based on the chemical's primary function (e.g., surfactant, solvent, etc.), potential product categories (e.g., cosmetics, paints, etc.), and release factors (as fractions of the chemical of interest released to indoor or outdoor air, wastewater, soil, and waste during use and post-use phases). OrganoRelease can provide rapid screening-level estimates of the release of chemicals contained in a range of consumer products during the use and post-use phases.

2. Methods

OrganoRelease estimates the distribution (in percent) of the release of a chemical directly released to indoor air, outdoor air, wastewater, soil, and waste, without considering any post-release environmental fate and transport processes. OrganoRelease consists of three components that connect the functional use (defined as the chemical categories grouped based on their primary function), product category, and release factors together: 1) a Chemical Functional Use Classifier that estimates the chemical's functional use if not known; 2) market share data that links the functional uses with different product categories to quantify the mass fraction

of chemical(s) entering corresponding product streams; and 3) release factors, based on functional uses and product categories, to estimate the initial release of the chemical(s) in products to the environment. The conceptual framework of OrganoRelease is shown in Fig. 1.

2.1. Chemical Functional Use Classifier

An artificial neural network (ANN) was employed to develop a Chemical Functional Use Classifier ("Classifier" for short) that estimates chemical functional uses such as solvents and surfactants based on the molecular structure of the chemical. The molecular structure information is represented by the molecular descriptors, including constitutional, topological, chemical properties, and many other descriptor blocks (Todeschini and Consonni, 2009). ANNs serve as a nonlinear, universal approximation model to extract the intrinsic knowledge within a large amount of data (Hornik et al., 1989).

Pairs of chemical-functional use data points were collected from Chemical Book (ChemicalBook, 2016) based on chemical functional uses with available market share data. This included nine functional uses: aerosol propellants, antibacterial agents, flame retardants, flavors and fragrances, solvents, surfactants, fungicides, herbicides, and insecticides, which are the major functional uses in consumer products. This is to ensure a seamless connection between estimating product use categories and functional uses. Since the molecular descriptors can only be computed for organic compounds, we removed mixtures, inorganics, salts, and organometallics. After the data curation process, we had a total of 2900 pairs of chemical-functional use to build the Classifier.

Dragon 7 (Dragon 7.0, 2016) was used to generate over 4000 molecular descriptors for each chemical, including constitutional, topological, chemical properties, and many other descriptor blocks. In order to reduce the number of molecular descriptors to the recommended ratio of number of entries to number of variables for quantitative structure-activity relationship (QSAR) models (Dearden et al., 2009), a filter-based feature selection algorithm was performed to remove the molecular descriptors that have a variance lower than 15 or a correlation coefficient higher than 0.65 with other descriptors (Dutta et al., 2007; Gramatica, 2007).

The collected dataset was randomly split into training, validation and test datasets. For each functional use category, 20 chemicals were first randomly selected as test dataset. For the rest of the data points within each functional use, 85% were randomly chosen as training set and 15% as validation set. The ANN models were built based on the training set, and the validation set was used to select the best fit model. The test set was applied to evaluate the performance of the final model. The Classifier was built in Python, using the Scikit-learn package (Pedregosa et al., 2011) for dataset random selection and final model evaluation. TensorFlow (Abadi et al., 2016) was implemented to build neural network models. A combination of grid search and random search methods were performed for hyperparameter optimization to optimize the set of parameters in the learning algorithm as well as avoid overfitting (Bergstra et al., 2013). Fig. 2 illustrates the conceptual diagram of the Classifier building process.

The performance of the Classifier is measured by its precision, recall, and F1 score, which are defined in Equations (1)–(3). Precision indicates the ability of the Classifier to not label a negative sample as positive, while recall implies the ability of the Classifier to find all positive samples (Powers, 2011). F1 score represents a weighted harmonic mean of precision and recall. All three metrics range from 0 to 1; values closer to 1 indicate better model performance.

Fig. 1. Conceptual framework of OrganoRelease.

Fig. 2. Conceptual diagram of Chemical Functional Use Classifier module building process.

$$\text{Precision} = \frac{\text{True Positive}}{\text{True Positive} + \text{False Positive}} \quad (1)$$

$$\text{Recall} = \frac{\text{True Positive}}{\text{True Positive} + \text{False Negative}} \quad (2)$$

$$F1 = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \quad (3)$$

2.2. Market share data

The use of market share data offers an approach to quantify the percentages of the functional use(s) of the chemical of interest entering the corresponding product categories. Grand View Research (Grand View Research Inc, 2016) (GVR) and The Freedonia Group (Freedonia Group, 2016) provided market research information on global market volumes (in tons) by application, including aerosol propellants, antibacterials, flame retardants, flavors and fragrances, pesticides, solvents, and surfactants. The three types of pesticides (fungicides, insecticides, herbicides) were combined into agricultural chemicals, since the release factors, even for consumer use, are not differentiated in the database developed by the European Crop Protection Agency (ECPA, 2013). The release category of crop protection products (Table S-1) also includes the use of the three types of pesticides by consumers in residences and commercial operations. The market volumes were transformed into percentages to capture the distribution of product applications for each chemical functional use. The original market volume data was developed by the consulting companies using interviews with suppliers, distributors as well as buyers. A certain level of uncertainty was associated with the market share estimates. To capture the uncertainty, we assumed a variation of $\pm 10\%$ in the market share percentage estimates based on our communications with the market research companies. We transformed the market volume data into market fractions with an uncertainty range.

2.3. Release factor data sources

Release factors to environmental compartments (indoor air, outdoor air, wastewater and soil) for chemicals in different products were gathered from the European Union (EU) specific environmental release categories (SPERCs) (Sättler et al., 2012). The scenario specific SPERCs were developed by a variety of European

trade groups and sector organizations, intending to provide realistic yet conservative default release estimates, considering narrower use scenarios and good operational practices. SPERC-based emission estimates have been incorporated into several environmental exposure assessment tools (CEFIC, 2012), such as CHESAR (CHEMical Safety Assessment and Reporting Tool) (ECHA, 2016), ECETOC TRA (European Center for Ecotoxicology and Toxicology of Chemicals Targeted Risk Assessment) (ECETOC, 2014), and EasyTRA (Jansen-Systems, 2014). Since we are only interested in consumer products used in wide dispersive use (also called consumer use) or professional use, 64 out of 190 SPERCs files were reviewed and extracted to use as release factors (Table S-1 in the Supplemental Information (SI)). The industry sector groups and their corresponding websites are shown in Table S-2. The default release factors in SPERCs consider the application type (e.g., down the drain, spray), use scenarios (e.g., indoor or outdoor use), and physicochemical properties, specifically vapor pressures for nine product sub-categories and water solubility for one product category (Table S-1). Among the nine product sub-categories that consider vapor pressures, four have varying release factors based on tiered vapor pressure values while the other broadly consider whether the chemical is solid or volatile. Most of the products in these categories are used indoors, and would thus result in an indoor air release. Some categories may be used both indoors and outdoors, such as paints and cleaning products. Another small number of categories, such as pesticides and fertilizers, are mainly used outdoors.

Another major data source for release factor estimates was the A-table of the European Union Technical Guidance Documents (EU TGD), specifically, under industrial category number 5 for “personal/domestic use”, which considers the private use phase in a chemical life cycle (European Commission, 2003; Vermeire et al., 2005). There are 55 use categories, and category 55 is designated as “Other” uses (Table S-3). Three categories in EU TGD have varying release factors based on the chemical’s water solubility and six categories are based on vapor pressure. Most of these functional use categories result in release to indoor air since these consumer products are generally (though not always) used indoors, with the exception of fertilizers and pesticides. Therefore, the release factors to air can be assigned to either indoor or outdoor air depending on the use scenarios.

Since most of the release factors in SPERCs take into account the values from EU TGD, measured release data, market research data, and expert judgement via questionnaires (CEFIC, 2012; Sättler et al., 2012; Umweltbundesamt, 2011), OrganoRelease gives top priority for the default values in SPERCs. When release factors for certain product categories are not available, the default values in EU TGDs are used. For the fraction of chemical that is not released into air, wastewater, or soil, we assume it would be disposed as waste at the post-use phase. OrganoRelease does not consider additional potential releases from solid waste management (e.g. landfill leachate, emissions from incinerators).

2.4. Framework workflow

The workflow of OrganoRelease is shown in Fig. 3. Based on different levels of knowledge available for a given chemical, the framework provides different paths to assess the potential environmental release of a chemical during the use and post-use phase of various consumer products. These release factors can be directly applied to chemicals for which the consumer product categories and use amounts (mass) are known (Path 1). When a chemical’s product categories are uncertain but the likely functional uses are known, which is often the case for upstream chemical producers, two paths can be applied depending on the availability of market

share data for those functional uses. If the market share data is available, it will be employed to match the functional use with the product use categories (Path 2a). If the market share data for a certain functional use is not available, the release factors will be generated solely based on functional use (Path 2b). For a chemical with both product categories and functional uses unknown, the Chemical Functional Use Classifier will be used to predict the most probable functional use. The release factors will then be assigned based on the predicted functional use and the availability of market share data (Path 3a if market share data available and Path 3b if not).

The framework workflow can be mathematically represented in Equations (4) and (5) as shown below:

Path 1:

$$M_k = M_{use} \left(\sum_j F_{j,k} \times \varphi_j \right) \quad (4)$$

Path 2a/b and Path 3a/b:

$$M_k = M_{use} \left(\sum_i \sum_j F_{i,j,k} \times \varphi_{i,j} \times \Phi_i \right) \quad (5)$$

where M_k is the amount of chemical release into a compartment k (indoor air, outdoor air, wastewater, soil, or waste), M_{use} is the amount of chemical consumed in the use phase, $F_{i,j,k}$ is the release factor to compartment k of the chemical used in product category j of functional use i , Φ_i is the fraction of chemical used in functional use i , and $\varphi_{i,j}$ is the fraction of chemical used in product category j of functional use i . OrganoRelease can only provide the release fractions of a chemical to various environmental compartments. To calculate the total amount of a chemical used (M_{use} in kg) in a particular location, country or globally, the user needs external data. For certain chemicals, production amount may serve as a surrogate of use as shown in a recent study (Shin et al., 2015).

We developed a case study using tertiary-butyl acetate (TBAC) to demonstrate the workflow of the OrganoRelease framework. TBAC is a commonly used solvent with wide applications such as paints, adhesives and cleaners (Geiser, 2015), listed by US EPA as a high production volume chemical with 5000–25000 metric tons produced in 2015 (EPA, 2017). Since TBAC is not within our Classifier’s training dataset, we used the Classifier to predict its functional use to demonstrate Paths 3a/b. Paths 1 and 2a/b were also considered in the demonstration.

3. Results

3.1. Functional uses and product categories considered

Table 1 presents the functional uses included in the Classifier, with market share data, or with default release factors in EU TGD. Two lists of product categories with default release factors in EU TGD and SPERC are also shown in Table 1. The release factors for the “Others” category in EU TGD depend solely on the chemical’s water solubility and vapor pressure. Currently, the Classifier can estimate nine functional uses and market share data is available for seven. Note that the Classifier was developed based on the highest quality of data we obtained and therefore it differentiated pesticides into fungicides, herbicides, and insecticides. However, these three functional uses in the Classifier are indifferently matched to pesticides in the market share data since such differentiation was not available for the market share data.

All currently published SPERCs that are relevant to consumer

Fig. 3. Workflow of OrganoRelease, depicting the various paths depending on the level of known information available for the chemical(s) of interest. The diamond symbol represents a decision that needs to be made and the rectangle indicates a process to identify the release factors.

Table 1
Functional uses and product categories in different components of OrganoRelease.

Data Source	Type	Number of Types	Description
Classifier	Functional Use	9	Aerosol Propellants, Antibacterials, Flame Retardants, Flavors and Fragrances, Fungicides, Herbicides, Insecticides, Solvents, Surfactants
Market Share Data	Functional Use	7	Aerosol Propellants, Antibacterials, Flame Retardants, Flavors and Fragrances, Pesticides (includes Fungicides, Herbicides, Insecticides), Solvents, Surfactants
EU TGD	Functional Use	15	Aerosol Propellants, Anti-freezing Agents, Anti-static Agents, Bleaching Agents, Cleaning Agents and Additives, Colorants, Complexing Agents, Corrosion Inhibitors, Fertilizers, Odor Agents, Pharmaceuticals, Softeners, Solvents, Surfactants, Others
	Product Category	5	Adhesives, Cosmetics, Food and Feedstuff Additives, Lubricants and Additives, Plant Protection Products (Agricultural)
SPERC	Product Category	13	Adhesives and Sealants, Coatings (Automotive), Coatings (Coal), Coatings and Inks and Artist Colors, Construction Chemicals, Crop Protection Products, Detergents and Cleaners, Metal Treatment Products, Hair and Skin Care Products, Lubricants and Greases, Paints and Coatings in Metal Packaging, Solvent in different products

products were collected from eight industrial sectors (SI Table S-1). Even though the EU TGD contains 55 categories, only 15 functional uses and 5 product categories with quantitative release information were available, including the category of “Others”, which covers anything outside the categories documented in EU TGD.

3.2. Chemical Functional Use Classifier performance

The performance of the Chemical Functional Use Classifier on nine functional uses is presented in Table 2. The Classifier achieved both high precision and recall rate for aerosol propellants, flame retardants, flavors and fragrances, surfactants, and herbicides, with F1 scores over 0.89. For other functional uses the F1 scores were over 0.70 except for fungicides, which had an F1 score of 0.60. A detailed misclassification table of the Classifier on 180 test chemicals (20 test chemicals for each functional use) can be found in SI Table S-4. The lower precision and recall rates of fungicides and insecticides is partially due to the high structure similarity between fungicides and insecticides, which leads to 20% of fungicides being misclassified as insecticides and 20% of insecticides being misclassified as fungicides (SI Table S-4). An alternative model was also constructed by aggregating fungicides, herbicides, and insecticides into one category of pesticides while keeping other functional uses. The overall F1 score for the alternative model is 0.88. SI Table S-5 shows the detailed value of precision, recall, F1 score, and SI Table S-6 displays the misclassification information for each functional use in the alternative model.

Training data is crucial to develop the Classifier. The Classifier can incorporate additional functional uses and expand its coverage as more data becomes available. This will increase the overlap between functional uses that can be estimated by the Classifier and included in the EU TGD to improve the connections between these two components in OrganoRelease.

3.3. Market share data results

Market share data was compiled for nine major functional uses that are relevant to consumer products, including antibacterial agents, aerosol propellants, flavors and fragrances, flame retardants, insecticides, herbicides, fungicides, solvents, and surfactants (Freedonia Group, 2016; Grand View Research Inc, 2016). Insecticides, herbicides and fungicides were combined into pesticides, since their product category is the same, in terms of the release factors (i.e. release to air and soils, since it is assumed they are not released to wastewater). Table 3 shows the distribution structure of each functional use across the product categories along the year of the data was collected. In some cases, it is possible that the functional use is assigned to a primary product category and is not reflected in the final product category (e.g. solvents are used in paints, which may end up in automotive uses, but are not captured

explicitly). As mentioned in the previous section of this paper, a factor of $\pm 10\%$ was considered to reflect the uncertainty in market shares. Under the scenario of unknown chemical product uses, the market share data provides valuable information on product flows for every available functional use, which can further improve the estimation accuracy of chemical releases. The coverage of functional uses and market share data can also be expanded and updated as additional information becomes available. At this stage our objective was to demonstrate proof-of-concept.

3.4. Release factor selection

The release factor selection is based on varying degrees of knowledge for a given functional use and/or product category as described in the methods section. For the functional use and product category pairs with matching SPERC document available, release factors from SPERC documents are selected. For example, ESVO SPERC 8.3c.v1 (uses in coatings: consumer) was chosen for solvents used in paints and coatings; ECPA SPERC 8d (crop protection products) was chosen for pesticides used as agricultural chemicals. If the product category (e.g., pharmaceuticals) for a chemical does not have a SPERC, release factors from EU TGD are selected to match the functional use (either known or estimated by the Classifier). Due to the spread in physicochemical properties (e.g. vapor pressure and water solubility), the release factors can vary across a wide range since these properties are considered in many of the SPERCs and EU TGDs. A comprehensive release factor selection table can be found in SI Table S-7. The release estimates may be applied to all regions, but wastewater collection rate and treatment efficiency in different regions (summarized in Keller and Lazareva, 2013) need to be considered to improve the accuracy of estimates for the fraction released to water. A wastewater treatment plant model, such as the Sewage Treatment Plant (STP) module in EPI Suite from US EPA, can be used to estimate the fractions of the chemical removed by various processes (e.g., biodegradation, and air stripping), released to the environment as effluent, or accumulated in biosolids (US EPA, 2012). The data from SPERC and EU TGD provides a starting point for estimating chemical releases, but product- or use-specific information should be used in OrganoRelease whenever available, to improve the accuracy of the estimates.

3.5. Case study

Tertiary-butyl acetate (TBAC, CAS 540-88-5), a chemical not in the training dataset of the Chemical Functional Use Classifier, was selected to showcase the workflow of OrganoRelease. TBAC is generally used as a solvent in paints (Cooper et al., 2001). It has a solubility of 8.3 g/L in water (US EPA, 2012) and a vapor pressure of 47 mm Hg at 25 °C (Pubchem, 2017). For demonstration purposes of

Table 2
Performance of the Chemical Functional Use Classifier on nine functional uses.

Functional Use	Number of Chemicals ^a	Precision	Recall	F1 Score	Number of Test Chemicals
Aerosol Propellants	68	1	0.9	0.95	20
Antibacterials	582	0.77	0.85	0.81	20
Flame Retardants	146	1	1	1	20
Flavors and Fragrances	488	0.86	0.95	0.9	20
Solvents	188	0.79	0.75	0.77	20
Surfactants	195	1	0.9	0.95	20
Fungicides	290	0.6	0.6	0.6	20
Herbicides	429	0.94	0.85	0.89	20
Insecticides	527	0.65	0.75	0.7	20
Average/Total		0.85	0.84	0.84	180

^a Total number of chemicals considered in a given functional use for Classifier.

Table 3
Market share of functional uses across product categories.^a

Product Category	Functional User						
	Aerosol Propellants ^b	Antibacterial Agents ^b	Flame Retardants ^c	Flavors and Fragrances ^c	Pesticides ^b	Solvents ^b	Surfactants ^b
Year of data	2014	2014	2013	2011	2014	2013	2014
Adhesives and Sealants						2.5%–3.0%	
Agricultural Chemicals					100.0%		3.2%–4.0%
Automotive			12.8%–15.6%				
Construction Chemicals			24.2%–29.5%				1.7%–2.1%
Personal Care Products	33.8%–41.4%	16.6%–20.3%				2.5%–3.0%	20.8%–25.4%
Electronics			20.2%–24.7%				
Emulsion Polymerization (plastics)							2.8%–3.4%
Foods and Beverages	5.8%–7.0%	21.4%–26.2%		41.7%–51.0%			3.7%–4.5%
Home Care Products	30.5%–37.3%						36.8%–45.0%
Industrial and Institutional Cleaner				37.4%–45.7%			4.4%–5.4%
Oilfield Chemicals							3.3%–4.1%
Others	3.1%–3.7%		9.4%–11.5%	10.9%–13.3%		14.8%–18.1%	9.3%–11.3%
Paints and Coatings	14.0%–17.1%	12.1%–14.8%				54.8%–67.0%	1.9%–2.3%
Pharmaceuticals	2.9%–3.5%					6.8%–8.3%	
Printing Inks						8.6%–10.6%	
Textiles			3.2%–4.0%				2.0%–2.4%
Water Treatment Chemicals		27.0%–33.0%					
Wires and Cables			20.2%–24.7%				
Wood Preservatives		12.9%–15.8%					

^a Each column shows the fraction of each functional use distributed across the product categories based on the market volumes. Pesticides includes fungicides, insecticides and herbicides.

^b Compiled from Grand View Research Inc (2016).

^c Compiled from Freedonia Group (2016).

the various paths of the framework, different levels of knowledge of the chemical were assumed: 1) TBAC used as solvent (functional use) only in paints (product category) as known information (Path 1); 2) TBAC used as solvent (functional use) as the only known information (Path 2a); and 3) no known use information for TBAC available (Path 3a). Corresponding results are shown in Table 4. The diagram in Fig. 4 displays the mass flow of TBAC from solvent to product categories and releases to air, wastewater, soil, and waste in Path 2a.

The market share data of solvents was utilized to quantify the mass flow from solvent to various product categories. For each product category, the default release factors in the corresponding SPERC and EU TGD were selected to quantify the releases to various environmental compartments. In Table 4, the release factors for Path 2a are ranges instead of point values due to the assumed $\pm 10\%$ uncertainty in the market share data. In Path 3a, the Classifier correctly estimated TBAC to be a solvent, so the release factors are the same as in Path 2a. Path 2b and Path 3b are not applicable as the market share data of solvent is available. Those two paths would only be applied when the functional use does not find a match in the market share data.

Path 1 has the most accurate estimates, since it uses known information. There is uncertainty in the release factors for Path 1, given that these are generic values for all chemicals used as solvents in paints, but Path 1 serves as a basis for the comparison. In Path 2, since the only known information is the functional use,

OrganoRelease considers possible product categories that use solvents and the corresponding SPERCs or TGDs, which results in a wider range of estimates and also a decrease in the estimated release to air, and a corresponding increase in release to wastewater (from treatment) or waste. For a given calculation, the sum of all releases must add up to 100% (as shown in Fig. 4), but we present the range of predicted values. The increase in predicted release to wastewater and waste is mostly due to the consideration of the use of TBAC in pharmaceuticals, printing inks and others. If the user has additional information indicating that a chemical of interest cannot be used in those product categories, OrganoRelease can be re-run to obtain more accurate estimates.

In this case study, we explored the use of OrganoRelease for estimating chemical releases to various environmental compartments. Although more knowledge for the chemical of interest can reduce the uncertainty of the results, OrganoRelease is able to provide a starting point for the release estimations based on only the molecular structure of the chemical with the built-in Classifier and various databases that work in coordination.

4. Discussion

4.1. Applications of OrganoRelease

The quantitative range of release estimates generated by OrganoRelease can be used as input for other environmental models

Table 4
Release factors to various environmental compartments for TBAC assuming different levels of knowledge. Path 2a and Path 3a have taken into account of $\pm 10\%$ uncertainty in market share data.

Framework Path	Release Data Description	Release Factor to Environmental Compartment				
		Indoor Air	Outdoor Air	Wastewater	Soil	Waste
Path 1	ESVOC SPERC 8.3c.v1 (solvent uses in coatings: consumer)	98.50%	0%	1.00%	0.50%	0%
Path 2a	Solvent market share data; release factors from SPERC and EU TGD	79.0%–96.5%	0%	5.3%–6.4%	0.68%–0.84%	5.1%–6.2%
Path 2b	Not applicable (N/A)	N/A	N/A	N/A	N/A	N/A
Path 3a	The Classifier predicts the chemical to be solvent	79.0%–96.5%	0%	5.3%–6.4%	0.68%–0.84%	5.1%–6.2%
Path 3b	Not applicable (N/A)	N/A	N/A	N/A	N/A	N/A

Fig. 4. Mass flow (in percent) of TBAC in Path 2a based on solvent market share data, using the midpoint of the range of values. The release factors for each product category are selected from SPERC and EU TGD.

answering various questions. The first-tier release factors from OrganoRelease can be used with second tier models such as STP (US EPA, 2012), to obtain aggregated release information of chemicals to different environmental compartments and provide the necessary input data for fate and transport models (e.g., Brandes et al., 1996; Garner et al., 2017; Mackay and Paterson, 1991; Nijhof et al., 2016), to predict the environmental concentrations of the chemicals, which can then be used as input to evaluate potential damages to humans and ecosystems. If the product application is indoors (e.g. paints, application of cosmetics), the estimated release to the indoor air environment from OrganoRelease can be used as an input for indoor air models (Chaudhary and Hellweg, 2014; Wenger et al., 2012) to calculate human exposure and assess risks.

OrganoRelease can also make contributions to Life Cycle Assessment (LCA). LCA is a tool to assess the environmental and human health impacts of a product throughout its entire life cycle, from raw material extraction, manufacturing, use, to end of life (Azapagic, 1999; Gavankar et al., 2012; Hellweg and Canals, 2014). Although emissions of chemicals during the cradle-to-gate phases (i.e., from raw materials to completion of manufacturing) is systematically covered by existing life cycle inventory (LCI) databases (National Renewable Energy Laboratory, 2012; Wernet et al., 2016), there is great need for similar data on the release information for the use and post-use phases of chemicals in consumer products to complete LCA's holistic goal. By integrating OrganoRelease as input to current life cycle impact assessment (LCIA) methodologies, the challenge of data gaps in use and post-use releases of chemicals in consumer products can be addressed with information on the use amount of chemicals in consumer products. This can potentially help decision makers understand the relative contributions of impacts to human health and ecosystem quality from the use and post-use phases of consumer products in the context of their entire life cycle impacts. Coupled with regionalized socioeconomic data or detailed regional market share data for different product

categories, this framework may provide insights on the different release factors to the environment based on the location where the products are consumed (Hodges et al., 2014; Keller and Lazareva, 2013). However, it should be noted that OrganoRelease cannot address near-field exposure related questions such as dermal contact and ingestion of leachate from packaging materials. Specialized exposure models such as PiF (Jolliet et al., 2015) and SHEDS-HT (Isaacs et al., 2014) should be considered for such exposure studies. In addition, the release factors estimated by OrganoRelease may be more conservative due to the methodologies of SPERC and EU TGD. This is in contrast with the average estimates of chemical emissions in current LCI databases. LCA practitioners should be mindful of this difference when applying OrganoRelease, compared to other LCI databases.

4.2. Coverage of OrganoRelease and comparison with other studies

Although detailed information of the chemical/product combination is always preferred, OrganoRelease is applicable even when minimal information other than the chemical structure is available. The Chemical Functional Use Classifier is built using machine learning to increase the applicability of OrganoRelease as more information becomes available. Machine learning techniques have been employed recently to solve challenging problems regarding sustainability of chemicals and consumer products. Isaacs et al. (2016) developed classifier models to predict chemical functions and their weight fraction in personal care products using random forest. Using the same random forest technique, Phillips et al. (2017) built binary models to predict the functional uses of chemicals and combined this information with high-throughput toxicity screening results to identify alternatives to existing ingredients of concern within consumer products. The F1 score calculated for the Classifier measures the model's accuracy of classification and hence is comparable to the complement of misclassification error

reported in Phillips et al. (2017), even when our Classifier is multiclass while the models developed by Phillips are binary. For the same functional uses covered in both studies (antibacterials, flame retardants, flavors and fragrances, solvents, and surfactants), the F1 scores of our Classifier are similar to the complements of misclassification errors from Phillips et al. (2017) indicating similar level of performance for these functional uses. Another distinction between the OrganoRelease classifier and that of Philips et al. is with regards to the functional uses covered. The Classifier in this model links with the market fraction data available in this study so that release information for a range of chemicals can be estimated. The binary models built by Phillips et al. would require market fraction data on several additional functional uses to be compatible with OrganoRelease. In addition, since the binary classifiers were built and trained with different data and features, the output from each classifier may not be directly comparable. OrganoRelease's Classifier uses the same features for estimating the probability of all functional uses, making each probability comparable before selecting the functional use with the highest probability as output.

The versatility of OrganoRelease, in terms of the amount of information needed to generate an estimate, can be compared with other studies on consumer products. Case studies on release of certain chemicals in specific products exist but cannot easily offer estimates for other chemical and products combinations (Quadros et al., 2013; van Wezel et al., 2016). Mechanistic diffusion models that estimate the release of chemicals from a product to indoor air are available but generally have high complexity and the limited availability of parameter values could hinder their application in screening risk or life-cycle assessments (Huang et al., 2017). The minimal requirements for OrganoRelease could be useful when information for a more complex model is not available.

The Consumer Exposure Model developed by US EPA requires information of the weight fractions of chemicals to complete estimates of release (US EPA, 2015). Obtaining this information can be challenging, as it is often proprietary knowledge with commercial value. The predictive model estimating the weight fractions of chemicals in consumer products developed by Isaacs et al. (2016) offers an opportunity to address this challenge. However, the Isaacs model is specialized in the relatively data-rich product category of personal care products and is not yet applicable to other products. The Chemical/Product Categories Database (CPCat) covers a much wider range of product categories, but the information it contains is rather general and includes all possible product applications where a known chemical may be found and all information is subject to the availability of chemicals already included in CPCat (Dionisio et al., 2015). In contrast, the Chemical Functional Use Classifier developed in this study allows OrganoRelease the ability to generate preliminary release estimates using mostly chemical structure (along with the available market fraction) thus being able to cover more chemicals.

The Chemical Functional Use Classifier developed in this study may also be useful to explore potential new functional uses of existing chemicals, using the “misclassification” results. This may also help in identifying unintended uses of chemicals and resulting consequences to human health and environment.

4.3. Limitations of OrganoRelease

The final results produced by OrganoRelease largely depend on the SPERC and EU TGD data. While offering a wide range of coverage over multiple product categories and functional uses with some considerations of physicochemical properties, SPERC and EU TGD data are not chemical specific but generic within each product category/functional use and should be interpreted as a preliminary estimate, useful when more specific information is absent. Isaacs

et al. (2014) demonstrated product composition, amount of product used, and frequency of product used are among the most sensitive parameters in estimating human exposure in the use phase of consumer products. Thus, OrganoRelease should be used as a screening level tool for chemicals when there are major data limitations and not be used when relevant data can be obtained in more detailed or product oriented studies. It should be noted that although OrganoRelease seeks to provide accurate release estimates, some of the SPERCs or EU TGD could be conservative in nature, and may result in conservative release estimates.

Based on the EU TGD data, OrganoRelease considers dermal application of certain pharmaceuticals, in which case 25% is released to wastewater; if the pharmaceutical is ingested, the EU TGD consider that only 5% is released to wastewater. We assume that the balance of the chemical in a pharmaceutical is absorbed and metabolized. As indicated before, OrganoRelease is intended for a generic release estimate; if a manufacturer or user has better information on the application, it should be used instead. OrganoRelease does not account for the possible transformation (e.g. photodegradation) of a chemical during the use phase, which may be significant for some chemicals or applications. More specific models would be needed for those cases.

The market data gathered so far covers nine functional uses. Although these categories represent a wide range of applications in different consumer products, there are gaps in linking other functional uses with product categories. Thus, expanding the market data is among the top priorities for future development of OrganoRelease. In addition, several product categories (wood preservative, wires and cable, electronic, automotive, textile, etc.) in the collected market share data cannot be matched to the SPERC database. The OrganoRelease framework thus estimates the release factors based on the functional use, which is less specific. Depending on the information available, the user may opt to not consider certain product categories if additional (external) information (e.g. toxicity) can be used to determine that a chemical is not suitable for use in a given product category.

The Chemical Functional Use Classifier predicts the potential functional uses among the nine developed categories when no detail information is available. The functional uses that can be estimated are limited by the amount of training data we were able to collect. To improve the coverage of the Classifier more training data with more diverse functional uses are needed. However, the Classifier estimates only the functional use with highest probability. If the user considers only the “most probable” functional use, then that limits the release to the product categories associated with that functional use. If the user has additional information on functional uses, those functional uses can be selected to consider a broader range of product categories.

Although the uncertainty in classification and market fractions is quantifiable in OrganoRelease, we were not able to characterize uncertainty for the SPERC and EU TGD data, since that information is not available from those databases. However, in some cases it is clear that the uncertainty is very small, for example when a product is applied 100% indoors and the release is 100% to indoor air. In other cases, the likely uncertainty is small (a few percent), for example when a solvent is used in water treatment chemicals, the release is 99% to waste water and 1% to air (indoor or outdoor depending on the point of use). Finally, in other cases the uncertainty may be larger (>10%), for example when a solvent is used in a product and the release depends on the solubility and vapor pressure of the compound; matrix effects may result in higher or lower release than the value available from the EU TGD for that particular combination of physicochemical properties. The user could consider a range of values to account for uncertainty in the release estimates. The performance metrics of the Chemical Functional Use

Classifier indicate the accuracy and uncertainty of its results. Without further insights, we refrain from assigning arbitrary uncertainty values for the SPERC and EU TGD data.

Finally, the nomenclatures for functional uses/product categories across the Chemical Functional Use Classifier, market share data, EU TGD data, and SPERC data are not always the same. Despite our best effort to match relevant nomenclatures in this framework, there may be discrepancies in connecting different data sources, which is a common challenge in studies on consumer products (Dionisio et al., 2015; Goldsmith et al., 2014).

5. Conclusions

This study presents the framework OrganoRelease to addresses the challenge of data availability of the release information for chemicals in consumer products during the use and post-use phases. We have developed a Chemical Functional Use Classifier and connected it with existing market share data and release factor estimates to cover 19 unique functional uses and 14 product categories. The versatility of OrganoRelease enables it to provide quantitative release estimates based mostly on chemical structure information, although better results can be obtained if market data is considered. The release estimates can be used as input for other models to assess the human exposure and ecological health risks of chemicals under different scenarios. OrganoRelease can be further expanded to cover more functional uses and product categories of chemicals by incorporating additional data as it becomes available.

Funding

This work was supported by U.S. Environmental Protection Agency through Science to Achieve Results (STAR) Program Grant No.83557907. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of US EPA. This work has not been subjected to US EPA review, and no official endorsement should be inferred.

Acknowledgements

The authors thank Grand View Research Inc. for providing us the market volume data.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.envpol.2017.11.058>.

References

- Abadi, M., Agarwal, A., Barham, P., Brevdo, E., Chen, Z., Citro, C., Corrado, G.S., Davis, A., Dean, J., Devin, M., Ghemawat, S., Goodfellow, I.J., Harp, A., Irving, G., Isard, M., Jia, Y., Józefowicz, R., Kaiser, L., Kudlur, M., Levenberg, J., Mané, D., Monga, R., Moore, S., Murray, D.G., Olah, C., Schuster, M., Shlens, J., Steiner, B., Sutskever, I., Talwar, K., Tucker, P.A., Vanhoucke, V., Vasudevan, V., Viégas, F.B., Vinyals, O., Warden, P., Wattenberg, M., Wicke, M., Yu, Y., Zheng, X., 2016. TensorFlow: Large-scale Machine Learning on Heterogeneous Distributed Systems. *CoRR abs/1603.04467*.
- Aronson, D.B., Bosch, S., Gray, D.A., Howard, P.H., Guiney, P.D., 2007. A comparative human health risk assessment of p-dichlorobenzene-based toilet rimblock products versus fragrance/surfactant-based alternatives. *J. Toxicol. Environ. Health-PART B-Crit. Rev.* 10, 467–526. <https://doi.org/10.1080/15287390600975103>.
- Azapagic, A., 1999. Life cycle assessment and its application to process selection, design and optimisation. *Chem. Eng. J.* 73, 1–21. [https://doi.org/10.1016/S1385-8947\(99\)00042-X](https://doi.org/10.1016/S1385-8947(99)00042-X).
- Bergstra, J., Yamins, D., Cox, D.D., 2013. Making a science of model search: hyperparameter optimization in hundreds of dimensions for vision architectures. *ICML 1* (28), 115–123.
- Brandes, L., den Hollander, H., van de Meent, D., 1996. SimpleBox 2.0: a Nested Multimedia Fate Model for Evaluating the Environmental Fate of Chemicals - RIVM (No. RIVM Report 719101029).
- CECIC, T.E.C.I.C., 2012. Cefic Guidance Specific Environmental Release Categories (SPERCs) - Chemical Safety Assessments, Supply Chain Communication and Downstream User Compliance.
- Chaudhary, A., Hellweg, S., 2014. Including indoor offgassed emissions in the life cycle inventories of wood products. *Environ. Sci. Technol.* 48, 14607–14614. <https://doi.org/10.1021/es5045024>.
- ChemicalBook, 2016. ChemicalBook—Chemical Search Engine [WWW Document]. URL https://www.chemicalbook.com/ProductCatalog_EN/13.htm. (Accessed 16 April 2016).
- Clarke, B.O., Smith, S.R., 2011. Review of “emerging” organic contaminants in biosolids and assessment of international research priorities for the agricultural use of biosolids. *Environ. Int.* 37, 226–247. <https://doi.org/10.1016/j.envint.2010.06.004>.
- Cooper, C., Galick, P., Harris, S., Pourreau, D., Rodriguez, C., 2001. Tert-butyl acetate: non-HAP solvent for high-solids epoxy formulations. *J. Coat. Technol.* 73, 19–24. <https://doi.org/10.1007/BF02730155>.
- Dann, A.B., Hontela, A., 2011. Triclosan: environmental exposure, toxicity and mechanisms of action: exposure, toxicity and mechanisms of action. *J. Appl. Toxicol.* 31, 285–311. <https://doi.org/10.1002/jat.1660>.
- Dearden, J.C., Cronin, M.T.D., Kaiser, K.L.E., 2009. How not to develop a quantitative structure–activity or structure–property relationship (QSAR/QSPR). *SAR QSAR Environ. Res.* 20, 241–266. <https://doi.org/10.1080/10629360902949567>.
- Dionisio, K.L., Frame, A.M., Goldsmith, M.-R., Wambaugh, J.F., Liddell, A., Cathey, T., Smith, D., Vail, J., Ernstoff, A.S., Fantke, P., Joliet, O., Judson, R.S., 2015. Exploring consumer exposure pathways and patterns of use for chemicals in the environment. *Toxicol. Rep.* 2, 228–237. <https://doi.org/10.1016/j.toxrep.2014.12.009>.
- Dragon 7.0, 2016. Kode - Chemoinformatics [WWW Document]. URL https://chm.kode-solutions.net/products_dragon.php. (Accessed 27 November 2016).
- Dutta, D., Guha, R., Wild, D., Chen, T., 2007. Ensemble feature Selection: consistent descriptor subsets for multiple QSAR models. *J. Chem. Inf. Model* 47, 989–997. <https://doi.org/10.1021/ci600563w>.
- ECETOC, 2014. European Center for Ecotoxicology and Toxicology of Chemicals - Targeted Risk Assessment (TRA) Tools [WWW Document]. URL <http://www.ecetoc.org/tra>. (Accessed 24 March 2016).
- ECHA, 2016. CHEMICAL Safety Assessment and Reporting Tool [WWW Document]. URL <https://chesar.echa.europa.eu/home>. (Accessed 24 March 2016).
- ECPA, S., 2013. REACH-IN - Registration, Evaluation, Authorisation and Restriction of Chemicals [WWW Document]. URL <http://www.ecpa.eu/industry-resources/reach-registration-evaluation-authorisation-and-restriction-chemicals>. (Accessed 17 August 2017).
- EPA, C., 2017. Tertiary-butyl Acetate (TBAC) [WWW Document]. URL <https://java.epa.gov/chemview>.
- European Commission, 2003. Technical Guidance Document on Risk Assessment in Support of Commission Directive 93/67/EEC on Risk Assessment for New Notified Substances and Commission Regulation (EC) No 1488/94 on Risk Assessment for Existing Substances and Directive 98/8/EC of the European Parliament and of the Council Concerning the Placing of Biocidal Products on the Market. Ispra (IT): Environmental Chemicals Bureau.
- Ezechias, M., Covino, S., Cajthaml, T., 2014. Ecotoxicity and biodegradability of new brominated flame retardants: a review. *Ecotoxicol. Environ. Saf.* 110, 153–167. <https://doi.org/10.1016/j.ecoenv.2014.08.030>.
- Freedonia Group, 2016. The Freedonia Group - Industry Market Research - Market Size, Market Share, Market Leaders, Demand Forecast, Sales, Company Profiles, Market Research, Industry Trends and Companies [WWW Document]. URL <http://www.freedoniagroup.com/>. (Accessed 11 July 2016).
- Garner, K.L., Suh, S., Keller, A.A., 2017. Assessing the risk of engineered nanomaterials in the environment: development and application of the nanoFate model. *Environ. Sci. Technol.* 51, 5541–5551. <https://doi.org/10.1021/acs.est.6b05279>.
- Gavankar, S., Suh, S., Keller, A.F., 2012. Life cycle assessment at nanoscale: review and recommendations. *Int. J. Life Cycle Assess.* 17, 295–303. <https://doi.org/10.1007/s11367-011-0368-5>.
- Geiser, K., 2015. Chemicals without Harm: Policies for a Sustainable World. MIT Press.
- Goebel, C., Diepgen, T.L., Krasteva, M., Schlatter, H., Nicolas, J.-F., Blömeke, B., Coenraads, P.J., Schnuch, A., Taylor, J.S., Pungier, J., Fautz, R., Fuchs, A., Schuh, W., Gerberick, G.F., Kimber, I., 2012. Quantitative risk assessment for skin sensitization: consideration of a simplified approach for hair dye ingredients. *Regul. Toxicol. Pharmacol.* 64, 459–465. <https://doi.org/10.1016/j.yrtph.2012.10.004>.
- Goldsmith, M.-R., Grulke, C.M., Brooks, R.D., Transue, T.R., Tan, Y.M., Frame, A., Egeghy, P.P., Edwards, R., Chang, D.T., Tornero-Velez, R., Isaacs, K., Wang, A., Johnson, J., Holm, K., Reich, M., Mitchell, J., Vallero, D.A., Phillips, L., Phillips, M., Wambaugh, J.F., Judson, R.S., Buckley, T.J., Dary, C.C., 2014. Development of a consumer product ingredient database for chemical exposure screening and prioritization. *Food Chem. Toxicol. Int. J. Publ. Br. Ind. Biol. Res. Assoc.* 65, 269–279. <https://doi.org/10.1016/j.fct.2013.12.029>.
- Gottschalk, F., Nowack, B., 2011. The release of engineered nanomaterials to the environment. *J. Environ. Monit.* 13, 1145–1155. <https://doi.org/10.1039/C0EM00547A>.
- Gottschalk, F., Sonderer, T., Scholz, R.W., Nowack, B., 2010. Possibilities and limitations of modeling environmental exposure to engineered nanomaterials by

- probabilistic material flow analysis. *Environ. Toxicol. Chem.* 29, 1036–1048. <https://doi.org/10.1002/etc.135>.
- Gramatica, P., 2007. Principles of QSAR models validation: internal and external. *QSAR Comb. Sci.* 26, 694–701. <https://doi.org/10.1002/qsar.200610151>.
- Grand View Research Inc., 2016. Market Research and Consulting Services: Grand View Research Inc [WWW Document]. URL <http://www.grandviewresearch.com/>. (Accessed 23 March 2016).
- Hellweg, S., Canals, L.M. i., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. *Science* 344, 1109–1113. <https://doi.org/10.1126/science.1248361>.
- Hodges, J.E.N., Vamshi, R., Holmes, C., Rowson, M., Miah, T., Price, O.R., 2014. Combining high-resolution gross domestic product data with home and personal care product market research data to generate a subnational emission inventory for Asia. *Integr. Environ. Assess. Manag.* 10, 237–246. <https://doi.org/10.1002/ieam.1476>.
- Hollander, A., Schoorl, M., van de Meent, D., 2016. SimpleBox 4.0: improving the model while keeping it simple. *Chemosphere* 148, 99–107. <https://doi.org/10.1016/j.chemosphere.2016.01.006>.
- Holmgren, T., Persson, L., Andersson, P.L., Haglund, P., 2012. A generic emission model to predict release of organic substances from materials in consumer goods. *Sci. Total Environ.* 437, 306–314. <https://doi.org/10.1016/j.scitotenv.2012.08.020>.
- Hornik, K., Stinchcombe, M., White, H., 1989. Multilayer feedforward networks are universal approximators. *Neural Netw.* 2, 359–366. [https://doi.org/10.1016/0893-6080\(89\)90020-8](https://doi.org/10.1016/0893-6080(89)90020-8).
- Huang, L., Ernstoff, A., Fantke, P., Csiszar, S.A., Jolliet, O., 2017. A review of models for near-field exposure pathways of chemicals in consumer products. *Sci. Total Environ.* 574, 1182–1208. <https://doi.org/10.1016/j.scitotenv.2016.06.118>.
- Huang, L., Jolliet, O., 2016. A parsimonious model for the release of volatile organic compounds (VOCs) encapsulated in products. *Atmos. Environ.* 127, 223–235. <https://doi.org/10.1016/j.atmosenv.2015.12.001>.
- Isaacs, K.K., Glen, W.G., Egeghy, P., Goldsmith, M.-R., Smith, L., Vallero, D., Brooks, R., Grulke, C.M., Özkaynak, H., 2014. SHEDS-ht: an integrated probabilistic exposure model for prioritizing exposures to chemicals with near-field and dietary sources. *Environ. Sci. Technol.* 48, 12750–12759. <https://doi.org/10.1021/es502513w>.
- Isaacs, K.K., Goldsmith, M.-R., Egeghy, P., Phillips, K., Brooks, R., Hong, T., Wambaugh, J.F., 2016. Characterization and prediction of chemical functions and weight fractions in consumer products. *Toxicol. Rep.* 3, 723–732. <https://doi.org/10.1016/j.toxrep.2016.08.011>.
- Janecko, N., Pokludova, L., Blahova, J., Svobodova, Z., Literak, I., 2016. Implications of fluoroquinolone contamination for the aquatic environment—a review. *Environ. Toxicol. Chem.* 35, 2647–2656. <https://doi.org/10.1002/etc.3552>.
- Jansen-Systems, 2014. easyTRA - Targeted Risk Assessment - Targeted Risk Assessment [WWW Document]. URL <http://easytra.com/>. (Accessed 24 March 2016).
- Jolliet, O., Ernstoff, A.S., Csiszar, S.A., Fantke, P., 2015. Defining product intake fraction to quantify and compare exposure to consumer products. *Environ. Sci. Technol.* 49, 8924–8931. <https://doi.org/10.1021/acs.est.5b01083>.
- Keller, A.A., Lazareva, A., 2013. Predicted releases of engineered nanomaterials: from global to regional to local. *Environ. Sci. Technol. Lett.* 1, 65–70.
- Keller, A.A., McFerran, S., Lazareva, A., Suh, S., 2013. Global life cycle releases of engineered nanomaterials. *J. Nanoparticle Res.* 15, 1–17.
- Keller, A.A., Vosti, W., Wang, H., Lazareva, A., 2014. Release of engineered nanomaterials from personal care products throughout their life cycle. *J. Nanoparticle Res.* 16, 1–10. <https://doi.org/10.1007/s11051-014-2489-9>.
- Kienhuis, A.S., Soeteman-Hernandez, L.G., Bos, P.M., Cremers, H.W., Klerx, W.N., Talhout, R., 2015. Potential harmful health effects of inhaling nicotine-free shisha-pen vapor: a chemical risk assessment of the main components propylene glycol and glycerol. *Tob. Induc. Dis.* 13, 15. <https://doi.org/10.1186/s12971-015-0038-7>.
- Kunhikrishnan, A., Shon, H.K., Bolan, N.S., El Saliby, I., Vigneswaran, S., 2015. Sources, distribution, environmental fate, and ecological effects of nanomaterials in wastewater streams. *Crit. Rev. Environ. Sci. Technol.* 45, 277–318. <https://doi.org/10.1080/10643389.2013.852407>.
- Liagkouridis, I., Cousins, A.P., Cousins, I.T., 2015. Physical–chemical properties and evaluative fate modelling of ‘emerging’ and ‘novel’ brominated and organophosphorus flame retardants in the indoor and outdoor environment. *Sci. Total Environ.* 524, 416–426. <https://doi.org/10.1016/j.scitotenv.2015.02.106>.
- Mackay, D., Paterson, S., 1991. Evaluating the multimedia fate of organic chemicals: a level III fugacity model. *Environ. Sci. Technol.* 25, 427–436. <https://doi.org/10.1021/es00015a008>.
- National Renewable Energy Laboratory, 2012. U.S. Life Cycle Inventory Database.
- Nijhof, C.O.P., Huijbregts, M.A.J., Golsteijn, L., van Zelm, R., 2016. Spatial variability versus parameter uncertainty in freshwater fate and exposure factors of chemicals. *Chemosphere* 149, 101–107. <https://doi.org/10.1016/j.chemosphere.2016.01.079>.
- Ortiz de Garcia, S.A., Pinto Pinto, G., Garcia-Encina, P.A., Irusta-Mata, R., 2014. Ecotoxicity and environmental risk assessment of pharmaceuticals and personal care products in aquatic environments and wastewater treatment plants. *Ecotoxicology* 23, 1517–1533. <https://doi.org/10.1007/s10646-014-1293-8>.
- Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., 2011. Scikit-learn: machine learning in Python. *J. Mach. Learn. Res.* 12, 2825–2830.
- Phillips, K.A., Wambaugh, J.F., Grulke, C.M., Dionisio, K.L., Isaacs, K.K., 2017. High-throughput screening of chemicals as functional substitutes using structure-based classification models. *Green Chem.* 19, 1063–1074. <https://doi.org/10.1039/C6GC02744J>.
- Powers, D., 2011. Evaluation: from precision, recall and f-measure to roc, informedness, markedness & correlation. *J. Mach. Learn. Technol.* 2, 37–63.
- Pubchem, 2017. Tert-butyl ACETATE | C6H12O2-pubchem [WWW Document]. URL https://pubchem.ncbi.nlm.nih.gov/compound/tert-butyl_acetate. (Accessed 6 January 2017).
- Quadros, M.E., Pierson, R., Tulve, N.S., Willis, R., Rogers, K., Thomas, T.A., Marr, L.C., 2013. Release of silver from nanotechnology-based consumer products for children. *Environ. Sci. Technol.* 47, 8894–8901. <https://doi.org/10.1021/es4015844>.
- Rosal, R., Rodea-Palmares, I., Boltes, K., Fernandez-Pinas, F., Leganes, F., Petre, A., 2010. Ecotoxicological assessment of surfactants in the aquatic environment: combined toxicity of docusate sodium with chlorinated pollutants. *Chemosphere* 81, 288–293. <https://doi.org/10.1016/j.chemosphere.2010.05.050>.
- Rosenbaum, R.K., Huijbregts, M.A.J., Henderson, A.D., Margni, M., McKone, T.E., Meent, D., van de Hauschild, M.Z., Shaked, S., Li, D.S., Gold, L.S., Jolliet, O., 2011. USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. *Int. J. Life Cycle Assess.* 16, 710–727. <https://doi.org/10.1007/s11367-011-0316-4>.
- Sattler, D., Schnöder, F., Aust, N., Ahrens, A., Bögi, C., Traas, T., Tolls, J., 2012. Specific environmental release categories—a tool for improving chemical safety assessment in the EC—report of a multi-stakeholder workshop. *Integr. Environ. Assess. Manag.* 8, 580–585. <https://doi.org/10.1002/ieam.1304>.
- Shin, H.-M., Ernstoff, A., Arnot, J.A., Wetmore, B.A., Csiszar, S.A., Fantke, P., Zhang, X., McKone, T.E., Jolliet, O., Bennett, D.H., 2015. Risk-based high-throughput chemical screening and prioritization using exposure models and in vitro bioactivity assays. *Environ. Sci. Technol.* 49, 6760–6771. <https://doi.org/10.1021/acs.est.5b00498>.
- Sun, T.Y., Bornhöft, N.A., Hungerbühler, K., Nowack, B., 2016. Dynamic probabilistic modeling of environmental emissions of engineered nanomaterials. *Environ. Sci. Technol.* 50, 4701–4711. <https://doi.org/10.1021/acs.est.5b05828>.
- Todeschini, R., Consonni, V., 2009. *Molecular Descriptors for Chemoinformatics*, vol. 41. John Wiley & Sons (2 Volume Set).
- Trudel, D., Horowitz, L., Wormuth, M., Scheringer, M., Cousins, I.T., Hungerbühler, K., 2008. Estimating consumer exposure to PFOS and PFOA. *Risk Anal. Off. Publ. Soc. Risk Anal.* 28, 251–269. <https://doi.org/10.1111/j.1539-6924.2008.01017.x>.
- Trudel, D., Scheringer, M., von Goetz, N., Hungerbühler, K., 2011. Total consumer exposure to polybrominated diphenyl ethers in north America and Europe. *Environ. Sci. Technol.* 45, 2391–2397. <https://doi.org/10.1021/es1035046>.
- Umweltbundesamt, 2011. Standardisation of Emission Factors for the Exposure Assessment under REACH. Umweltbundesamt.
- US EPA, 2015. Consumer Exposure Model (CEM) DRAFT User Guide (No. EP-w-12-010). Washington, DC.
- US EPA, 2012. Estimation Programs Interface Suite™ for Microsoft® Windows, V. 4.11. United States Environmental Protection Agency, Washington, DC, USA [WWW Document]. URL <https://www.epa.gov/tsca-screening-tools/epi-suite-tm-estimation-program-interface>. (Accessed 14 February 2017).
- van Wezel, A., Caris, I., Kools, S.A.E., 2016. Release of primary microplastics from consumer products to wastewater in The Netherlands: release of microplastics from consumer products to wastewater. *Environ. Toxicol. Chem.* 35, 1627–1631. <https://doi.org/10.1002/etc.3316>.
- Vermeire, T., Rikken, M., Attias, L., Boccardi, P., Boeije, G., Brooke, D., de Bruijn, J., Comber, M., Dolan, B., Fischer, S., Heinemeyer, G., Koch, V., Lijzen, J., Müller, B., Murray-Smith, R., Tadeo, J., 2005. European union system for the evaluation of substances: the second version. *Chemosphere* 59, 473–485. <https://doi.org/10.1016/j.chemosphere.2005.01.062>.
- Wenger, Y., Li, D., Jolliet, O., 2012. Indoor intake fraction considering surface sorption of air organic compounds for life cycle assessment. *Int. J. Life Cycle Assess.* 17, 919–931. <https://doi.org/10.1007/s11367-012-0420-0>.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21, 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>.
- Zota, A.R., Calafat, A.M., Woodruff, T.J., 2014. Temporal trends in phthalate exposures: findings from the national health and nutrition examination survey, 2001–2010. *Environ. Health Perspect.* <https://doi.org/10.1289/ehp.1306681>.