METHODS ARTICLE

Using information flow analysis to establish key data gaps in the assessment of marine microplastic pollution

Valentina H. Pauna¹,² | Cecilia Askham²

¹International PhD Programme/UNESCO Chair “Environment, Resources and Sustainable Development,” Department of Science and Technology, Parthenope University of Naples, Centro Direzionale, Naples, Italy
²Norwegian Institute for Sustainability Research (NORSUS), Kråkerøy, Norway

Abstract

Despite the persistent research interest in marine microplastic (MP) particles, the pollutant is still largely misunderstood. Significant data gaps hinder experts’ understanding of the sources, pathways, and fate of marine MPs, making it difficult to assess its environmental implications. Interdisciplinary work is required to fully understand the complexity of marine MPs (MMPs) and to address the potential stress that this form of pollution may put on marine ecosystems. This study introduces an approach called information flow analysis (IFA), which intends to connect different fields of study through data flows, demonstrating the importance of these fields in the development of life cycle impact assessment (LCIA) of MMPs. The IFA approach was used to clarify where microplastic data is expected to come from with the goal of providing insight into how to obtain the data required for risk assessment (RA) and life cycle assessment (LCA). In order to observe and demonstrate these links, the next step was to develop a site-specific coarse material flow analysis (MFA) based on previously estimated MP emissions from Norway and data from MP sampling in the inner Oslofjord. The coarse MFA demonstrated that MP sources in Norway were estimated to contribute between 85% and 96% rubbery MP particles and between 4% and 15% semisynthetic MP particles in 2018, while blue mussels sampled by the Norwegian Institute for Water Research (NIVA) contained 93% rubbery MP particles and 7% semisynthetic MP particles. This seems to demonstrate a connection between Norwegian MP sources (emissions) and MP levels observed in the environment.

KEYWORDS
industrial ecology, interdisciplinary, life cycle assessment, life cycle impact assessment, marine microplastics, material flow analysis, SDG 14

1 INTRODUCTION

1.1 Background

Marine microplastic (MMP) pollution has become a topic of increasing interest and the number of studies has followed an exponential trend in recent years (Cowger et al., 2020). The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) has suggested that microplastics (MPs) be commonly defined by an upper size boundary of 5 mm in diameter (GESAMP, 2019). MPs can also be further categorized from a source perspective as primary, that is, plastic particles manufactured in small sizes for specific purposes, and secondary, that...
is, plastic particles that result from the wearing and weathering of macroplastics (Lusher & Pettersen, 2021). Despite numerous efforts to determine the sources (Peano et al., 2020; Sundt et al., 2014), pathways (Peano et al., 2020; Sundt et al., 2014), fate (Woods et al., 2021), and risks (Everaert et al., 2020) of MPs, in the context of LCIA, there remain significant data and knowledge gaps. These data needs introduce uncertainty in each step of the environmental analyses attempting to determine the significance and nature of MP impacts on the environment.

In terms of sources, more detailed data associated with leakage from regional and industrial sources is needed (Peano et al., 2020). Regarding pathways, there is a lack of quantitative knowledge about the quantity of MP within, and released from, each path, that is, the amount of MPs trapped within a pathway to the environment and the amount of MPs released from this pathway into the environment (Sundt et al., 2016). Regarding the fate of MPs, data from life cycle inventory (LCI) is still evolving (Kawecki & Nowack, 2019; Woods et al., 2021) and data to estimate environmental concentrations more accurately are limited (Koelmans et al., 2020; Kvale et al., 2020). For example, there appears to be a significant accumulation of MPs within the biomass of fish and other animals; however, there is currently no global estimate of what this stock value might be (Kvale et al., 2020). Meanwhile, MMPs present in surface waters tend to be used as a reference point; however, they only account for a small fraction of the overall MP pollution found in the marine environment (Lusher & Pettersen, 2021; Pohl et al., 2020). Finally, risk analysis of MPs, both for human and environmental health, is a topic of great importance and has been significantly challenged by a lack of synergistic data (Koelmans et al., 2020).

### 1.2 Overview of the interdisciplinarity of MP information flows

Interdisciplinary work suggests that analytical approaches can be enhanced, if combined. However, it can be the case that experts in one field of study are not fully aware of the methods used by experts in another until they work in collaboration. Therefore, it could further benefit the scientific community to demonstrate which fields of study should be working in collaboration to ensure that these relevant data are acquired. In MP research, guidelines are being generated to address knowledge gaps. One example of the interdisciplinary collaboration among 23 MP experts from diverse areas of expertise and nationalities in Cowger et al. (2020), used to enhance the compatibility of reported MP data. In addition, a critical review by Gouin et al. (2019) discussing the development of risk assessment (RA) of MPs highlights the need for interdisciplinary work to address uncertainties, specifically noting synergies among environmental sciences, waste management, and material sciences. Interdisciplinary collaboration is also required to specify the necessary and desired data for life cycle impact assessment (LCIA) given that effect factors (EFs) and characterization factors (CFs) are informed by toxic influence assessments of pollutants. Quantities of pollutant emissions are often established through material flow analysis (MFA) (Askham et al., submitted). Fate factors (FFs) also require interdisciplinary approaches to understand the pathways and fate of the different types and forms of plastic that are emitted to the environment and where, and in what form, they travel and break down through different environmental compartments. Therefore, the aim of the present work is to provide a method for demonstrating synergies among research fields relevant to the LCIA of MMP research. This is done through mapping MP information and data flows to highlight which areas of study could gain mutual benefit from filling data gaps throughout the sampling, extraction, analysis, and assessment of MMPs.

### 1.3 The importance of laws and regulations in the advancement of LCIA of MPs

In the context of marine plastic pollution (and consequently MMP pollution), the increasing interest of governments and environmental organizations has acted as a catalyst for the development of research approaches aimed at defining the sources, pathways, and fate of plastic pollution (Lusher et al., 2021; van Emmerik, 2021). To include MMP data in LCIA, the EU directive on single-use plastics and the UN Sustainable Development Goal 14: Life Below Water (SDG 14) act as relevant information pathways in the study of MMPs, due to their focus on understanding the consequences of plastic pollution that enables establishing effective decision-making strategies related to plastic production, consumption, and waste. Furthermore, there have been numerous government sanctioned interventions and bans worldwide for lightweight plastic bags, which could break down into MPs over time (a form of secondary MPs) due to exposure in the environment (Xanthos & Walker, 2017). However, European regulations related to banning the sale and use of microbeads (a form of primary MPs) have only just come into fruition since 2014 (Kentin & Kaarto, 2018; Xanthos & Walker, 2017). While legislation related to the mitigation of MP pollution continues to develop, there remains limited evidence of the success of related rules and regulations (Xanthos & Walker, 2017). Therefore, this study also aims to demonstrate the connection between MP science and MP policy, particularly focusing on the marine compartment.

### 2 METHODS

### 2.1 The IFA method

The source-, pathway-, fate-, and risk-related data gaps described in Section 1.1 persist and introduce levels of uncertainty that cannot be ignored despite numerous projects devoted to quantifying the impacts of MP pollution (i.e., GESAMP. Global Life Cycle Impact Assessment Method [GLAM],
While the research community has demonstrated a need and willingness to participate in interdisciplinary collaboration, the authors believe that there has been little clarification on why interdisciplinary work is not only beneficial but required in establishing CFs (as well as the EFs and FFs they are based on) of MMP pollution, as described in Section 1.2. For this reason, a new approach called information flow analysis (IFA) is proposed to highlight the need for interdisciplinary collaboration in MMP research and how data from different fields of study can be mutually beneficial. An IFA was then carried out to create a map of the flows of MP information from different fields of study (Figure 2). The IFA follows the format of a MFA in that it is composed of processes (boxes) and flows (arrows). What sets an IFA apart from an MFA is that in an IFA, the processes represent areas of study and areas of decision-making, while the flows represent the types of data that are produced and utilized by these areas of study and decision-makers. Each field of study in the map represents keywords resulting from a VOSViewer bibliometric analysis. Connections among the study areas result from the authors’ experience with LCA, LCIA, and LCI and are validated with the network map generated by the VOSViewer bibliometric analysis.

2.2  IFA category selection and traffic-light color coding

A literature search was carried out in Scopus using the search term "microplastic AND assessment AND marine". All results were exported in CSV format and included the information from categories: Author, Document title, Year, Source title, Citation count, Publisher, Author keywords, and Index keywords. The CSV file was uploaded into VOSViewer software, Version 1.6.18 (van Eck & Waltman, 2022). VOSViewer is a bibliometric analysis tool, which allows for visualization of connections among bibliometric data, such as keywords, authors, and journals, to demonstrate a network of collaborative relationships (Pauna et al., 2019). A keyword co-occurrence analysis was carried out to validate collaboration across study areas, given that keywords can be indicative of the area of focus of literature. Additionally, a thesaurus was created to aggregate the areas of study that had been present in the resulting list of keywords, allowing for more effective visualization of the co-occurrence analysis results. Finally, the keywords that were not present in the thesaurus were deselected for the final network map to ensure that irrelevant words for this study were not included in the final image. Keywords directly related to the study areas relevant for LCA and LCIA of MMPs were selected to include in the IFA. The curved lines connecting each selected keyword to LCA on the network map (Figure 1) were highlighted to display the link strength between the keyword and LCA (see Supporting Information S2). After transferring each link strength to a table, the values were categorized in a "traffic light"
TABLE 1  Keywords from VOSViewer keyword co-occurrence analysis selected to be included in the IFA. Attributional values (i.e., Links, Total Link Strength, Occurrences, and Links) were calculated by the VOSViewer software. Links to “life cycle assessment” were also calculated by the VOSViewer software and visualized by hovering the cursor over each connection (see Supporting Information S2). Color coding reflects the categories: green (4 to 5 link strength), yellow (2 to 3 link strength), red (0 to 1 link strength).

| Keyword (As Seen in Figure 2)                                                                 | Links | Total Link Strength | Occurrences | Link strength to “life cycle assessment” |
|-----------------------------------------------------------------------------------------------|-------|---------------------|-------------|-----------------------------------------|
| environmental monitoring (Environmental Monitoring)                                           | 87    | 1143                | 345         | 4                                       |
| risk assessment (Risk Assessment)                                                             | 84    | 881                 | 272         | 2                                       |
| characterization and identification (MP characterization and Identification)                    | 80    | 716                 | 196         | 4                                       |
| decision making (International Laws & Regulations, National Laws & Regulations, Corporate Action, Public Actions) | 54    | 241                 | 74          | 5                                       |
| ecotoxicology (Ecotoxicology)                                                                 | 52    | 199                 | 55          | 1                                       |
| toxicology (Toxicology)                                                                      | 47    | 156                 | 39          | 2                                       |
| material flow analysis (MFA)                                                                  | 8     | 8                   | 2           | 1                                       |
| life cycle impact assessment (LCIA Characterization)                                          | 6     | 7                   | 2           | 2                                       |
| field sampling (Sampling (Field, in situ, Environmental))                                    | 40    | 153                 | 41          | 2                                       |

format, that is, green, yellow, and red. Category 4 to 5 was given green to indicate the largest presence, category 2 to 3 was given yellow to indicate a less strong presence, and category 0 to 1 was given red to indicate the least strong presence in the literature search (Table 1).

2.3  Selecting and mapping site-specific MP source pathways

The challenges of defining the sources, pathways, and fate of MP pollution in MP research (Fältström et al., 2021; Woods et al., 2021) could be due to the complexity of MPs in terms of their characteristics. For example, complexity related to the diverse sizes, morphologies, chemical compositions, associated additives and stabilizers, and colors of MPs (Rochman et al., 2019). In addition to the inherent complexity of MPs as contaminants, the types of environments where they originate, pass through, and are deposited are also complex (Fältström et al., 2021).

A sampling site from a Norwegian Institute for Water Research (NIVA) study carried out to investigate MPs in biota within the Nordic marine environment was selected as the study site to apply the IFA method in the present study. We referred to the principle of IFA, namely, following the flows of data, to create a coarse MFA to allow us to observe whether there is a possible relationship between observed values of MP from environmental samples and calculated values of MP emissions.

2.3.1  Study area for coarse MFA

The inner Oslofjord is within the Brunnefjord and experiences 3–4 years between water cycles (Powell et al., 2018). The water cycle timeframe of 3–4 years is the result of the semi-enclosed fjord basin of the Oslofjord, which has been observed to trap chemical substances present in municipal...
wastewater, resulting in elevated levels compared to those in the outer Oslofjord (Powell et al., 2018). This water cycle rate has been demonstrated to affect the lifetime of chemical substances (not specifically MPs) in the inner Oslofjord. We have assumed that the MPs present in the selected study site (Akershuskaia) will remain for 3–4 years, which contributes to uncertainty in the present study. It is important to note that this assumption does not account for the complex nature of MP fate from land to ocean because this area of study is still largely under development (He et al., 2021; Malli et al., 2022). However, despite these limitations, Akershuskaia appears to represent a useful study area for the presented coarse MFA because, under the assumption that the MPs will remain in the Inner Oslofjord for 3–4 years, it is possible to connect the MP sources for Norway calculated in 2014 by Sundt et al. (2014) to the observed MPs from sampling carried out in 2018 by Bråte et al. (2020).

Akershuskaia is the site of the Nordic Construction Company (NCC) Construction AS snowmelt facility (Søndre), where snow collected from the streets of Oslo during winter is melted, purified of contaminants, and disposed of into the Oslo harbor pool (NCC SnowClean, Oslo, 2021). NIVA has previously conducted two studies (Bråte et al., 2018; Vogelsang et al., 2020), which have both suggested that one of the direct contributors to the presence of rubbery particles in blue mussels could be the Søndre Akershuskaia snowmelt facility, via tire wear. Therefore, Akershuskaia represents a unique study area where some data for both sources and presence of MP particles are available.

### 2.3.2 Mapping known Akershuskaia sources, pathways, and fate

To calculate the share of MP particles from relevant Norwegian sources to the Akershuskaia sampling area, several direct and indirect pathways were first mapped in a coarse MFA format, with reference to the IFA approach we have developed (Figure 2). These pathways were validated through literature review, described subsequently. The Norwegian study (Sundt et al., 2014) shows that the most prevalent estimated MPs are from tire wear, paint, and consumer or commercial laundry, and textiles. Tire wear and wastewater treatment plants (WWTPs) were the MP source pathways assessed in the Akershuskaia coarse MFA. Bråte et al. (2020) found that the types of MP particles found in the sampled blue mussels at the Akershuskaia sampling station (labeled M-19 in Bråte et al., 2020) are most likely to come from these two sources. This present study is limited to the MMPs that originate from tire wear and textiles, transported by way of snowplow melt and WWTP outlets. We have focused on these sources and pathways because they are the best documented assumptions for this location according to the supporting literature analyzing field samples from Bråte et al. (2020); Vogelsang et al. (2020), and the Norwegian MP emission estimates form Sundt et al. (2014). Keeping this narrow focus allows us to explore and validate the connections between the observed MPs in the environment and their assumed pathways.

### 2.4 Scaling Norwegian MP emissions to Oslo

#### 2.4.1 Tire wear

Annual MP estimates resulting from tire wear in Norway calculated by Sundt et al. (2014) were scaled to 2018 (the year of blue mussel sampling at NIVA, Bråte et al., 2020) by using national (i.e., Norway) and local (i.e., Oslo municipality) passenger transportation data (the year of sampling) from Statistics Norway (2020). Lorry transportation data was excluded from the analysis because the Akershuskaia area of Oslo is a city center/pedestrian area of Oslo that is dominated by passenger traffic rather than lorry traffic. In addition, we have assumed a linear relationship between population increase and MP emission increase when determining the proportion of the 2018 national data belonging to the Oslo municipality. An estimate of the annual MP from tire wear from the Oslo municipality was calculated using Equation (1):

\[
T_{\text{WE}_{\text{Oslo},2018}} = \left( \frac{T_{\text{Oslo},2018}}{T_{\text{Norway},2018}} \right) \times T_{\text{WE}_{\text{Norway}}}
\]

where \(T_{\text{WE}_{\text{Oslo},2018}}\) represents the estimated MPs generated from tire wear in Oslo municipality in the year 2018, \(T_{\text{Oslo},2018}\) represents the total transportation in Oslo in the year 2018, \(T_{\text{Norway},2018}\) represents the total transportation in Norway in the year 2018, and \(T_{\text{WE}_{\text{Norway}}}\) represents the estimated MPs generated from tire wear in Norway annually from Sundt et al. (2014).

Equation (1) is likely to give an overestimation because it is not expected that all tire abrasion is picked up along with the snow plowed and it is possible that some of the resulting rubbery particles will be trapped in the purification process at the Akershuskaia snow melting facility.

The snowmelt facility (Søndre Akershuskaia) was running from January 7, 2018 until April 6, 2018 (Norconsult, 2019). This time frame was used to determine which fraction of the \(T_{\text{WE}_{\text{Oslo},2018}}\) could have entered the inner Oslofjord via snow melting as rubbery MP particles. Therefore, the total \(T_{\text{WE}_{\text{Oslo},2018}}\) was divided by 4 (given that 3 months is 1/4 of a year) to determine \(T_{\text{WE}_{\text{Oslo},2018}}\).
FIGURE 2  IFA: Relevant fields of study and areas of decision-making are shown in boxes (i.e., processes from the MFA perspective). Arrows in black represent data in the form of calculated and observed values. Arrows in magenta represent data in the form of information. The research areas come from the keywords that were found to co-occur with "life cycle assessment" in the network map generated by bibliometric analysis (Figure 1). The boxes representing these fields of study are colored according to a "traffic light" approach, such that green represents the greatest link strength to "life cycle assessment" (i.e., 4 to 5), yellow represents the moderate link strength to "life cycle assessment" (i.e., 2 to 3) and red represents the weakest link strength to "life cycle assessment" (i.e., 0 to 1). LCA-Midpoint and LCA-Endpoint are not color-coded because "life cycle assessment" will always co-occur with itself; therefore, its link strength to itself is not relevant. Additional data on the color coding of this figure can be found in Supporting Information S2.
2.4.2 Textiles

Given that WWTPs are assumed to contain semisynthetic (i.e., cellulose material, including rayon and viscous; Bråte et al., 2018) MPs in their effluent (Bråte et al., 2020), we have assumed that semisynthetic MPs can originate from textiles, a contributor to MP presence in WWTPs (Bråte et al., 2018). MP inputs from textiles were estimated by localizing national MP estimation data for Norway from Sundt et al. (2014) to reflect the Oslo municipality. We have only considered consumer laundering because the study area represents a city center/residential area of Oslo that does not have a significant presence of commercial laundry. The national annual MP estimate for textiles for Oslo was calculated using Equation (2):

\[
SSE_{Oslo,2018} = \left( \frac{P_{Oslo,2018}}{P_{Norway,2018}} \right) \ast SSE_{Norway}
\]  

where \( SSE_{Oslo,2018} \) represents the estimated MPs generated from textiles in Oslo municipality via consumer laundering in the year 2018, \( P_{Oslo,2018} \) represents the total population in Oslo in the year 2018, \( P_{Norway,2018} \) represents the total population in Norway in the year 2018, and \( SSE_{Norway} \) represents the estimated MPs generated from textiles in Norway annually from Sundt et al. (2014).

The assumed WWTP efficiency for removing microfibers from the effluent ranges between 65% and 92% (Henry et al., 2018). Therefore, the available estimated MPs from textiles entering Akershuskaia in 2018 was calculated as a range by multiplying \( SSE_{Oslo,2018} \) with 35% and 8%.

3 RESULTS AND DISCUSSION

3.1 Bibliometric analysis for field of study selection in IFA

The bibliometric keyword co-occurrence analysis resulted in 6650 keywords (see Supporting Information S1). After aggregation of like keywords by adding a thesaurus (see Supporting Information S1) and selecting a minimum occurrence of 2, the VOSViewer software calculated 2200 keywords that met the threshold. Finally, keywords directly associated with MP assessment (i.e., regarding sampling, extraction, identification, and analysis) were manually selected and the resulting network map (Figure 1) displayed 97 keywords (see Supporting Information S1).

The links, occurrences, and total link strengths for all displayed keywords are found in Supporting Information S1. Table 1 represents the keywords from the VOSViewer analysis that were used to populate the IFA in Figure 2.

The link strengths that resulted from the connections between the keyword “life cycle assessment” to all other keywords in Table 1 allowed for a validation of the assumed development of the fields of study that are both relevant to LCA and enable the assessment of MPs in the environment. By carrying out this bibliometric network analysis, the IFA could be generated such that it is representative of the existing literature.

3.2 IFA

The green, yellow, and red boxes (fields of study) in the IFA (Figure 2) demonstrate the most relevant keywords to LCA and LCIA that were observed in the keyword co-occurrence network map provided by the VOSViewer software analysis (Figure 1). The connecting arrows (flows of information) in the IFA represent the pathways of information among fields in the context of LCA and demonstrate the need for effective collaboration for more efficient data acquisition in the assessment of MMPs. It is worth noting that there are numerous other fields of study that have taken interest in MPs and MMPs that have not been included in Figure 2; we have left these fields out to allow for a more thorough discussion on the fields currently most relevant to LCA.

Arrows that are magenta represent data in the form of information (i.e., qualitative data and metadata) and arrows that are black represent data in the form of calculated quantitative values and observed quantitative values. The color coding in the IFA depicts the prevalence of each study area in the context of LCA and is described in further detail in Section 2.2. Red boxes represent keywords that co-occur less frequently with “life cycle assessment,” likely reflecting severe data and knowledge gaps in these related study areas. Yellow boxes represent keywords that co-occur moderately with “life cycle assessment,” therefore, they currently provide moderate contributions on the issue of MP pollution in the context of LCA. Green boxes are keywords that co-occur the most with “life cycle assessment” in our MP literature search, indicating that these study areas currently link more strongly with LCA and have the potential to link well with data relevant for LCA of MPs. It is important to note the inherent connection between LCA research and decision-making; this is indicated by the prevalence of the keyword “decision making” co-occurring with “life cycle assessment.” Therefore, one should recognize that this strong co-occurrence relationship does not indicate that decision-making has no room for growth. It should be noted that LCA-Midpoint and LCA-Endpoint are in white boxes. This is because the color coding is based on the co-occurrence with the keyword “life cycle assessment.” As LCA is not an independent keyword from these terms, the color coding is not relevant for these boxes.
3.2.1 Data gaps in MFA and ecotoxicology in the context of LCA of MPs

Given that the bibliometric analysis resulted in a weak link strength between MFA and LCA as well as between ecotoxicology and LCA, these areas of study were color coded in the least prevalent category (red) in the IFA. MFA can provide information that connects the quantity of MPs present in the environment and the quantity of MPs present in a system (i.e., their assumed pathways from the anthropogenic activities to nature) because the method considers the flows, stocks, inputs, and outputs of a substance (Fältström et al., 2021). MFA can also be a useful tool for populating LCI, a crucial step in LCA and required for LCIA (Wang et al., 2022). Meanwhile, ecotoxicity of MPs has been a topic of increasing interest over the past 10 years as there is a persistent need to define the environmental consequences of the pollutant (Barrick et al., 2021). The consequences of MPs from an ecotoxicological perspective are still being investigated (Everaert et al., 2018), however, and more research is needed in this area to quantify the impact of MPs on the marine organisms that interact with the plastic particles (Koelmans et al., 2017). The IFA shows that there is a weak presence of ecotoxicology in the literature in the context of the LCA of MPs, despite its importance in LCIA characterization of MPs. The results of the IFA suggest that MFA and ecotoxicology are areas of study experiencing severe data and knowledge gaps in the context of LCA focused on MPs.

3.2.2 Room for improvement in RA, LCIA, sampling, and toxicology in the context of LCA of MPs

RA is important for decision-making because it leads to the implementation of risk-mitigating strategies (Romero-Franco et al., 2017), making it a critical area to address in terms of data gaps related to MP research (Gouin et al., 2019). While there is awareness that MPs are potentially damaging to the environment, there remains a poor understanding of how exposure to the pollutant impacts marine organisms (Everaert et al., 2020). The bibliometric analysis demonstrated that in MP assessment research, RA, LCIA, sampling, and toxicology moderately co-occur with LCA. The IFA shows the connection between RA and LCA by way of threshold values. These threshold values are calculated by considering the effects of MPs on humans (in toxicology) and species (in ecotoxicology). Toxicology is additionally connected to LCA through characterization factors used in LCIA, in which toxicity data is used to inform the potential effects of a pollutant. Toxicology (and ecotoxicology data) related to MPs are reliant on sampling practices; despite this, there was only a moderate link strength connecting Sampling to LCA. The IFA demonstrates a moderate presence of RA, LCIA, sampling, and toxicology in the context of LCA. This indicates that these areas of study could benefit from an increasing focus in MP research.

3.2.3 Significant relative research presence of environmental monitoring, MP characterization and identification, and decision-making in the context of LCA of MPs

The bibliometric analysis demonstrated a significant occurrence of environmental monitoring and co-occurrence with LCA. This is a positive result for the development of LCA of MPs given that environmental monitoring is an area of study used to depict the status of the environment (Lusher et al., 2021). Additionally, MP characterization and identification was a popular keyword to occur alongside LCA; this is a hopeful result, given that the type of plastic observed in environmental MP samples could indicate the sources of particles (Bråte et al., 2020), which are relevant to sources (emissions), fate (FFs) and effect (EFs) needed for LCIA. Finally, decision-making (corporate, national, and international) often co-occurred with LCA; this indicates that the LCA links could be exploited in order to develop solution-oriented results from the assessment of MPs.

3.3 Akershuskaia coarse MFA

We have (see 2.3) referred to the principle of IFA (following the flows of data) and created a coarse MFA to observe and demonstrate the information flows and links. This will elicit the possible relationship between observed values of MP from environmental samples and calculated values of MP emissions. Several flows of information of varying certainty levels resulted from the Akershuskaia coarse MFA (Figure 3). Unlike the IFA (Figure 2) in which the processes consist of areas of study and the flows consist of the types of data, the Akershuskaia coarse MFA is generated with processes that consist of the sources, pathways, or fate of MPs, while the flows consist of descriptions of the MPs that result from one process and enter another process.

3.3.1 Akershuskaia rubbery particles

Table 2 lists the values used in Equation (1) as well as the calculated estimate of rubbery MPs from tire wear available in Akershuskaia for consumption by blue mussel in 2018. The Norwegian tire wear estimates used to calculate the Oslo tire wear estimates come from Lusher et al. (2017), which
FIGURE 3  Akershuskaia coarse MFA: The assumed sources, pathways, and fate of MPs in Oslo and Akershuskaia are shown in boxes (i.e., processes from the MFA perspective). Arrows represent descriptions of the MPs that travel from one process to another and encompass calculated estimate values, unknown values, observed estimate values, and unknown observable values.

TABLE 2  Tire wear calculation values

| Variable name | Variable definition | Value (units) | Source |
|---------------|---------------------|---------------|--------|
| TWE_{Oslo,2018} | Estimated MPs generated from tire wear in Oslo municipality in the year 2018 | 592,417 (kg) | Calculated |
| T_{Oslo,2018} | Total transportation in Oslo in the year 2018 | 6,055 (million km) | Statistics Norway |
| T_{Norway,2018} | Total transportation in Norway in the year 2018 | 45,999 (million km) | Statistics Norway |
| TWE_{Norway} | Estimated MPs generated from tire wear in Norway annually | 4,500,000 (kg) | Lusher et al. (2017) based on Sundt et al. (2014) estimates |
| ATWE_{Oslo,2018} | Available estimated MPs from tire wear entering Akershuskaia in 2018 | 148,104 (kg) | Calculated |

had categorized country scale MP emission estimates from Sundt et al. (2014) into three tiers (primary MPs, secondary MPs, and tertiary MPs) in order to connect the emissions to their relevant pathways to the environment. In this report, the summarized tire wear related MPs from the Sundt et al. (2014) estimates, that is 4,500 tonnes MP, were used when assigning emission sources to pathways to the sea with respect to the primary, secondary, and tertiary categories. Bråte et al. (2020) described that the Søndre Akershuskaia snowmelt facility is a highly probably direct pathway for MPs to enter the inner Oslofjord; however, it is not likely that the snow that arrives at Søndre Akershuskaia contains all the MP particles that result from tire wear in the Oslo municipality each year. Given that there is so far no method for determining which proportion of tire wear particles can be accounted for in plowed snow, we have assumed that all tire wear enters the inner Oslofjord via this pathway. This has been done as the purpose of this study is to provide a method for drawing connections between field sampling data and MP estimates from larger scale analyses, not to quantify the MP emissions per pathway type. It is therefore important that the reader is aware that this assumption means that the resulting calculated values are likely to represent an overestimate.
### Table 3: Semisynthetic MP calculation variables

| Variable name               | Variable definition                                           | Value (units) | Source                        |
|-----------------------------|---------------------------------------------------------------|---------------|-------------------------------|
| \( S_{\text{SSE, Oslo, 2018}} \) | Estimated MPs generated from textiles in Oslo municipality in the year 2018 | 76,304 (kg)   | Calculated                    |
| \( P_{\text{Oslo, 2018}} \)    | Total population in Oslo in the year 2018                      | 1,012,000 (persons) | Statistics Norway             |
| \( P_{\text{Norway, 2018}} \)    | Total population in Norway in the year 2018                     | 5,295,619 (persons) | Statistics Norway             |
| \( S_{\text{SSE, Norway}} \)     | Estimated MPs generated from textiles in Norway annually       | 600,000 (kg)   | Sundt et al. (2014)           |
| \( A_{\text{SSE, Oslo, 2018}} \) | Available estimated MPs from textiles entering Akershuskaia in 2018 | 6,104–26,706 (kg) | Calculated                    |

### 3.3.2 Akershuskaia semisynthetic particles

As with the rubbery MP particle estimate in Oslo, the semisynthetic MP particle estimate in Oslo is also an overestimate for the Akershuskaia sampling area. This is because the effluent from the WWTP outlet to the inner Oslofjord does not directly enter the sampling area; rather, it enters several degrees south of Akershuskaia. In addition, it is not expected that all semisynthetic MPs from the Oslo municipality will be released directly into the environment. The uncertainties related to our overestimate for the Akershuskaia sampling area highlight sampling needs because we cannot validate that the WWTP outlet selected for our investigation is a direct source for semisynthetic MP fibers into Akershuskaia. Despite this, our assumption is relevant for our estimation because semisynthetic MPs have been observed in the blue mussels in this area and likely originate from a WWTP source. Table 3 lists the values used in Equation (2) as well as the calculated estimate of semisynthetic MPs from textiles available in Akershuskaia for consumption by blue mussel in 2018.

### 3.4 Relationship between calculated estimates of MP emissions in Oslo and observed MPs at Akershuskaia

The coarse MFA analysis given earlier can be used to estimate the proportion of tire wear and semisynthetic (textile) particles that should be observed in the marine environment at Akershuskaia. If the local food web takes in these particles, the proportion of MP particles that are rubbery and semisynthetic present in the organisms in the food web could be expected to reflect the same proportions (Vázquez-Rowe et al., 2021). The quantities in Tables 1 and 2 (ATWE\text{Oslo, 2018} and ASSE\text{Oslo, 2018}) were used to calculate the proportions of these two different particles, giving a range of approximately 85–96% rubbery MP particles and 4–15% semisynthetic MP particles. Blue mussels collected from Akershuskaia by NIVA in 2018 were found to contain an approximate average of 93% rubbery MP particles expected to have originated from tire wear and 7% semisynthetic MP particles that, according to their polymeric composition, could likely have originated from the washing of textiles (Bråte et al., 2020).

### 3.5 Akershuskaia coarse MFA key takeaways

#### 3.5.1 Sources and pathways

Based on the Akershuskaia IFA, some key areas in need of data are highlighted. There is a severe lack of knowledge which makes it difficult to connect the tire wear particles to the observed rubbery particles in Akershuskaia. However, the site-specific analysis of the Oslo municipality allows for the consideration of a direct pathway for tire wear to enter the sea via the melting of snow plowed within the Oslo municipality at Søndre Aker- shuskaia. This observation highlights another possible pathway for tire wear to enter the marine environment and demonstrates the importance of selecting sensible geographical boundary conditions considering that this snow melting facility is characteristic of Oslo, but probably cannot be used to assume presence of rubbery MPs in other parts of Norway.

MPs that result from textiles have been proven to escape via WWTPs (Henry et al., 2018). So far, there is a range of efficiency associated with the removal of microfibers in the effluent (Henry et al., 2018). It would be beneficial to sample and analyze effluents on a case-by-case basis to establish the average leakage of semisynthetic fibers from WWTP effluents related to their technologies. Local WWTP effluent sampling would validate whether WWTPs could be a direct source for semisynthetic MP fibers to enter Akershuskaia.

#### 3.5.2 Fate

Figure 3 shows that rubbery MP particles from tire wear and semisynthetic MP particles from textiles can enter Akershuskaia. It is assumed that these particles are consumed by blue mussels, due to studies which validate this assumption, that is, Bråte et al. (2020). There is a need to investigate
other species within Akershuskaia to understand how much of the MP particles that enter Akershuskaia should be considered a stock value within the food-web. This data should also help inform the missing information related to the expected quantities of MP particles within the fishing catch from Akershuskaia.

3.5.3 Relationship between estimated Oslo municipality MP emissions and observed MPs in Akershuskaia blue mussels

The coarse MFA analysis of Akershuskaia resulted in an estimated available proportion range of approximately 85–96% rubbery MP particles and 4–15% semisynthetic MP particles. It is interesting to note that the proportion of rubbery MP particles and semisynthetic MP particles observed in blue mussels sampled from Akershuskaia is within the proportion range of the estimated emissions of rubbery MP particles to semisynthetic MP particles calculated in this study (see Section 3.3). This finding helps to demonstrate that there could be valuable connections between observed MP data and estimated MP emissions data for validating the sources, pathways, and fate of MPs in the environment.

4 CONCLUSION

Current LCA methodologies do not account for plastics or MPs as pollutants (Boucher et al., 2020). However, projects such as MarILCA, GLAM, and the PLP are currently working to include marine litter impacts in life cycle impact assessment (LCIA) (Lavoie et al., 2021). Despite these efforts, there simply is not enough synergistic data at the global scale to quantify MP presence and interaction in the marine environment (Koelmans et al., 2020) leading to significant data gaps. To help demonstrate why these data gaps might exist and to propose an approach to address these gaps, this study had two aims. First, to provide an approach for mapping the connections between relevant fields of study to the development of LCA of MPs. Second, to use existing data to validate MP emission estimates at the local scale and assess whether these estimates reflect observed levels in environmental samples. To achieve our aims, we first gathered a thorough overview of the literature related the assessment of MPs in the marine environment through bibliometric network analysis. This network approach allowed for the mapping of study areas (extracted from keywords) in our novel IFA. The IFA demonstrated that MFA and ecotoxicology should receive more attention from the MP scientific community because they resulted in the lowest co-occurrence with respect to LCA. Next, we discovered that RA, LCIA, sampling, and toxicology have a moderate co-occurrence with LCA. Furthermore, we found that environmental monitoring, MP characterization and identification, and decision-making often occurred alongside LCA in the literature. This is a positive result because it demonstrates that the fields of study that form a basis for the understanding of the MP problem are considered in the context of LCA. Finally, the strong links between LCA and decision-making indicate that interdisciplinary links between the disciplines with the lowest co-occurrence with LCA links could be further exploited to facilitate solution-orientated change.

The results of the IFA demonstrated the interdisciplinarity of MP research. We then tested the success of interdisciplinary work by attempting to validate Norwegian MP emission estimates through the creation of a coarse MFA of relevant environmentally observed MP concentrations. Our coarse MFA resulted in a ratio of rubbery MP particles to semisynthetic MP particles found in blue mussels sampled in Akershuskaia that was comparable to the estimated MP emissions from Oslo, Norway. We believe this result demonstrates the applicability of an interdisciplinary approach in MP research. It also highlights the need to investigate how other species might be interacting with MP particles, to better understand if this trend is characteristic of the entire food-web or only for benthic species.

The IFA and coarse MFA presented here can be used as a template to guide future studies on MPs, specifically MMPs.

ACKNOWLEDGMENTS

The authors would like to thank NIVA, with specific thanks to Inger Lise N. Bråte and Amy Lusher, for providing detailed information associated with the data used in this study. This work was partially funded by both the Research Council of Norway via the PacKnoPlast project (Grant 299326) and the International PhD Programme / UNESCO Chair “Environment, Resources and Sustainable Development” at the Parthenope University of Naples, Italy.

Open Access Funding provided by Universita degli Studi di Napoli Parthenope within the CRUI-CARE Agreement.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The statistical data related to transportation and population of Norway that support the findings of this study are available in Statistics Norway at https://www.ssb.no/statbank/table/12576/tableViewLayout1/ and https://www.ssb.no/en/statbank/table/11667/tableViewLayout1/, respectively, and internal reference codes Mileage and Population, respectively. Microplastic data were derived from the following resources available
in the public domain: Miljødirektoratet (https://www.miljodirektoratet.no/publikasjoner/2015/februar/sources-of-microplastic-pollution-to-the-marine-environment/) and the Norwegian Environment Agency publication series: M-1629/2020 (https://pub.norden.org/temanord2020-504/#20219).

ORCID

Valentina H. Pauna  https://orcid.org/0000-0002-7778-526X
Cecilia Askham  https://orcid.org/0000-0001-6867-4536

REFERENCES

Askham, C., Pauna, V. H., Boulay, A.-M., Fantke, P., Jolliet, O., Lavoie, J., Booth, A. M., Coutris, C., Verones, F., Weber, M., Vijver, M., Lusher, A., & Hajjar, C. (n.d.). How relevant environmental sampling and testing data for micro- and nanoplastics can be generated for the development of LCIA models. Manuscript submitted for publication.

Barrick, A., Champeau, O., Chatel, A., Manier, N., Northcott, G., & Tremblay, L. A. (2021). Plastic additives: Challenges in ecotox hazard assessment. PeerJ, 9, 1–26. https://doi.org/10.7717/peerj.11300

Boucher, J., Billard, G., Simeone, E., & Sousa, J. (2020). The marine plastic footprint. In The marine plastic footprint. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2020.01.en

Bråte, I. L. N., Hurley, R., Iversen, K., Beyer, J., Thomas, K. V., Steindal, C. C., Green, N., Olsen, M., & Lusher, A. (2018). Mytilus spp. as sentinels for monitoring microplastic pollution in Norwegian coastal waters: A qualitative and quantitative study. Environmental Pollution, 243, 383–393. https://doi.org/10.1016/j.envpol.2018.08.077

Bråte, I. L. N., Hurley, R. a., Lusher, A., Buenaventura, N., Halsband, C., & Green, N. (2020). Microplastics in marine bivalves from the Nordic environment. Norwegian Environment Agency publication series M-1629/2020. Nordic Council of Ministers. TemaNord report TN2020:504. https://doi.org/10.6027/TemaNord2020-504

Cowger, W., Booth, A. M., Hamilton, B. M., Thaysen, C., Primpke, S., Munno, K., Lusher, A., Buenaventura, N., Halsband, C., & Goonetilleke, A. (2021). Dispersal and transport of microplastics in river sediments. Sustainability (Switzerland), 13(10), 10393. https://doi.org/10.3390/su13105404

Koelmans, A. A., Besseling, E., Foekema, E., Kooi, M., Mintenig, S., Ossendorp, B. C., Redondo-Hasselerharm, P. E., Verschoor, A., Van Wezel, A. P., & Verschaeren, R. (2020). Solving the nonalignment of methods and approaches used in microplastic research to consistently characterize risk. Environmental Science and Technology, 54(19), 12307–12315. https://doi.org/10.1021/acs.est.9b02998

Koelmans, A. A., Redondo-Hasselerharm, P. E., Mohamed Nor, N. H., & Kooi, M. (2020). Solving the nonalignment of methods and approaches used in microplastic research to consistently characterize risk. Environmental Science and Technology, 54(19), 12307–12315. https://doi.org/10.1021/acs.est.9b02219

Koelmans, A. A., Besseling, E., Foekema, E., Kooi, M., Mintenig, S., Ossendorp, B. C., Verschoor, A., Van Wezel, A. P., & Scheffer, M. (2017). Risks of plastic debris: Unravelling fact, opinion, perception, and belief. Environmental Science and Technology, 51(20), 11513–11519. https://doi.org/10.1021/acs.est.7b02219

Koelmans, A. A., Redondo-Hasselerharm, P. E., Mohamed Nor, N. H., & Kooi, M. (2020). Solving the nonalignment of methods and approaches used in microplastic research to consistently characterize risk. Environmental Science and Technology, 54(19), 12307–12315. https://doi.org/10.1021/acs.est.9b02982

Kvale, K., Prowe, A. E. F., Chien, C.-T., Landolfi, A., & Oschlies, A. (2020). The global biological microplastic particle sink. Scientific Reports, 10(1), 16670. https://doi.org/10.1038/s41598-020-72898-4

Lavoie, J., Boulay, A.-M., & Buller, C. (2021). Micro- and nanoplastics in LCA: Development of an effect factor for the quantification of their physical impact on aquatic biota. Journal of Industrial & Ecological Engineering, 2021, 1–13. https://doi.org/10.1007/s10203-020-00316-7

Lusher, A., Bråte, I. L. N., Hurley, R., Iversen, K., & Olsen, M. (2017). Testing of methodology for measuring microplastics in blue mussels (Mytilus spp) and sediments, and recommendations for future monitoring of microplastics (R&D-project). 87(7209). https://doi.org/10.13140/RG.2.2.24399.59041

Lusher, A. L., Hurley, R., Arp, H. P. H., Booth, A. M., Bråte, I. L. N., Gabrielsen, G. W., Gomiero, A., Gomes, T., Grøsvik, B. E., Green, N., Haave, M., Hallberg, I. G., Halsband, C., Herzeke, D., Joner, E. J., Kögler, T., Rakkestad, K., Rannekleiv, S. B., Wagner, M., … Olsen, M. (2021). Moving forward in microplastic research: A Norwegian perspective. Environment International, 157, 106794. https://doi.org/10.1016/j.envint.2021.106794

Lusher, A. L., & Pettersen, R. (2021). Sea-based sources of microplastics to the Norwegian marine environment. In NIVA Report 7568–2021 for the Norwegian Environment Agency.

Malli, A., Corella-Puertas, E., Hajjar, C., & Boulay, A.-M. (2022). Transport mechanisms and fate of microplastics in estuarine compartments: A review. Marine Pollution Bulletin, 177, 113553. https://doi.org/10.1016/j.marpolbul.2022.113553
NCC SnowClean, Oslo. (2021). https://www.ncc.no/vare-prosjekter/ncc-snowclean-oslo/

Norconsult. (2019). Søknad om tillatelse til videre drift av snøsmelteanlegget ved Granlia. 11. statsforvalteren.no/contentassets/5b37a68c7f4b41cd8065bbee426b6cd/ncc-soknad.pdf

Pauna, V. H., Buonocore, E., Renzi, M., Russo, G. F., & Franzese, P. P. (2019). The issue of microplastics in marine ecosystems: A bibliometric network analysis. Marine Pollution Bulletin, 149(October), 110612. https://doi.org/10.1016/j.marpolbul.2019.110612

Peano, L., Kounina, A., Maagau, V., Chalumeau, S., Zgola, M., & Boucher, I. (2020). Plastic leak project methodological guidelines. https://quantis-intl.com/report/the-plastic-leak-project-guidelines/

Pohl, F., Eggenhuisen, J. T., Kane, I. A., & Clare, M. A. (2020). Transport and burial of microplastics in deep-marine sediments by turbidity currents. Environmental Science & Technology, 54(7), 4180–4189. https://doi.org/10.1021/acs.est.9b07527

Pohle, D. E., Schøyen, M., Øxnevad, S., Gerhards, R., Böhmer, T., Koerner, M., Durham, J., & Huff, D. W. (2018). Bioaccumulation and trophic transfer of cyclic volatile methylsiloxanes (cVMS) in the aquatic marine food webs of the Oslofjord, Norway. Science of the Total Environment, 622(623), 127–139. https://doi.org/10.1016/j.scitotenv.2017.11.237

Romero-Franco, M., Godwin, H. A., Bilal, M., & Cohen, Y. (2017). Needs and challenges for assessing the environmental impacts of engineered nanomaterials (ENMs). Beilstein Journal of Nanotechnology, 8, 989–1014. https://doi.org/10.3762/bjnano.8.101

Statistics Norway. (2020). 12576: Kjørelengder, etter eierens bostedsfylke, hovedkjøretøytype og drivstofftype (F) 2005–2020. https://www.ssb.no/statbank/table/12576/tableViewLayout1/

Sundt, P., Schulze, P.-E., & Syversen, F. (2014). Sources of microplastic-pollution to the marine environment [Project report].

Sundt, P., Syversen, F., Skogesal, O., & Schulze, P.-E. (2016). Primary microplastic-pollution: Measures and reduction potentials in Norway.

van Eck, N. J., & Waltman, L. (2022). VOSViewerVersion (1.6.18). VOSViewer visualizing scientific landscapes. Universiteit Leiden & CWTS. https://www.vosviewer.com/

van Emmerik, T. (2021). Macroplastic research in an era of microplastic. Microplastics and Nanoplastics, 1(1), 4–5. https://doi.org/10.1186/s43591-021-00003-1

Vázquez-Rowe, I., Ita-Nagy, D., & Kahhat, R. (2021). Microplastics in fisheries and aquaculture: implications to food sustainability and safety. Current Opinion in Green and Sustainable Chemistry, 29, 100464. https://doi.org/10.1016/j.cogsc.2021.100464

Vogelsang, C., Lusher, A. L., Dadkhah, M. E., Sundvor, I., Umar, M., Ranneklev, S. B., Eidsvoll, D. P., & Meland, S. (2020). Microplastics in road dust—Characteristics, pathways and measures. Report for Miljødirektoratet M-959. 174pp.

Wang, D., Tang, Y-T., Sun, Y., & He, J. (2022). Assessing the transition of municipal solid waste management by combining material flow analysis and life cycle assessment. Resources, Conservation and Recycling, 177, https://doi.org/10.1016/j.resconrec.2021.105966

Woods, J. S., Verones, F., Jolliet, O., Vázquez-Rowe, I., & Boulay, A.-M. (2021). A framework for the assessment of marine litter impacts in life cycle impact assessment. Ecological Indicators, 129(July), 107918. DOI:10.1016/j.ecolind.2021.107918

Xanthos, D., & Walker, T. R. (2017). International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): A review. Marine Pollution Bulletin, 118(1–2), https://doi.org/10.1016/j.marpolbul.2017.02.048

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Pauna, V. H., & Askham, C. (2022). Using information flow analysis to establish key data gaps in the assessment of marine microplastic pollution. Journal of Industrial Ecology, 26, 1895–1907. https://doi.org/10.1111/jiec.13312