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A flexible risk assessment framework for marine plastic pollution that synthesizes waste management and ecological impact data

Kaleigh E. Davis [a,*,1], Fiona Beaty [a,b,1], Carolina Sánchez [c]

[a] Department of Zoology and Biodiversity Research Centre, University of British Columbia, Unceded xʷməθkʷəy̓əm (Musqueam) Territory, 2212 Main Mall, Vancouver V6T1Z4, British Columbia, Canada
[b] Institute for the Ocean and Fisheries, University of British Columbia, Unceded xʷməθkʷəy̓əm (Musqueam) Territory, Vancouver, British Columbia, Canada
[c] Yale School of the Environment, Yale University, New Haven, CT, USA

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ABSTRACT

The vast quantity of plastic in the world's ocean poses an urgent problem for marine ecosystems and coastal communities. While considerable research has aimed to understand how plastics impact marine life, there remains a gap in connecting this knowledge with waste management practices. Because these practices often determine the end fate of plastic items, bridging this gap is critical to reducing the flow of harmful plastics into the ocean. The framework proposed here identifies policy actions to reduce consumption of high-impact plastics using a compound risk score that encompasses both an item's likelihood of entering the ocean and its negative ecological impact. We illustrate the framework's application using a case study of single-use plastic (SUP) consumption at a large Canadian university. We quantified SUPs purchased over one year at the University of British Columbia and collected data from its associated waste management system to identify factors that influence an item's end fate. We used these data to estimate the relative risk of items exiting the recycling stream, then combined this with published data on the items' marine impacts to calculate their compound risk scores. The results identify high-risk plastic items to prioritize in waste reduction strategies and lower-risk alternatives. The results also highlight specific policy avenues to improve the efficiency of the focal waste management system. This framework is flexible to diverse contexts, requiring only information about plastic consumption and waste management practices. It is thus an accessible and useful tool to support local transitions toward a reduced marine footprint.

1. Introduction

Plastic pollution is increasingly recognized as one of the great threats to ocean ecosystems [1–3]. The decade of 2010–2020 saw a drastic increase in transnational policy and partnerships focused on solving plastic pollution, with a specific emphasis on ocean plastics (e.g. Ocean Plastics Charter, Global Plastic Action Partnership, New Plastics Economy Global Commitment) [4,5]. Similarly, in the scientific literature, marine plastic pollution research has ballooned to comprise 1.2% of all environmental publications (up from 0.4% in 2010) [4]. One of the core reasons for this surge in political, public, and scientific attention is the realization that the vast majority (79%) of plastic items produced to date have ended up in landfills or the environment, where they can persist and contaminate ecosystems for hundreds to thousands of years [6–8]. Additionally, only 9% of plastics produced over the last century have been recycled globally [6]. This gap in the production and recovery of plastic materials represents a substantial economic loss and socio-ecological risk.

Strategies to reduce marine plastic pollution are increasingly focused toward improving the sustainability and circularity of plastic production, consumption, and disposal [9–11]. A circular plastic economy requires transitioning from the current linear material flow (i.e. production-consumption-waste chains that result in plastic ending up in a landfill or the environment), to a closed-loop material flow, which maximizes the recovery, re-use, and recycling of plastic materials and treats plastic waste as a resource [2,11,12]. An important first step toward reducing marine plastic pollution using the circular economy framework is to understand how and why plastic items exit waste

* Corresponding author.
E-mail address: kdavis@zoology.ubc.ca (K.E. Davis).
[1] Kaleigh E. Davis and Fiona Beaty contributed equally to this work.

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management systems and subsequently end up in the environment.

Plastics find their way to the ocean during and between the three main stages of waste management: collection, sorting, and recycling [1,2,12–15]. The transportation of waste and recyclable materials between these stages can take place both on land and at sea, providing indirect and direct avenues for plastics to enter the ocean. Plastic items that end up in open dumps and landfills are susceptible to eventual surfacing and subsequent movement into the ocean via wind, inland waterways, or wastewater outflows [1,16]. Importantly, even recyclable items, when disposed of improperly due to contamination or mis-sorting, can end up in dumps or landfills and thus find their way to the ocean. Other land- and sea-based sources of marine plastic include unmanaged waste (e.g. litter, illegal dumping), virgin or recycled pellets spilled during transportation, and discarded maritime gear (e.g. fishing, aquaculture, ghost gear) [13–15,17].

Upon entering the ocean, plastic items have varying impacts on marine organisms based on their specific physical and chemical characteristics [18]. These impacts are commonly grouped into three main effect categories: entanglement, ingestion, and contamination (via transfer of toxic chemicals)[2,16,18–20]. While clarifying the physiological and ecological effects of plastic items is critical in estimating their overall impact on marine ecosystems, swift and strategic policy development to mitigate the scale of those impacts requires linking environmental risk data with local economic, social, and waste management data [11,21]. Additionally, integrating these types of data at a scale relevant to specific waste management systems may facilitate the translation of scientific data into effective waste reduction policies.

Here we present a framework that identifies management priorities by estimating the risk that specific plastic items pose to marine life based on both their likelihood of leaking out of the recycling waste stream and into the ocean ("leakage risk") and the magnitude of their impacts on marine life ("harm risk"). We apply this risk assessment framework to a case study of single-use plastics (SUPs) purchased at the University of British Columbia (UBC) and processed through a network of waste management facilities in Vancouver, Canada. Our results identify single-use plastic items used at UBC that pose a high-risk to marine life, as well as lower-risk plastic alternatives. Importantly, this framework can be customized according to the specific harm reduction goals of any institution that seeks to apply it to their context and can incorporate a diverse array of harm-risk indices. This flexible approach advances the ability for institutional policymakers and managers to identify strategies that will slow the flow of plastic into the ocean and advance the circularity of plastic production, consumption, and management systems.

2. Methods

2.1. Framework and case study context

The proposed framework comprises six stages: 1) identify goals and targets; 2) identify target plastic items; 3) identify leakage risk parameters and calculate leakage risk (leakage risk analysis); 4) select harm risk index and calculate harm risk (harm risk analysis); 5) identify high risk plastic items; and 6) select and implement impact and waste reduction strategy (Fig. 1). Stages 1 and 6 involve decision making by policymakers and/or management entities. Stages 2–5 comprise the risk assessment portion of the framework and involve collecting and analyzing data on plastic consumption and waste management to inform the compound risk score calculations. The scope of this framework is

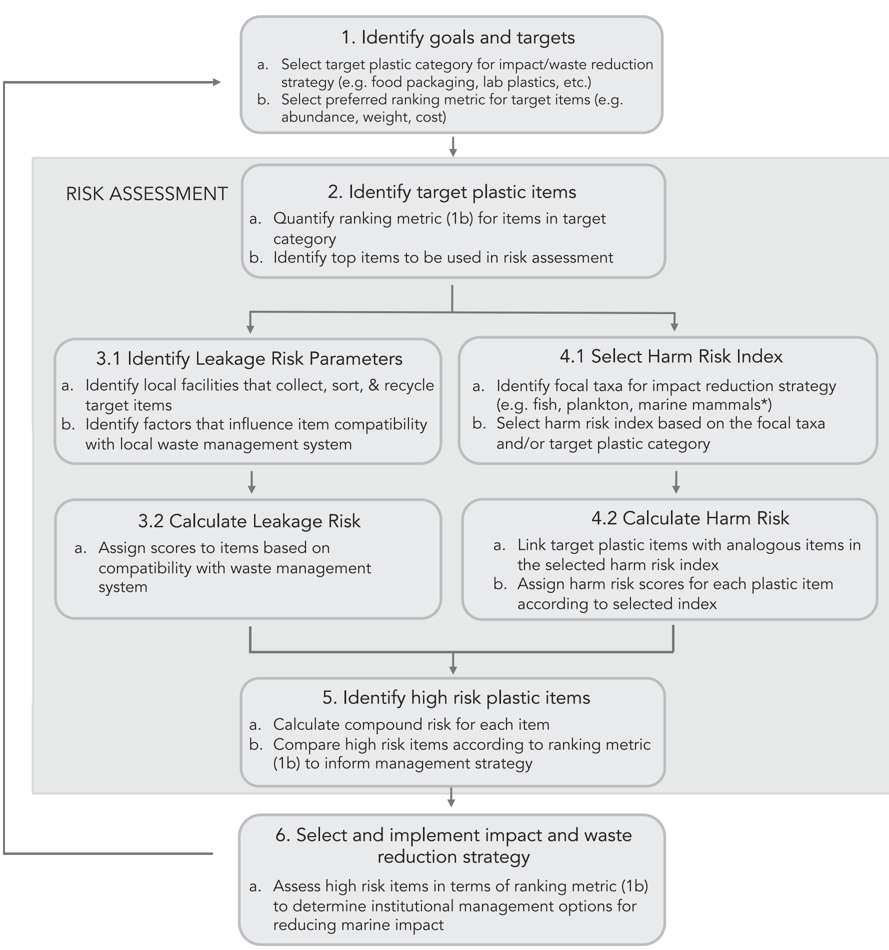

Fig. 1. Proposed risk assessment framework to calculate compound-risk scores for plastic items, which can be used to inform context-specific management strategies for impact and waste reduction. Stages one and six allow for the involvement of stakeholders in setting the objectives and outcomes of the assessment. Stages 2–5 comprise the risk assessment itself. The framework can be iteratively implemented to inform waste reduction strategies, as represented by the arrows connecting Stages 6 and 1. *This framework can also be applied to terrestrial systems with adjusted harm and leakage risk indices.

restricted to managed waste originating from land-based sources.

Our case study implements this framework to inform waste reduction strategies at UBC. We focus on stages 1–5, as the risk assessment portion is the framework's main novel contribution toward plastic risk assessments. Stage 6 is not covered within this case study, as it requires further input from UBC decision makers.

2.2. Framework: definitions and process

Stage 1: identify goals and targets

The focal institution defines the specific pollution reduction goals, target plastic category (e.g. single-use plastics, microplastics) and ranking metrics for evaluating which items will be targeted for reduction (e.g. most consumed by weight or count, most expensive). Here, we define the focal institution as any organization, community, business, university, or municipality that is employing the proposed framework.

Stage 2: identify target plastic items

To conduct a waste audit or procurement analysis, the focal institution quantifies the number of plastic items purchased or consumed by the focal institution in a given time period. Since conducting a risk assessment for every item included in the audit is infeasible for most institutions and municipalities, we recommend refining the target category to a manageable scale (e.g. top ten most purchased plastic items).

Stage 3: leakage risk analysis

Leakage risk is defined here as the likelihood of a plastic item exiting the recycling stream of the focal waste management system and entering the environment. Here, we define focal waste management system as the network of facilities that process (e.g. collect, sort, recycle) waste generated at the focal institution. Since plastics that are not recycled have a higher likelihood of entering the ocean [1], we assume that these plastics also have a higher leakage risk. We do not consider post-production or maritime leakage risk (e.g. resin pellets, fishing gear), although they are both important sources of plastic pollution in the ocean [13].

Since waste management systems generally operate at local scales, leakage risk is largely determined by local waste management practices [14]. Stage 3 characterizes the flow of recyclable materials through the focal waste management system and identifies the factors that cause plastic items to enter or exit the recycling stream (i.e. the leakage risk parameters associated with plastic polymers and items). Thus, the calculation of leakage risk is inherently context specific.

Stage 4: harm risk analysis

Harm risk is defined as the likelihood that marine organisms will ingest, be entangled by, or be contaminated by plastic items [2,20]. This risk is determined by the physical (e.g. size, buoyancy, shape) and chemical (e.g. polymer, additives) characteristics of a plastic item upon entry into the marine environment, and is quantified according to a published harm risk index. There exist many indices that estimate the harm risk that plastic items pose to various taxonomic groups, such as seabirds, invertebrates, marine mammals, plankton, fish (see discussion for examples). This framework allows users to choose an index that addresses the types of plastic items and taxonomic group(s) that are priorities for policy and management development (see Stage 1).

Stage 5: identify high-risk plastic items

A compound risk score, which combines an item's leakage and harm risk scores, is calculated and used to identify high risk plastic items. Compound risk scores can be interpreted on their own or in combination with audit data from Stage 2 to identify high-risk items consumed at the institution.

Stage 6: select and implement impact and waste reduction strategy

The focal institution creates and implements policy interventions for target items identified in Stage 5, according to the institution's goals. This framework can be used iteratively to refine policy targets and guide ongoing waste reduction strategies.

2.3. Case study

Stage 1: identify goals and targets

The focal institution for this case study is the University of British Columbia (UBC; see Supplement for additional information). In 2014, UBC's Sustainability department created a Zero Waste Action Plan that identified the reduction of SUPs consumed on campus as a high priority for management. Accordingly, we selected SUPs as the target plastic category, and quantity of SUPs purchased as the ranking metric (Fig S1, Stage 1).

Stage 2: identify target plastic items

To quantify single-use plastic items purchased at UBC, we gathered food-related SUP procurement data from businesses on campus for one year (2017–2018; Fig. 1 Stage 2a). We sampled the main retail provider and 54% of campus food businesses (n = 36). We classified procurement data according to plastic item (e.g. cold cup, cutlery, takeout container) and polymer composition (Table 1). We identified the polymer composition of items using procurement listings and in-person verification of items. When this was not possible, we utilized information available online to identify the polymer composition of those or similar items. Our audit excluded plastic items that were labeled #7.

We selected the top 16 most purchased SUP items for further analysis (Fig. 1, Stage 2b; see Table S1 for list). In addition to total abundance (count), we also estimated total weight by weighing representative items from each category and multiplying these weights by the total abundance. For items that were purchased in various polymers with a uniform shape and size, we measured one sample item and assumed that the weight of items was similar across the different polymers (e.g. PP and PET lids). For categories with a variety of items (e.g. food containers), we averaged the weights of several items (e.g. large and small containers, bowls and boxes).

Stage 3: leakage risk analysis

3.1 Identify leakage risk parameters

To inform the leakage risk score calculation, we gathered data about our focal waste management system using a mixed-methods approach. First, we identified the processing facilities involved in the management of UBC's plastic waste. This comprised four waste management facilities, including one recycling waste collector privately contracted by UBC, one sorting facility, and two recycling facilities (Fig. 1 Stage 3.1a). We requested data on the recyclability of plastic polymers and items from these four facilities. The data request served two purposes: 1) identify factors that influence a plastic item's likelihood of exiting the recycling stream (i.e. leakage risk parameters); and 2) understand how items made of different plastic polymers move through these waste management facilities (hereafter, material flow; see Table S2 for data request format). Finally, we conducted a grey literature review of reports and audits associated with additional waste management systems that interact with our focal system (e.g. Recycle BC; see supplement for further elaboration on the regional context). The purpose of the grey literature review was to identify factors that may influence how plastic items are disposed of by consumers at UBC, given that most individuals

Table 1
Glossary of plastic polymers and their associated codes and numbers.

Polymer	Polymer Code	Polymer Number
Polyethylene terephthalate	PET	1
High density polyethylene	HDPE	2
Polyvinyl chloride	PVC	3
Low density polyethylene	LDPE	4
Polypropylene	PP	5
Polystyrene[a]	PS	6
Variable	N/A	7

[a] The polystyrene category includes expanded polystyrene (EPS), or Styrofoam.

live off campus and interact frequently with these other systems [22–25]. This mixed-methods approach to data collection allowed us to gain a better understanding of why and where plastic leakage may occur within our focal waste management system.

Using this information, we identified two distinct leakage risk parameters in our system: local recyclability and penalty factors (Fig. 1 Stage 3.1b). Local recyclability is the ability for a plastic item to be recycled by a recycling facility within the focal waste management system when in like-new condition. Penalty factors are characteristics that reduce the likelihood of locally recyclable plastic items being recycled within the focal waste management system or increase their likelihood of entering the marine environment. The penalty factors used in this study were identified using the data provided by local waste management facilities and the literature review. If no data were provided to inform a given polymer's penalty factor, we assumed the likelihood of that penalty factor applying to that polymer to be low. We do not distinguish here between full recycling and downcycling because of data limitations.

3.2 Calculate leakage risk

Leakage risk is calculated here as: leakage risk = local recyclability * (1 + $\sum$(penalty factors)) (Eq. (1)). A higher leakage risk score corresponds to a higher likelihood of exiting the recycling stream and entering the ocean. Local recyclability is a binary factor: the plastic polymer or item is either able to be recycled within the focal waste management system and receives the lowest possible leakage risk score or it is not and receives the highest leakage risk score. If the polymer or item is locally recyclable, penalty factors may reduce the likelihood of it being recycled, thus increasing the leakage risk score. Polymers or items were assigned a binary score for each penalty factor where 0 means the penalty factor does not apply, and 1 means it does. We assumed that each penalty factor had an equivalent impact on an item's likelihood of leaking out of the recycling waste path, because there was minimal information available on the relative impacts of each penalty factor provided by local waste management facilities. The framework can accommodate higher resolution data about the different leakage-risk-impacts of various penalty factors if they are available.

Stage 4: harm risk analysis

4.1 Select harm risk index

Since this case study focuses on single-use plastics (SUP), we selected a harm risk index that estimates the risk of SUP items to marine life (Fig. 1 Stage 4.1). Wilcox et al. used expert elicitation to estimate the entanglement, ingestion, and contamination risks of SUP items on a few large marine taxa (seabirds, marine turtles, and marine mammals) [20]. Given this taxonomic focus, our compound risk analysis is also constrained to these taxa.

4.2 Calculate harm risk

In Wilcox et al. [20], the severity of entanglement, ingestion, and contamination risks are rated on a scale of 1–4 for each item, with 4 being the highest risk. To apply these risk estimates to items consumed at UBC, we associated each unique item from the UBC purchasing dataset with an analogous item from the Wilcox et al. [20] analysis based on similar physical characteristics (Table S1). For each item, we extracted the estimated entanglement, ingestion, and contamination effect sizes from Wilcox et al. [20] Fig. 2 using WebPlot Digitizer (version 4.1) [26] and averaged them to estimate a single harm risk score. For further details on the methodology used to estimate the raw entanglement, ingestion, and contamination risk severity scores, please refer to Wilcox et al. [20].

Stage 5: identify high risk plastic items

We combined the harm and leakage risk scores to calculate a compound risk score for each item. Because the mean and variance differed between the harm and leakage risk scores, we standardized both scores using the formula: standardized score = (score - mean (score))/sd (score). We then normalized both scores to a scale of [0,1] and calculated compound risk scores using the equation: compound risk = normalized leakage risk + normalized harm risk. Compound risk scores were considered in concert with procurement data (Stage 2) to identify high-risk and high-use plastic items and polymers.

3. Results

All results are specific to stages 2–5 of the UBC case study (i.e. the risk assessment; Figs. 1, S1).

Stage 2: identify target plastic items

In 2017–2018, PP cutlery, LDPE coffee cup linings (from paper coffee cups), PVC gloves, PET cold cups, and PS coffee cup lids were the five most abundant SUP items purchased by UBC's food and retail businesses and comprised 79% of the total SUP's quantified in this study (Fig S2). Of note, in the years prior to the study, UBC's Zero Waste Food Ware Strategy recommended a phase out and prohibition of the use of EPS in campus food services unless no viable alternatives exist, so no EPS items appeared in the procurement data.

Stage 3: leakage risk analysis

3.1 Identify leakage risk parameters

All four of the major facilities involved in processing UBC's plastic waste provided data on plastic recycling practices and completed the full data request template (Table S2). The provided data indicated that the end-fate of plastic items disposed of at UBC is first driven by an item's

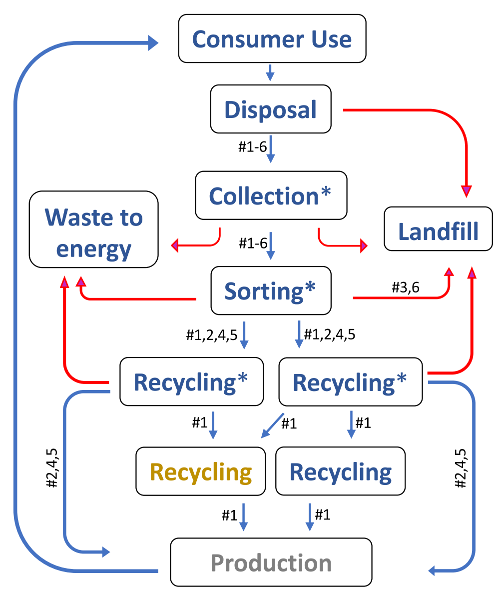

Fig. 2. The material flow of plastic from disposal at the University of British Columbia (UBC) through the focal waste management system. Each box represents a different stage of the waste management process, and boxes with asterisks indicate the facilities that provided data toward this study. Arrows indicate the flow of materials from one stage to the next. The numbers adjacent to each arrow indicate which polymers flow to the next stage of processing or disposal (landfill or waste to energy). For example, after collection from UBC's campus, plastic items labelled with polymers #1–6 are transported to a sorting facility. Following processing at the sorting facility, plastics labelled with #3 or #6 are sent to the landfill, while plastics labelled #1,2,4 or 5 are sent to one of two recycling facilities. Arrows without numbers represent paths of plastic waste that are not directly associated with polymer number, i.e. removal from recycling stream due to contamination. Arrows are color-coded depending on whether the recycling is circular (closed-loop, blue arrows) or linear (end points are waste-to-energy or landfill, red arrows). Facilities located within Metro Vancouver are in blue font, and those outside Metro Vancouver are in yellow. Grey font indicates unknown geographic location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

local recyclability, based on polymer composition and item type, then by penalty factors, based on plastic condition and consumer behavior during disposal (i.e. sorting accuracy). We also noted variation in distance traveled for processing among items, which we assume to pose additional risk for leakage into the environment. These three determinants became the penalty factors that informed our leakage risk score.

Local recyclability is determined primarily by an item's polymer composition. PET, HDPE, LDPE, PP and PS (polymers #1, 2, 4, 5, and 6, respectively) are locally recyclable, because they can be recycled within our focal waste management system when in like-new condition. PVC (#3) items are not locally recyclable and are sent to the landfill by the sorting facility (Fig. 2). Straws and cutlery are also not locally recyclable, regardless of their polymer composition, and are sent to landfill at the collection stage. Importantly, while PS (#6) is able to be recycled at some recycling facilities in our focal waste management system, the sorting facility in this system reported that they send all PS to the landfill upstream of the recycling facilities (Fig. 2). This contributes to an increased leakage risk score for PS (see Section 3.2). The only items that travel outside of Metro Vancouver for recycling are some PET (#1) items (Fig. 2). Items with no plastic polymer label, black plastics, and composite polymer items are usually sent to the landfill or to waste-to-energy.

Data provided by the focal waste management facilities indicate that after accounting for the polymer composition of an item, there are three main penalty factors that increase the likelihood of those items exiting (i.e. leaking from) the recycling stream: 1) contamination due to food residue; 2) contamination due to mis-sorting; and 3) escape (via spill or blow-away) during transportation between waste management facilities (Table 2). Here, contamination means that the material is unable to be accepted in the waste management system's recycling stream because of its condition or because of mis-sorting at time of disposal [22]. In this case study, facilities that collect and sort plastics reported that they send items contaminated with food residue to the landfill (Fig. 2). Additionally, recyclable plastic items that are sorted into the wrong waste receptacle by the consumer (e.g. plastic bags put into the garbage, rather than taken to a local recycling depot) exit the recycling management stream at the collection or sorting stage and go to the landfill. Finally, items made of plastic polymers that are transported outside of Metro Vancouver for recycling (e.g. PET #1, Fig. 2) are more susceptible to being blown off transportation trucks and boats, and subsequently enter the environment, than items made of polymers that can be recycled locally [1,13,17].

3.2 Calculate leakage risk

In this case study, we designated the leakage risk range as 1–4. Items that are not locally recyclable were assigned a leakage risk score of 4 and were not eligible for subsequent penalty factors. Items that were locally recyclable could reach a score of 4 if they received high risk scores for all three penalty factors (Table 2).

Upon determining each polymer or item's local recyclability and penalty factors, polymers rank from highest to lowest leakage risk as follows: PVC (4), straws and cutlery (4), PS & PET (3), PP and LDPE (2), HDPE (1; Table 3). Straws, cutlery, and items made of PVC received the highest possible leakage risk score (4) because they are not locally recyclable (Fig. 2; Table 3). PS received a leakage risk score of 3 based on high mis-sorting and residue contamination likelihoods (Table 3). Additionally, while polystyrene (excluding EPS) is accepted for recycling on campus, disposal within the Metro Vancouver waste management system requires consumers to bring certain PS items (e.g. packaging, foam) to specific sorting facilities [23]. This discrepancy increases the likelihood for PS items at UBC to be mis-sorted into the garbage waste stream. PET also received a leakage risk score of 3 based on its residue contamination likelihood and transportation distance. PET items are sometimes recycled locally and sometimes sent to recycling facilities outside of Metro Vancouver (e.g. Alberta, Canada or Oregon, US). This additional transportation step and the distance associated with it increases the leakage risk for PET relative to locally recycled polymers. PS, PET, and PP are all commonly used for food containers, which increases their likelihood of ending up in landfills due to food residue contamination. PP received a leakage risk score of 2 because of this penalty factor. LDPE received a leakage score of 2 due to its high contamination likelihood through mis-sorting. Soft plastics (e.g. plastic bags and food packaging) are often made of LDPE and are not accepted for recycling at UBC. They are, however, accepted for recycling at specific recycling depots and facilities in Metro Vancouver's waste management system [23]. Mis-sorting into recycling waste containers at UBC contaminates the recycling stream and can lead to soft plastics not being recycled [22]. HDPE received the lowest possible leakage risk score (1 out of 4), because it is locally recyclable and it is usually cleaned and sorted correctly, resulting in no penalty factors.

Table 2
Definitions of local recyclability and penalty factors (PF) used to calculate leakage risk for plastic polymers #1–6. Numeric values used to calculate leakage risk appear in parentheses next to the assigned qualitative risk score.

Leakage risk parameter	Definition	Score
Local recyclability	Polymer is able to be recycled by a recycling facility within the focal waste management system	No (4) Yes (1)
PF1: Contamination due to residue	Polymers used to make plastic items likely to contain food or other residue are more likely to contaminate the recycling waste management stream end up in the landfill stream (e.g. food packaging)	High (1) Low (0)
PF2: Contamination due to mis-sorting	Polymers used to make plastic items likely to be mis-sorted are more likely to contaminate the recycling stream and end up in the landfill stream (e.g. plastic bags, polystyrene). These items are often ones that need to be deposited at special depots, rather than on campus curbside sorting stations.	High (1) Low (0)
PF3: Transportation distance	Polymers that are transported outside of Metro Vancouver for recycling (e.g. to facilities in other provinces or countries) are more likely to be lost during transportation and enter the environment.	Outside (1) Inside (0)

Stage 4: harm risk analysis

Upon aligning UBC's SUP items with the Wilcox et al. [20] harm risk scores, coffee cup linings, plastic bags, gloves, and cutlery posed the greatest harm risk to sea birds, sea turtles, and marine mammals (Fig. 3A). These items are not associated with any particular polymer composition as the Wilcox et al. [20] harm risk index provided no polymer-specific analysis.

Stage 5: identify high-risk plastic items

Upon combining the item-specific harm risk scores with the polymer- and item-specific leakage risk scores, PVC gloves, PP cutlery, PVC film, LDPE coffee cup linings, and LDPE and PP bags had the highest compound risk to marine life (Fig. 3B). While these items are the same as the top-ranked harm risk items, including polymer-specific leakage risk data introduces variability in compound risk scores for items that can be composed of various polymers. For example, bottles made from HDPE have a lower compound risk score than those made from PET, and food containers, lids, and cups made from PP or LDPE have lower compound risk scores than the same items made of PS or PET. When compared with abundance data from UBC's food and retail services, two of the top three highest risk items (PP cutlery and PVC gloves) are also among the top three most purchased items (Fig. 4; see Fig S3 for items arranged by weight and compound risk score).

4. Discussion

This study provides a novel method for institutions to assess the marine risk of plastic items due to their structural properties and

Table 3
Polymer- and item-specific leakage risk parameters and scores from the UBC case study. Final leakage risk scores were calculated based on data provided by waste management facilities and definitions provided in Table 2.

Polymer or Item	Polymer Code	Polymer Number	Local Recyclability	Penalty Factors			Leakage Risk Score
				Residue Contamination	Mis-sorting Contamination	Transportation Distance	
Polyethylene terephthalate	PET	1	1	1	0	1	3
High density polyethylene	HDPE	2	1	0	0	0	1
Polyvinyl chloride	PVC	3	4	NA	NA	NA	4
Low density polyethylene	LDPE	4	1	0	1	0	2
Polypropylene	PP	5	1	1	0	0	2
Polystyrene[a]	PS	6	1	1	1	0	3
Straw	PP / PS	5/6	4	NA	NA	NA	4
Cutlery	PP / PS	5/6	4	NA	NA	NA	4
Black Plastic	Variable	Variable	4	NA	NA	NA	4

[a] Expanded polystyrene (EPS/Styrofoam) is included in this category.

interaction with waste management systems. By combining information on local waste management practices with an ocean plastic harm index, the framework assesses the compound risk that plastic consumption presents to marine life and points to priority policy actions to mitigate that risk. Through applying this framework to a focal institution, the University of British Columbia, we identified several high-risk plastic items that can be targeted for waste reduction, and alternative plastic items that can be substituted to reduce the overall impact of UBC's plastic consumption on marine ecosystems (Figs. 3, 4, S3). Beyond this case study, the framework is flexible to the specific harm reduction goals and waste management systems of any focal institution, given sufficient data.

Depending on the specified waste management goals, there are many ways that the assessment's output (a risk-ranked list of plastic items and polymers) can inform waste management strategies and policy development. For example, if reducing plastic consumption is the goal, users can combine the compound risk score with plastic procurement data to identify and target high-use or high-cost plastic items (Figs. 4, S3, top half). Alternatively, if avoiding high-risk plastic items is the goal, users can target items with higher compound risk (Figs. 4, S3, right half), or high-use and high-risk items (Figs. 4, S3, top right quadrant). This compound risk assessment can be conducted by any institution to yield case-specific target items for policy and management. The strategies derived from this framework will depend upon the quality of the data acquired in stages 3.1 and 4.1 (Fig. 1). While obtaining the necessary purchasing data from relevant vendors may be challenging at larger institutions, other information (e.g. waste audits or supply shipment data) could be used to inform this type of evaluation.

Reducing total single-use plastic consumption is an important overall goal for solving the ocean plastic problem (i.e. turn off the tap [9]); however, transitions to non-plastic alternatives can be difficult to implement due to barriers such as cost, availability, and performance factors [27–30]. Under these circumstances, institutions seeking to reduce their plastic-associated environmental impact often need to identify lower-risk alternatives that can sustain the original item's function. Understanding the variation in polymer leakage risks in the local waste management system facilitates the identification of lower-risk plastic alternatives that enable the transition toward more

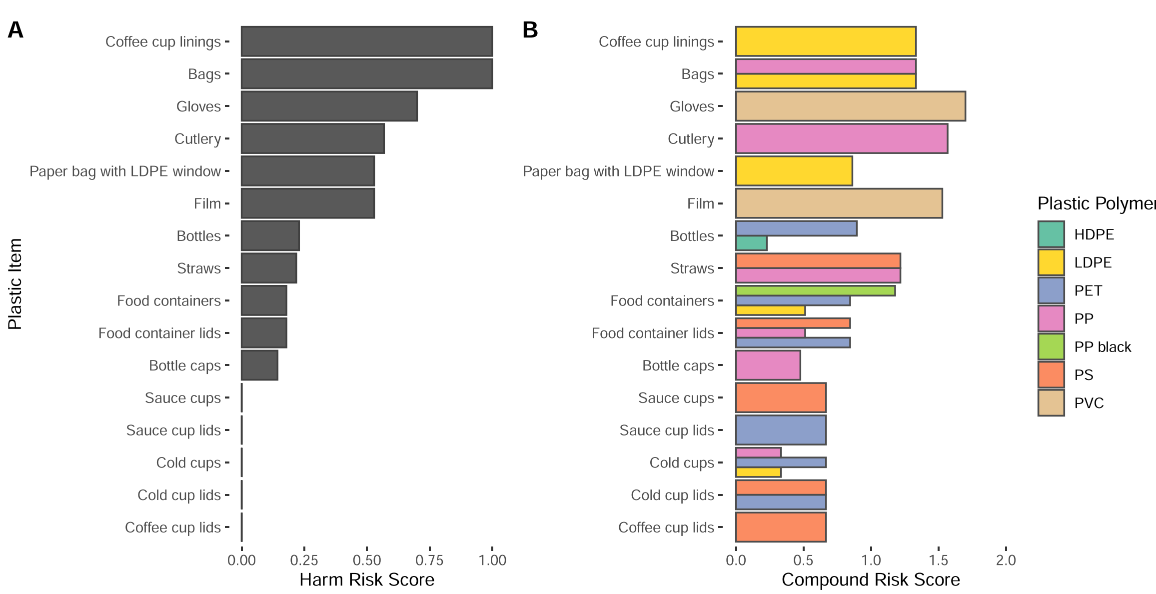

Fig. 3. The harm and compound risk that different single-use plastic items pose to marine life. A) Normalized average harm risk (averaged entanglement, ingestion, and contamination scores from Wilcox et al. [20]) of single-use plastic items purchased at the University of British Columbia, 2017–2018. These harm risk values are all shaded grey as Wilcox et al., 2016 did not account for the polymer composition of plastic items. B) Compound risk scores for the same plastic items, calculated as the sum of the normalized leakage and harm risks for each plastic polymer-item. Items that are made from different polymers have distinct bars for distinct polymer compositions (i.e. bottles made of PET vs HDPE).

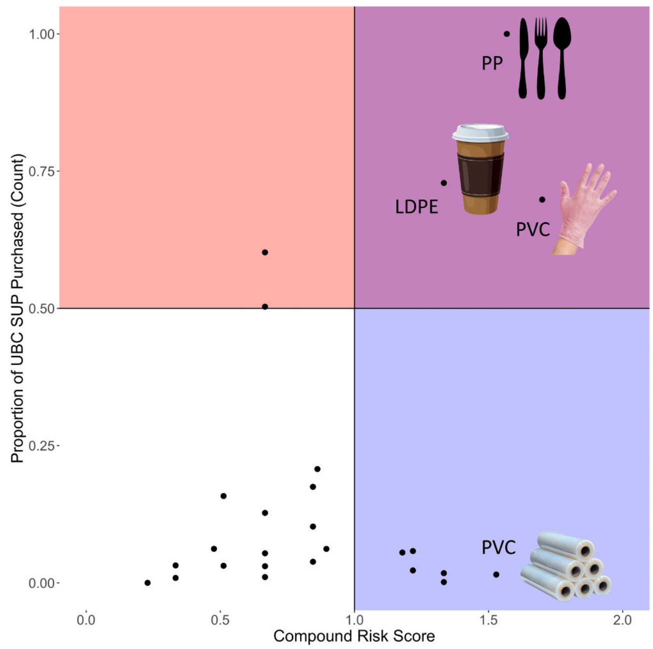

Fig. 4. Compound risk score and relative amounts of single-use plastic items (SUPs) purchased at UBC in 2018, by count. Areas of interest for management priorities are shaded as follows: top half (pink) - most consumed items; right half (blue) - items with the highest compound harm risk. The top rightregion (purple) represents items that are consumed in high amounts and have high compound harm risk scores. The items highlighted with illustrations comprise the most consumed and/or highest compound-risk items and are suitable priorities for waste or impact reduction strategies within this case study context. Proportion of consumption is normalized to a scale of 0–1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

circular plastic procurement practices. Within the case study presented here, plastic straws, cutlery, items composed of PVC (#3) or any #7 polymers, including composite-polymers are not locally recyclable. Thus, their continued consumption is incompatible with a transition toward lower marine impact and a circular plastic economy. Straws and cutlery may need to be replaced with non-plastic alternatives, since they are unrecyclable regardless of their polymer composition. However, items made of PVC or #7 plastics can be replaced with the same items composed of different, more easily recycled polymers. This framework's locally specific output may also inform larger scale policy outcomes if certain items or polymers are repeatedly found to be high-risk across institutions.

In addition to informing plastic alternatives, this framework can highlight specific avenues for waste management policy to address plastic flow into the ocean. Plastic debris enters the marine environment predominantly through litter, maritime transportation, and mismanaged waste [1,13]. Of these three vectors, the latter is most suitable for waste managers to address [13]. Waste management systems are incredibly complex and variable across institutions. Our proposed framework accommodates this complexity through its general applicability and its system-specific output. We demonstrate that in UBC's waste management system, leakage out of the recycling stream is largely driven by contamination due to food and product residue, mis-sorting, and transportation distance. Actions to address these contamination problems could include: developing policy that requires food containers and packaging to be manufactured from compostable materials [31,32], providing accessible sorting infrastructure and education to consumers to reduce mis-sorting and food contamination at time of disposal [33, 34], but see [35]; and supporting the improvement of source-separation and material recovery technologies [36,37]. Finally, addressing the leakage of plastics into the environment during the transportation of plastic resin pellets, materials, and waste is an important policy priority, and will involve coordination across multiple stages of the post-consumption plastic life cycle (e.g. facilities represented in Fig. 2).

It is important to note that this framework's output is highly dependent upon the chosen harm risk index, whose selection is driven by both the target plastic category and the taxonomic group identified in Stages 1 and 4 (Fig. 1). In this case study, we selected a harm risk index that used expert elicitation to estimate the ingestion, entanglement, and contamination risk of single-use plastic items for turtles, marine mammals, and marine birds [20]. Other harm risk indices focus on: taxonomic groups, including fish [38–40]; level of biological organization (e.g. organism, population, ecosystem) [18]; microplastics [41–45]; coastal debris [46–48]; and holistic socio-economic and socio-ecological approaches [3,49].

Different harm risk indices capture various aspects of the complex risk associated with each harm risk subcategory, i.e. entanglement, ingestion, and contamination. Entanglement and ingestion risks vary within and across taxonomic groups because factors like body size, feeding behavior and digestive tract structure can substantially influence an organism's vulnerability to these effects [50–52]. Contamination risk varies across polymer types, as different polymers are known to sorb harmful chemicals to differing degrees [53–56]. Further, the magnitude and nature of each of these risks can change over a plastic item's marine lifetime, as it breaks down into smaller plastic particles (i.e. microplastics) [8,57]. Policy-makers can enhance the robustness of their strategies by acknowledging this complexity and clearly identifying their focal taxa and impact priorities prior to selecting the harm risk index for use within the framework (Fig. 1 Stage 1). Importantly, significant knowledge gaps still exist regarding the impacts of plastic pollution on ecosystem and human health [14,18] (e.g. how contaminants and plastics transfer between trophic levels and from organism to population scales). As new knowledge and harm risk indices are created, this framework can be adapted to accommodate and incorporate this new information.

While some recent movements have shown success in motivating individuals to reduce their plastic consumption [58], today's societies are too dependent on plastic to rely on consumers to eliminate all plastic use. This study presents a framework to instead focus on reducing the flow of plastic into the ocean with an emphasis on procurement and waste management solutions. Additionally, it prioritizes plastic items and polymers that pose the greatest compound risk to marine life. Through integrating local waste management and ecological impact data, this framework brings us one step closer toward slowing the flow of plastic into the ocean and mitigating the negative effects that plastic has on marine ecosystems. A meaningful next step would be for lawmakers and managers to build upon this research by creating policies that reduce production and consumption of non-recyclable plastics that are more likely to end up in marine ecosystems. Overall, using this framework to develop targeted plastic reduction policies can support locally effective measures to combat the global issue of marine plastic pollution.

CRediT authorship contribution statement

Kaleigh E. Davis: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Fiona Beaty:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Carolina Sánchez:** Investigation, Data curation, Writing – review & editing.

Declarations of interest

None.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2021.104833.

References

[1] J.R. Jambeck, et al., Plastic waste inputs from land into the ocean, Science 347 (2015) 768–771.
[2] B. Worm, H.K. Lotze, I. Jubinville, C. Wilcox, J. Jambeck, Plastic as a persistent marine pollutant, Annu. Rev. Environ. Resour. 42 (2017) 1–26.
[3] N.J. Beaumont, et al., Global ecological, social and economic impacts of marine plastic, Mar. Pollut. Bull. 142 (2019) 189–195.
[4] T.D. Nielsen, J. Hasselbalch, K. Holmberg, J. Stripple, Politics and the plastic crisis: a review throughout the plastic life cycle, WIREs Energy Environ. 9 (2020), e360.
[5] J. Vince, B.D. Hardesty, Plastic pollution challenges in marine and coastal environments: from local to global governance, Restor. Ecol. 25 (2017) 123–128.
[6] R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made, Sci. Adv. 3 (2017), e1700782.
[7] D. Xanthos, T.R. Walker, International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): A review, Mar. Pollut. Bull. 118 (2017) 17–26.
[8] A. Chamas, et al., Degradation rates of plastics in the environment, ACS Sustain. Chem. Eng. 8 (2020) 3494–3511.
[9] Ellen MacArthur Foundation and Micinsey & Company, The new plastics economy: rethinking the future of plastics, (2016). ⟨https://www.ellenmacarthurfoundation.org/assets/downloads/EllenMacArthurFoundation_TheNewPlasticsEconomy_Pages.pdf⟩.
[10] Smart Prosperity Institute, A vision for a circular economy for plastics in Canada: the benefits of plastics without the waste and how we get it right, 42, (2019). ⟨https://institute.smartprosperity.ca/sites/default/files/report-circulareconomy-february14-final.pdf⟩.
[11] E. van Eygen, D. Laner, J. Fellner, Circular economy of plastic packaging: current practice and perspectives in Austria, Waste Manag. 72 (2018) 55–64.
[12] C.W. Tallentire, B. Steubing, The environmental benefits of improving packaging waste collection in Europe, Waste Manag. 103 (2020) 426–436.
[13] K.L. Law, Plastics in the marine environment, Annu. Rev. Mar. Sci. 9 (2017) 205–229.
[14] E. Mendenhall, Oceans of plastic: a research agenda to propel policy development, Mar. Policy 96 (2018) 291–298.
[15] S.B. Sheavly, K.M. Register, Marine debris & plastics: environmental concerns, sources, impacts and solutions, J. Polym. Environ. 15 (2007) 301–305.
[16] D.K.A. Barnes, F. Galgani, R.C. Thompson, M. Barlaz, Accumulation and fragmentation of plastic debris in global environments, Philos. Trans. R. Soc. B Biol. Sci. 364 (2009) 1985–1998.
[17] J. Hammer, M.H.S. Kraak, J.R. Parsons, Plastics in the marine environment: the dark side of a modern gift, Rev. Environ. Contam. Toxicol. 220 (2012) 1–44.
[18] C.M. Rochman, et al., The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived, Ecology 97 (2016) 302–312.
[19] C.M. Rochman, et al., Policy: classify plastic waste as hazardous, Nature (2013). ⟨https://www.nature.com/articles/494169a⟩.
[20] C. Wilcox, N.J. Mallos, G.H. Leonard, A. Rodriguez, B.D. Hardesty, Using expert elicitation to estimate the impacts of plastic pollution on marine wildlife, Mar. Policy 65 (2016) 107–114.
[21] E. Mendenhall, E.M. Baron Lopez, Solving the oceans' plastic problem, Curr. Hist. 119 (1) (2020) 22–28.
[22] Recycle BC, What is contamination? Recycle BC, (2017). ⟨https://recyclebc.ca/what-is-contamination/⟩.
[23] Recycle BC, What Can I Recycle? Recycle BC, (2017). ⟨https://recyclebc.ca/what-can-i-recycle/⟩.
[24] TRI Environmental Consulting, 2018 Single-use items waste composition study, Metro Vancouver, (2019). ⟨http://www.metrovancouver.org/services/solid-waste/SolidWastePublications/2018Single-UseItemsWasteCompositionStudy.pdf⟩.
[25] City of Vancouver, Report: Bylaw to reduce single-use items, 57, (2019). ⟨https://council.vancouver.ca/20191127/documents/pspc2.pdf⟩.
[26] A. Rohatgi, WebPlotDigitizer, (2018). ⟨https://automeris.io/WebPlotDigitizer/index.html⟩.
[27] M. Islam, C. Siwar, A comparative study of public sector sustainable procurement practices, opportunities and barriers, Int. Rev. Bus. Res. Pap. 9 (3) (2013) 62–84.
[28] K. Senechal, Barriers to the elimination of plastic in single use beverage containers in Byron Bay, NSW (2018).
[29] L. Milios, L. Holm Christensen, D. McKinnon, C. Christensen, M.K. Rasch, M. Hallstrøm Eriksen, Plastic recycling in the Nordics: a value chain market analysis, Waste Manag. 76 (2018) 180–189.
[30] X. Ma, C. Park, J. Moultrie, Factors for eliminating plastic in packaging: the European FMCG experts' view, J. Clean. Prod. 256 (2020), 120492.
[31] Seattle City Ordinance 122751, (2008).
[32] City of Vancouver, City of Vancouver single-use item reduction strategy 2018–2025: a priority action in zero waste 2040 (Standing Committee on Policy and Strategic Priorities, approved by Vancouver City Council), (2018). ⟨https://council.vancouver.ca/20180516/documents/pspc20180516min.pdf⟩.
[33] A. Bernstad, Household food waste separation behavior and the importance of convenience, Waste Manag. 34 (2014) 1317–1323.
[34] S.F. Sidique, F. Lupi, S.V. Joshi, The effects of behavior and attitudes on drop-off recycling activities, Resour. Conserv. Recycl. 54 (2010) 163–170.
[35] C. Lakhan, Exploring the relationship between municipal promotion and education investments and recycling rate performance in Ontario, Canada, Resour. Conserv. Recycl. 92 (2014) 222–229.
[36] M.K. Eriksen, A. Damgaard, A. Boldrin, T.F. Astrup, Quality assessment and circularity potential of recovery systems for household plastic waste, J. Ind. Ecol. 23 (2019) 156–168.
[37] K. Pivnenko, L. Jakobsen, M. Eriksen, A. Damgaard, T. Astrup, Challenges in plastics recycling, in (2015).
[38] A. Markic, J.-C. Gaertner, N. Gaertner-Mazouni, A.A. Koelmans, Plastic ingestion by marine fish in the wild, Crit. Rev. Environ. Sci. Technol. 50 (2020) 657–697.
[39] F.E. Possatto, M. Barletta, M.F. Costa, J.A. Ivar do Sul, D.V. Dantas, Plastic debris ingestion by marine catfish: an unexpected fisheries impact, Mar. Pollut. Bull. 62 (2011) 1098–1102.
[40] H.S. Carson, The incidence of plastic ingestion by fishes: from the prey's perspective, Mar. Pollut. Bull. 74 (2013) 170–174.
[41] L.G.A. Barboza, A. Dick Vethaak, B.R.B.O. Lavorante, A.K. Lundebye, L. Guilhermino, Marine microplastic debris: an emerging issue for food security, food safety and human health, Mar. Pollut. Bull. 133 (2018) 336–348.
[42] M.B. Phillips, T.H. Bonner, Occurrence and amount of microplastic ingested by fishes in watersheds of the Gulf of Mexico, Mar. Pollut. Bull. 100 (2015) 264–269.
[43] R.A. Schoof, J. DeNike, Microplastics in the context of regulation of commercial shellfish aquaculture operations, Integr. Environ. Assess. Manag. 13 (2017) 522–527.
[44] G. Covernton, et al., Microplastics in bivalves and their habitat in relation to shellfish aquaculture proximity in coastal British Columbia, Can. Aquac. Environ. Interact. 11 (2019) 357–374.
[45] V. S. Lin, Research highlights: impacts of microplastics on plankton, Environ. Sci. Process. Impacts 18 (2016) 160–163.
[46] A.G.J. Driedger, H.H. Dürr, K. Mitchell, P. Van Cappellen, Plastic debris in the Laurentian Great Lakes: a review, J. Gt. Lakes Res. 41 (2015) 9–19.

[47] B.A. Walther, A. Kunz, C.-S. Hu, Type and quantity of coastal debris pollution in Taiwan: a 12-year nationwide assessment using citizen science data, Mar. Pollut. Bull. 135 (2018) 862–872.
[48] C. Konecny, V. Fladmark, S. De la Puente, Towards cleaner shores: assessing the Great Canadian Shoreline Cleanup's most recent data on volunteer engagement and litter removal along the coast of British Columbia, Canada, Mar. Pollut. Bull. 135 (2018) 411–417.
[49] B.D. Hardesty, C. Wilcox, A risk framework for tackling marine debris, Anal. Methods 9 (2017) 1429–1436.
[50] C. Scherer, N. Brennholt, G. Reifferscheid, M. Wagner, Feeding type and development drive the ingestion of microplastics by freshwater invertebrates, Sci. Rep. 7 (2017) 1–9.
[51] F. Collard, B. Gilbert, G. Eppe, L. Roos, P. Compère, K. Das, E. Parmentier, Morphology of the filtration apparatus of three planktivorous fishes and relation with ingested anthropogenic particles, Mar. Pollut. Bull. 116 (1–2) (2017) 182–191.
[52] N.A.C. Welden, P.R. Cowie, Environment and gut morphology influence microplastic retention in langoustine, Nephrops norvegicus, Environ. Pollut. 214 (2016) 859–865.
[53] E.L. Teuten, S.J. Rowland, T.S. Galloway, T.S. Galloway, Potential for plastics to transport hydrophobic contaminants potential for plastics to transport hydrophobic contaminants, ACS Publ. 41 (2007) 7759–7764.
[54] C.M. Rochman, E. Hoh, B.T. Hentschel, S. Kaye, Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: implications for plastic marine debris, Environ. Sci. Technol. 47 (2013) 1646–1654.
[55] C.M. Rochman, C. Manzano, B.T. Hentschel, S.L.M. Simonich, E. Hoh, Polystyrene plastic: a source and sink for polycyclic aromatic hydrocarbons in the marine environment, Environ. Sci. Technol. 47 (2013) 13976–13984.
[56] C.M. Rochman, E. Hoh, T. Kurobe, S.J. Teh, Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress, Sci. Rep. 3 (2013) 3263.
[57] N. Raddadi, F. Fava, Biodegradation of oil-based plastics in the environment: existing knowledge and needs of research and innovation, Sci. Total Environ. 679 (2019) 148–158.
[58] L.M. Heidbreder, J. Steinhorst, M. Schmitt, Plastic-free July: an experimental study of limiting and promoting factors in encouraging a reduction of single-use plastic consumption, Sustainability 12 (2020).