Plastic pollution research in Indonesia: state of science and future research directions to reduce impacts

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Abstract

Several studies have suggested Indonesia to be among the top plastic polluting countries globally. Data on the presence and amounts of plastic pollution are required to help design effective plastic reduction and mitigation strategies. Research quantifying plastic pollution in Indonesia has picked up in recent years. However, a lack of central coordination in this research has led to research output with different goals, methods, and data formats. In this study we present a meta-analysis of studies published on plastic pollution in Indonesia to uncover gaps and biases in current research, and to use these insights to suggest ways to improve future research to fill these gaps. Research gaps and biases identified include a clear preference for marine research, and a bias towards certain environmental compartments within the marine, riverine, and terrestrial systems that have easy to apply methods. Units of measurement used to express results vary greatly between studies, making it difficult to compare data effectively. Nevertheless, we identify polypropylene (PP) and polyethylene variants (PE, HDPE, LDPE) to be among the most frequently found polymers in both macro- and microplastic pollution in Indonesia, though polymer identification is lacking in a large part of the studies. Plastic research is mostly done on Java Island (49 studies, 59%). We recommend research methods used to quantify plastic pollution to be harmonized. Moreover, we recommend a shift in focus of research towards the riverine and terrestrial environments and a shift of focus of environmental compartments analyzed within these systems, an increase in spatial coverage of research across Indonesia, and lastly, a larger focus on polymer characterization. With these changes we envision future research which can aid with the design of more effective and targeted reduction and mitigation strategies.

1 Introduction

Plastic pollution has been a topic of rising environmental concern in recent years. Model estimates show that between 0.8-30 million metric tonnes of plastic waste enter the marine environment annually around the globe (Borrelle et al., 2020; Lau et al., 2020; Meijer et al., 2019). The majority of plastic pollution is generated on land and transported through rivers to the marine environment (Lebreton & Andrady, 2019; Schmidt et al., 2017; Pawar et al., 2016). Plastic pollution can have adverse effects in all three of these systems, which include mortality of fauna through ingestion or entanglement, reduction of livelihoods of those dependent on ecosystem health (e.g. fishing and tourism), contamination of seafood with microplastics with implications for food safety and human health, property damage, and an increased risk of floods in urban areas (van Emmerik & Schwarz, 2020; Gall & Thompson, 2015; Hantoro et al., 2019; Koelmans et al., 2017; Conchubhair et al., 2019; Honingh et al., 2020).

Indonesia is estimated to be among one of the top emitting countries of plastic pollution in the world (Lebreton et al., 2017). This is supported by a comparative study of previously published field observations, which ranked drains in Jakarta (Indonesia Capital City) among the highest polluting rivers globally (van Calcar & van Emmerik, 2019). Plastic pollution found in the Indonesian Seas not only comes from inland, but also from several countries surrounding it. The ocean currents transport this plastic pollution to the inner seas (Purba et al., 2021). High plastic emission rates are hypothesized to be caused by Indonesia's high population densities in coastal areas in combination with improper waste management and insufficient service coverage (Lebreton & Andrady, 2019; Lestari & Trihadiningrum; 2019). Indonesia is located within the Coral Triangle, a hotspot for global marine biodiversity which is highly susceptible to the negative effects of plastic pollution (Tomascik et al., 1997; Spalding et al., 2001; Lasut et al., 2018). Reducing plastic emissions in Indonesia will therefore have a large impact on both reduction of global plastic emissions to the oceans, and on protecting global biodiversity. The Indonesian government has committed to reduce plastic pollution. To this end, it has set a target to improve solid waste management (Presidential Decree No 97/2017) as well as the goal to reduce marine plastic debris by 70% in 2025. This commitment is followed up by the establishment of the national action plan for marine debris management 2018 – 2025 (Presidential Decree No. 83/2018).

Reliable and frequent data on plastic pollution and its effects on fauna and ecosystems are required for the development and assessment of policy measures aimed to reduce plastic emissions to the oceans (Conchubhair et al., 2019; Owens & Kamil, 2020; Vriend et al., 2020). Moreover, data on exposure and toxicity are needed to assess microplastics' human health risks from exposure to, for example, contaminated seafood (Hantoro et al., 2019). Plastic pollution has been extensively studied in Indonesia (e.g. Uneputty et al., 1997; Rochman et al., 2015; Cordova & Wahyudi, 2016; Van Emmerik et al., 2019; Syakti et al., 2017). However, observations are scattered across the country and vary widely in the methods that are used. To gather reliable and frequent data, a nationally coordinated monitoring strategy is required which, in turn, will form the basis for prioritizing and designing effective plastic pollution reduction and mitigation strategies.

This review study provides an overview of the current state of knowledge on plastic pollution in Indonesia and provides insights into current research biases and knowledge gaps. We then use these data to suggest ways forward for plastic research in Indonesia to overcome these gaps. This overview was gathered through a review of current literature on plastic pollution in Indonesia, and through performing a meta-analysis of the 83 identified peer-reviewed articles. The goal of this study is to provide insights on what types of research questions should be answered to fill research gaps, with the aim of having a clear picture for effective policy measures to be implemented and their efficacy to be monitored.

2 Methodology

2.1 Literature review

The literature search was performed using a snowball method. First, a literature search was performed in the Google Scholar and ResearchGate databases, using different combinations of the following keywords: plastic, macroplastic, microplastic, litter, marine, river, Indonesia, debris, and waste. Studies that quantified plastic pollution in Indonesia were selected. Second, selected articles were scanned for references to other studies concerning plastic pollution in Indonesia. These studies were then also added to the review. Lastly, a large group Indonesian researchers specialized in plastic pollution was asked to identify any literature missing in the review. These studies were also added to the literature review. The literature search was concluded on October 1, 2020. Studies published after this date have therefore not been included in the subsequent analysis. The corresponding author of this paper read all identified literature (n = 83), and the following information was extracted to a unique dataset:

1) The environmental system which was studied for plastic pollution (e.g. terrestrial, river, ocean)
2) The compartment in the system that was studied for plastic pollution (e.g. floating plastic, in the water column, beached plastic, plastic in biota)
3) The location of the study (coordinates)
4) The size of plastic that was studied (e.g. microplastic, macroplastic, or both)
5) The year the study was published
6) The institutions the authors were affiliated to
7) The top three most frequently found plastic polymer types and/or shapes that were reported in the study
8) The units in which the data were reported

2.2 Meta-analysis

The dataset created through the literature review was used for several analyses, including a spatial analysis of research locations, an analysis of research output over time, an analysis of units of measurement in which the data were reported, and an analysis of most frequently found polymers and shapes.

The majority of the literature identified during the review used a size classification that deviated from more recent definitions. For example, van Emmerik & Schwarz (2020) define four size classes of plastic pollution, these being macro- (>50 mm), meso- (5-50 mm), micro-(0.1 µm – 5 mm), and nanoplastic (<0.1 µm). Most literature identified during the review aggregate nano- and microplastic and call this size range microplastic (<5 mm), and aggregate meso- and macroplastic and call this size range macroplastic (>5 mm). To avoid confusion during the analysis it was decided to use the same terminology as used in the identified literature.

The spatial analysis of research locations was performed by importing the logged coordinates into ESRI ArcMap, plotting the latitude and longitude data, and aggregating the point data to Indonesia's administrative sub-regions. The shapefiles on sub-regions of Indonesia were retrieved from DIVA-GIS (n.d.). Point data within a specific region were then aggregated and summed to determine the total amount of studies per region. Point data in the open sea were aggregated to their closest landmass.

For each study, where possible, the top three most frequently found shapes, and polymers were noted. The number of studies in which each shape and polymer were present in the top three was then counted to determine those most frequently found items in plastic pollution in Indonesia.

3 Results and discussion

3.1 Research per size category and environmental system

A total of 83 studies were considered for the meta-analysis (Table 1). The majority of studies on plastic pollution in Indonesia quantify macroplastic pollution (40), a smaller group quantified microplastics (37), and a handful of studies quantified both (6). This is in contrast with the findings on global plastic research by Blettler et al. (2018), who found that microplastic is most frequently studied on a globally. We suspect that the lower number of microplastic studies is due to the limited availability of research equipment and suited laboratories in Indonesia, as well as the absence of a standardized protocol for monitoring microplastics (Michida et al., 2019). Plastic pollution is most frequently studied in the marine environment, with 68 papers studying marine plastic, compared to 10 studies in the riverine and 3 in the terrestrial environments.

Table 1 - Overview of studies included in the meta-analysis sorted by environmental system and size class of plastic considered. Note, we only considered the categories microplastic (<0.5 cm) and macroplastic (>0.5 cm).

Environmental system	Number of studies	Macroplastic	Microplastic	Macro- and Microplastic
Terrestrial	3	3	0	0
Riverine	10	5	5	0
Marine	68	30	32	6
Riverine + Marine	1	1	0	0
Terrestrial + Riverine + Marine	1	1	0	0
Total	**83**	**40**	**37**	**6**

Within environmental systems, there is a bias to study specific sub-compartments (Table 2). For example, plastics on the beach and floating plastic are most frequently studied for the marine environment (29 and 15 out of 77 studies respectively), while the water column (9 out of 77), seafloor sediment (9 out of 77) biota (7 out of 77), and mangroves (4 out of 77) receive less attention. A similar bias can be identified in riverine plastic research, where most research so far has been done on floating plastics (5 out of 15) and plastics in the water column (4 out of 15), while research on other compartments such as the riverbank (2 out of 15), riverbed (2 out of 15), or in biota (2 out of 15) are lagging behind.

The observed bias can be attributed to the type of research method available for each system compartment. Some methods used to quantify plastics in aquatic environments are cheaper and easier to apply than others, leading to a preference of application. For example, method to quantify riverine macroplastic on the river surface or the riverbanks can be easily applied without any heavy and/or expensive equipment (e.g. González-Fernández & Hanke, 2017; van Emmerik et al., 2018; Vriend et al., 2020; Cordova et al., 2021), and are therefore most frequently applied in river systems. Similarly, the analysis of beached plastic and floating plastic in the marine environments can be done by visual observation, and therefore do not require any large equipment (e.g. OSPAR Commission, 2010). The limited number of research dealing with microplastic measurement and identification so far can also be attributed to the fact that research institutions in Indonesia are still building their capacity to perform proper microplastic analyses. However, some progress on the development of standard methods for microplastics analysis has already taken place (e.g. Hantoro et al., 2020).

Table 2 - Overview of studies included in the meta-analysis, categorized by the environmental system and relevant sub-compartment that is studied. Totals add up to over 83 since a handful of studies quantified multiple environmental compartments and/or environmental systems. Note, review category includes studies that present overviews of a subset of studies included in this papers (e.g. floating plastic in marine environments).

Compartment	**Marine**	**Riverine**	**Land**	**Total**
Floating	15	5	0	20
Column	9	4	0	13
Sediment	9	2	0	11
Riverbank/beach	29	2	0	31
Biota	7	2	0	9
Mangrove	4	0	0	4
Land surface	0	0	0	0
Waste management	0	0	2	2
Review	4	0	0	4
Other	0	0	2	2
Total	77	15	4	

3.2 Research output over time

Similar to findings by Blettler et al. (2018), Indonesian plastic pollution research has been dominated by marine plastic research. Plastic pollution in the Indonesian marine environment was observed and reported starting from 1986 (Willoughby, 1986), with a total of six papers that flagged plastic pollution on Indonesia beaches being published in the period between 1986 and 2013. These studies were qualitative in nature and did not quantify the plastics which were observed. Papers that quantified plastic pollution started to be published around the year 2013 (Fig. 1). Since 2013, 77 papers on plastic pollution were published in peer reviewed journals, of which 67 were focused on the marine environment. Studies on plastic pollution in the riverine environment started being published in 2018, with 18 studies quantifying riverine plastic pollution. The terrestrial environment is the least studied system, with only four studies having been identified, all of which were published since 2019.

The focus on plastic pollution can be explained by the fact that a large portion of the Indonesian population's livelihoods depends on it. Approximately 16.11 million tourists visited the country in 2019 (Statistics Indonesia, 2020), with the pristine beaches and coral reefs being an essential part of their visit (Akhlas, 2020). Marine plastic pollution can negatively impact tourism revenue (Jang et al., 2014; Petten et al., 2020), which can explain the fact that studies quantifying plastic pollution in the marine environment outnumber studies quantifying plastic pollution in the riverine and terrestrial environments. Another explanation to the marine environment bias is that microplastic is considered a novel contaminant expected to pose food safety risks due to consumption of coastal seafood, i.e. bivalves, shellfish and fish (Hantoro et al., 2019). Accordingly, several studies have found microplastics contamination in commercial edible fishes and bivalves in Indonesia (Rochman et al., 2015; Khoironi et al., 2018; Hastuti et al., 2019; Cordova et al., 2020).

To better understand potential sources of plastic pollution, more research is needed to determine the type and sources of pollution in the riverine and terrestrial systems of Indonesia. Rivers are widely regarded as the largest sources of marine plastics (Li et al., 2016; van Emmerik & Schwarz, 2020). Plastic pollution is in turn produced through the consumption and improper disposal of waste on land, and is transported to the oceans by rivers (Lebreton & Andrady, 2019, Schmidt et al., 2017; Lestari & Trihadiningrum. 2019). Here, plastic pollution is dispersed over a large volume of water, which causes the plastic pollution to be more diluted in the ocean compared to plastic pollution in the riverine and terrestrial environments. Quantifying plastic pollution earlier in its journey from land to sea allows for the quantification of more plastic while using fewer resources. We, therefore, underscore the importance of the shift towards the monitoring of plastic pollution in the riverine and terrestrial environments.

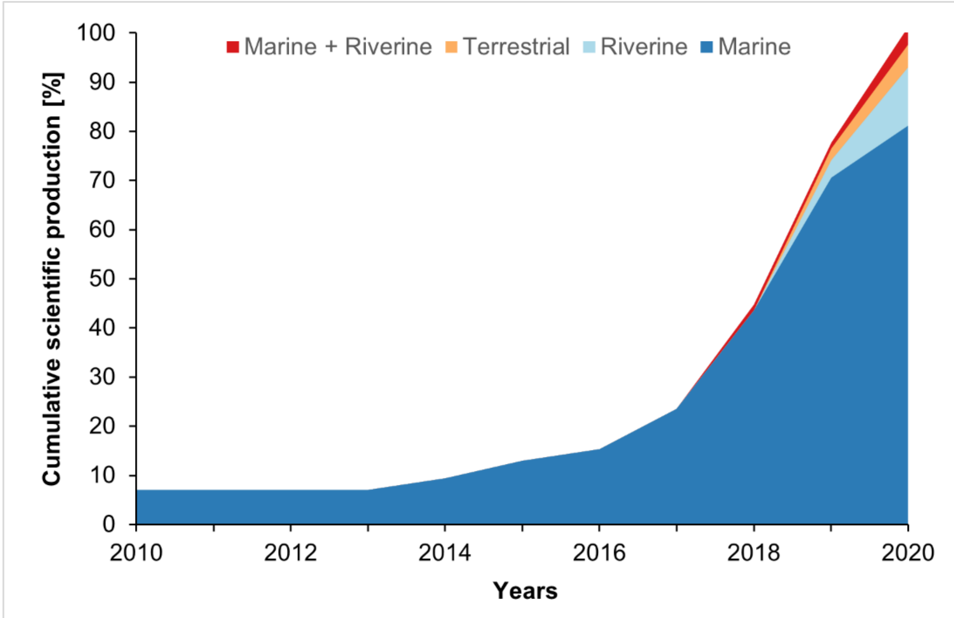

Figure 1 – Research output on plastic pollution in Indonesia per environmental system over time. Dark blue represents studies concerning plastic pollution in the marine environment, light blue represents studies concerning pollution in the riverine environment, orange represents research studies concerning plastic pollution in the terrestrial environment, and red represents studies concerning both marine and riverine environment. Output from 1986 – 2009 was omitted due to incompatibility to current scientific standards, output for 2020 was cut off on 1 October 2020.

3.3 Units of measurement in plastic research

While all research considered in this study quantifies plastic pollution in some capacity, the units of measurements in which they report their findings differ greatly. Such differences create difficulties when comparing data from multiple studies since some units are not compatible with each other. Studies on macroplastic pollution in Indonesia generally use two types of units to express their results in. They either express results in items per area, volume or sample, or in a mass per area, volume or sample (Table 3). While some studies report in both types of units (e.g. van Emmerik et al., 2018; Cordova & Nurhati, 2019; Cordova et al., 2021), a large part only reports in one type.

The usage of different units in macroplastic research leads to two challenges when trying to compare data from different studies. First, data expressed in items per sampling unit cannot be directly converted into data expressed in mass (e.g. kg) per sampling unit. Previous studies on floating macroplastic pollution in rivers have tried to solve this issue using a conversion rate based on the average mass of macroplastics in rivers (Castro-Jimenez et al., 2019). However, this increases uncertainty in the results due to the variability in plastic pollution characteristics between different locations. A second problem relates to the sampling unit used. When ignoring the fact that data are expressed in either items or kg, a range of sampling units is used, including macroplastic per volume, per area, and per sample (Table 3). These differences stem from the use of different methods to quantify plastic pollution across environmental compartments (e.g. a sample of water is expressed in volume while a beach sample is taken in a certain area).

Similarly, data presented in microplastic research are difficult to compare because a wide range of sampling units are used. While most microplastic research expresses their results in terms of particles per sampling unit (Table 3), the sampling units range from particles per volume, mass, and mass of tissue. Again, these differences are caused by the methods that are utilized for each environmental compartment: volumetric samples are mostly taken in the water column, tissue samples are taken from biota, and area samples are taken from riverbanks, beaches, and from sediment at the bottom of the waterbody (Table 3). While these units allow for the comparison of data between studies that examine the same environmental compartment, the differences in sampling units do not allow for an integrated comparison of plastic pollution in all river compartments.

Besides the size class, the differences in the presentation of data also hinder comparing data between different environmental systems. The nature of the measurements that are done in each system differ. For example, plastic pollution in the marine environment is often quantified in terms of concentration (e.g. kg or items per sample), while plastic pollution in the riverine environment is mostly quantified in terms of flux (e.g. kg/day, items/day) (Table 3). These differences are caused by the environmental system itself since rivers are often seen as a "conveyor belt" for pollution to be transported to the oceans. It is therefore important to consider these factors when trying to compare data between the two environmental systems.

Standardization of protocols is needed to allow for better data comparison. Such a protocol should include what units should be used for reporting data in each environmental compartment. This would facilitate combining and analyzing data from different studies on the same environmental compartments. Such analysis would lead to better insights into the plastic pollution problem across Indonesia. Standardization would also allow for a more convenient comparison of data between different environmental compartments. For example, by ensuring that the mass of items found is included in such a protocol, data can be expressed in both items and kg per sampling unit.

Table 3 - Overview of units used to express plastic pollution in marine and riverine systems and each of the environmental compartments. The terrestrial environment was excluded from this table due to the low number of studies performed in this system.

	Ocean		**River**	
Compartment	**Micro**	**Macro**	**Micro**	**Macro**
Floating	particles/m^3 particles/m^2	items/m^2 kg/100m^2 kg/survey	particles/m^3 particles/l	kg/year tons/day
Riverbank/beach	particles/m^3 particles/kg	items/m^2 m^3/m^2 kg/m^2	-	kg/m^2 kg/hour
Column	particles/l particles/m^3	Items/m^3	particles/l	-
Sediment	particles/sample particles/kg particles/100 g dry weight	kg/sample item/sample	particles/m^3 particles/100g sediment	
Biota	particles/organ particles/animal particles/g dry weight	-	particles/fish particles/m^3	-
Mangrove	particles/m^2 kg/m^2	items/kg dry weight	-	-

3.4 Frequently found materials and shapes

A small portion of studies quantifying plastic pollution in Indonesia report polymer types of the plastic (9 out of 46 for macroplastic, 10 out of 43 for microplastic, Table 4). When polymers are reported, polypropylene (PP) is the most often found polymer type in both macroplastic (56%) and microplastic (90%) pollution. Polyethylene (PE), and its high- and low-density variants (HDPE, LDPE) are also among the most abundant plastics for both macro- and microplastic. Other polymers found in Indonesian aquatic environments include polystyrene (PS) and expanded polystyrene (EPS).

Polymer characterization makes plastic research more labor-intensive, but should be included more frequently in plastic pollution studies. Polymer characterization is easier for macroplastic than for microplastic since certain items have identification codes or logos indicating what polymer types they are made of. Besides, macroplastic characterization can be simplified by grouping difficult to distinguish polymers, or by using an item list that indicates what polymers items are most frequently made of (e.g. van Emmerik et al., 2018; Vriend et al., 2020). Microplastic polymers are often characterized using a form of spectroscopy (e.g. Fourier transform infrared, Raman) and thermal analysis (e.g. py-GC-MS), which greatly increases the labor required to gather data (Shim et al., 2017). The characterization of polymers is one of the few ways to compare macroplastic and microplastic presence directly. Besides, polymer types may give an indication of possible sources of plastic pollution. Polymer characterization should therefore be encouraged to be included in studies on plastic pollution in Indonesia more often.

Table 4 - Count of polymers found in top three most abundant polymers per study, with abbreviations for the following polymer types: polypropylene (PP), polystyrene (PS), low density polyethylene (LDPE), expandable polystyrene (EPS), polyethylene terephthalate (PET), polyethylene (PE), high density polyethylene (HDPE), and polyamide (also known as nylon, PA).

	Studies that reported polymers	**Percentage of studies that present polymer types in top 3 frequently found polymers**							
		PP	**PS**	**LDPE**	**EPS**	**PET**	**PE**	**PA**	**HDPE**
Macro (n=46)	9	56%	33%	33%	22%	11%	22%	0%	11%
Micro (n=43)	10	90%	20%	30%	10%	0%	40%	20%	0%

More than half of the studies that studied microplastic pollution characterized the shape of the particles (24 out of 43, Table 5). This is in line with the fraction of global microplastic studies that report shapes found by Koelmans et al. (2019). Among the top three most abundant particles, shapes that are more frequently are fragments (71%), fibers (63%), and films (46%). Shapes that are less frequently found among the top three most abundant shapes are granules and foams (both 21%). The shape of particles can be an indication of the possible sources of the microplastic, though the applicability of this is still limited. Several potential sources of particular shapes of microplastic particles have been studied by Free et al. (2014). However, no studies considered in this meta-analysis tried to identify sources based on the shape of particles. Moreover, Kooi & Koelmans (2019) argue that the shape of particles is continuous, and therefore no classification will be able to accurately capture the full variability of shapes. One of the particular reasons for this situation is complex degradation mechanisms (photodegradation, mechanical-physical, weathering, even biodegradation) that continuously occur in nature, which may breakdown larger plastics into microplastics (Kooi et al., 2019).

Table 5 - Count of microplastic shapes found in the top three most abundant shapes per study.

		Percentage of studies that present each shape in the top 3 most abundant shapes				
	Reported shape	**Fragment**	**Fiber**	**Film**	**Granule**	**Foam**
Micro (n=43)	24	71%	63%	46%	21%	21%

3.5 Locations of studies

Plastic research for all size classes and environmental systems is highly localized on Java Island, especially for riverine and terrestrial focused studies (Fig. 2). Studies that quantify plastic pollution in the marine environment are more evenly spread across Indonesia, though Java Island is still represented in almost half of all studies (32 out of 67) focused on marine plastic pollution in seas near Java. Studies quantifying plastic pollution in rivers are either performed on Java (14 out of 15) or Bali Islands (1 out of 15). The same goes for terrestrial focused studies, with so far only 3 being done on Java and 1 on Bali Islands.

Although a larger spread would be ideal, this strong focus on Java Island is reasonable since it houses a large part of the Indonesian population. Lebreton et al. (2017) identified Java and Sumatra Islands to be areas of concern with their estimates predicting these islands to be responsible for 14.2% of global annual plastic exports to the oceans. More recently, Meijer et al. (2019) identify 51 rivers on Java Island to be among the global top 1000 most polluting river. However, Java is not the only Indonesian island with high rates of plastic pollution. Data from all Indonesian islands are required to design and prioritize reduction and mitigation strategies, requiring a larger spatial spread of studies.

Another factor that could explain the research focus on Java is the location of Indonesian institutes that research plastic pollution. Many of these institutes are located on Java island, especially in the Jakarta metropolitan area (Fig. 3). Besides Java, institutes with relatively large plastic research output are located on Sumatra, Bali, and Sulawesi Islands, and the city of Makassar (Fig. 3). When comparing the locations of these institutes with the numbers of studies aggregated to the regional level (Fig. 2), it can be concluded that regions with large amounts of studies coincide with the locations of specialized institutes, indicating that research is mostly done close to these institutes.

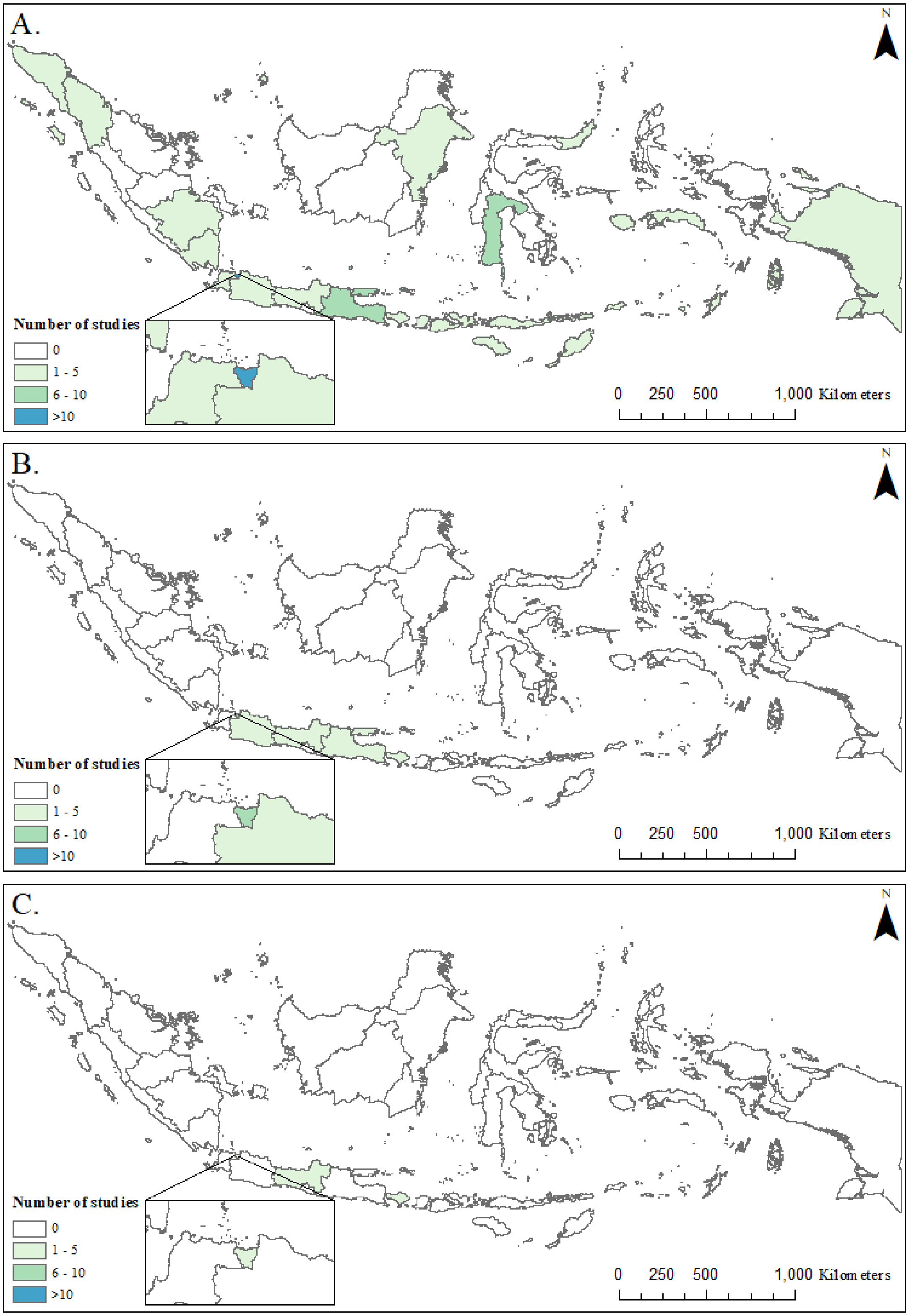

Figure 2 - Number of plastic pollution studies performed in Indonesia aggregated to sub-regions, where A. depicts marine focused literature (land mass closest to research area), B. depicts studies focused on rivers literature, and C. represents land focused research

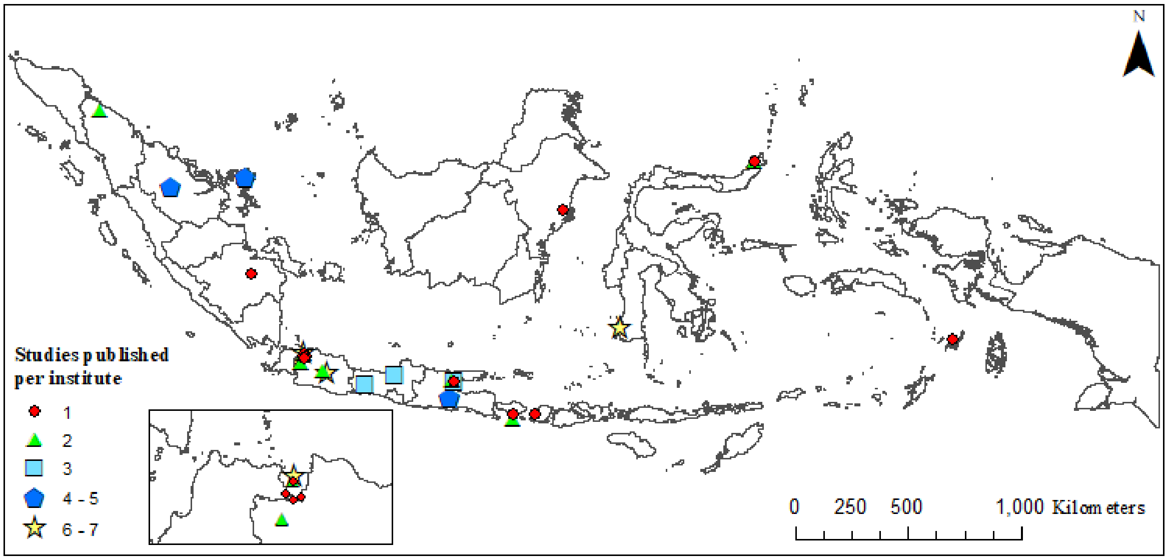

Figure 3 - Location of institutes that published on plastic pollution in Indonesia, and the number of publications they (co-) authored, where red circles indicate 1 study, green triangle represents 2 studies, blue square represents 3 studies, blue pentagon represents 4-5 studies, and the yellow start represents 6-7 studies (co-) published per institute.

4 Future plastic pollution research directions in Indonesia

Based on the biases and gaps identified in the meta-analysis, we propose four directions for future research: 1) Standardization of research methods, 2) expansion of environmental system focus, 3) expansion in spatial coverage, and 4) expansion in plastic characterization methods. These suggestions aim to ensure reliable and intercomparable data on plastic pollution in Indonesia, which can aid the design of plastic removal and mitigation strategies.

4.1 Harmonization of research methods and data

We recommend establishing standard research methods for each environmental system and sub-compartment in Indonesia. Standardizing methods ensures homogeneity in the data gathered and shared by different studies. Current methods differ per study, geographical area, and research group, which causes data to be expressed in different units of measurement and plastic items to be categorized differently. This complicates the comparison of data between studies. Standardized methods can alleviate this problem and would supply easier to interpret data for policy makers, which will hopefully lead to tailored mitigation and removal strategies.

We suggest a national Indonesian scientific authority to set these standard methods in collaboration with local and international experts. First efforts for standardization have been recently published by the Indonesian Institute of Sciences (LIPI) (Nurhati & Cordova, 2019). Moreover, three institutions (LIPI, DCA, and Universitas Padjadjaran) have built marine debris database to centralize data (https://marinedebris.id). We recommend this process to be further expanded for method standardization and data harmonization of plastic in all environmental systems and sub-compartments.

4.2 Expansion of environmental system focus

A shift in research prioritization on specific environmental systems is required to get an accurate overview of plastic pollution in Indonesia. In the current form, plastic research mainly focuses on the marine environment, which is in line with global research trends (Blettler et al., 2018). However, plastic pollution abundance in the marine environment is diluted compared to riverine pollution. For example, macroplastic pollution concentrations on riverbanks in Indonesia found in this meta-analysis ranged between 0.007-0.029 kg/m^2, or 7000 – 29000 kg/km^2 (Widyarsana et al., 2020; Owens & Kamil. 2020), while concentrations of floating macroplastics in the great pacific garbage patch are estimated to range between 10 – 100 kg/km^2 (Lebreton et al. 2018). Such dilution makes the determination of possible sources, and the removal of plastic pollution more difficult. Therefore, knowledge on plastic pollution transport earlier in its presence is important for the design of effective removal and mitigation strategies. The research focus should, therefore, be moved higher up in the transport chain, ideally at the source, as well.

The focus of future research should also diversify in terms of compartments within environmental systems. The meta-analysis shows that specific compartments within environmental system are studied more than others (e.g. beaches in the marine environment, floating and riverbank in the riverine environment). This is mainly due to these compartments being more accessible and having easy to apply methods. However, only quantifying plastic pollution in these compartments gives a biased view of the problem. Therefore, we recommend to keep observing pollution in these compartments while also expanding to lesser studied compartments such as sub-surface plastics in the marine and riverine environments, and surface pollution in the terrestrial environment.

4.3 Expansion in spatial coverage

Plastic research in all environmental systems should have a broader spatial coverage in Indonesia. While plastic pollution has been quantified at least once in places with high population densities, research is biased towards Java Island. This bias is more pronounced in riverine and terrestrial research where all but one study has been performed on Java Island. While Java Island is predicted to have a considerable contribution towards plastic exports to the ocean by models (e.g. Lebreton et al., 2017), data on plastic pollution in all of Indonesia's geographic areas are required in order to set priorities for mitigation and removal strategies. We, therefore, recommend expanding the spatial coverage to all major islands of Indonesia, while keeping research focus on areas with predicted high pollution rates such as Java and Sumatra Islands. Additionally, Purba et al. (2021) mention that plastic pollution is a transboundary issue in south-east Asian countries. We therefore also suggest that research should expand to boundary seas. Indonesia has six surrounding countries and more collaboration is needed to mitigate plastic pollution. Increasing insight into how plastic pollution transboundary patterns would help stress the urgency and direction of this transnational collaboration.

4.4 Expansion in plastic characterization methods

We recommend both macro- and microplastic characterization to be expanded by performing research on both size categories at the same location. 77 out of 83 studies in this meta-analysis characterize just one plastic size category (macro- or microplastic). Integrating macro- and microplastic research at the same location allows for comparisons to be made between the two size classes. This would, in turn, allow for more accurate determination of possible sources of plastic pollution, and provide insights in the relation between presence of macro- and microplastic. Such insights could allow for macroplastic research to act as a proxy for microplastic pollution and reduce the need for microplastic research, possibly saving valuable time and resources (Vriend et al. 2020). However studies on microplastics occurence and distribution might still be of value since they can portray the past behaviour of the community in plastic use and disposal.

Characterization methods can be further expanded by including polymer analysis more frequently. 19 out of 83 studies considered in this meta-analysis characterized plastic polymers found. Increasing the number of studies that identify polymers allows for data to be more easily compared between different environmental systems, compartments, and size classes. This data can in turn be used for the design of more targeted mitigation and removal strategies. We, therefore, recommend increasing the frequency of polymer analysis in future research.

5 Conclusions

Indonesia is suspected to be among the top plastic polluting countries in the world. A large body of research has been published that quantifies plastic pollution with the aim to facilitate the design of effective mitigation and removal strategies. In this study we perform a meta-analysis of this body of literature to identify research biases and gaps, with the goal to streamline future research.

The majority of the research output on plastic pollution in Indonesia has focused on the marine environment (70 out of 83 studies), with first efforts to quantify plastic pollution in other environmental systems (riverine and terrestrial environments) recently being undertaken on Java Island. Research within environmental systems is biased towards compartments that are easy to access and have already established research methods. These compartments include the beach for marine plastic pollution, and floating and riverbank plastics for riverine plastic pollution. Considering research output since 2010, macroplastic pollution has been studied more frequently than microplastics (43 and 40 studies respectively), and research within environmental systems is biased towards a size class as well. For example, microplastic is mostly characterized in the marine environment, while macroplastic is mostly studied in the riverine environment. Methods, and with it the measurement units in which data is expressed, vary widely between studies, which complicates comparison between studies. Last, the plastic research focus is highly area focused, with almost half of all studies being focused on Java Island.

We recommend four good practices for future research which can provide data that can aid the Indonesian government with designing monitoring strategies to reduce plastic pollution more effectively. These being 1) the harmonization of research methods, and therefore units used, for each environmental systems and sub-compartments across Indonesia, 2) a shift in research focus expanding beyond the marine environment towards riverine and terrestrial plastic pollution research, 3) an expansion in spatial coverage to ensure more representative research taking place in the whole of Indonesia, and 4) an expansion in methods used to characterize plastic pollution, especially in terms of polymer type.

6 Author Contributions

PV, TvE, and H conceived the idea. PV performed the literature search, extracted data from the identified literature, performed the data analysis, and prepared the initial draft. All authors identified missing literature and wrote the final manuscript.

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8 List of references

Akhlas, A. W. (2020) Indonesia welcomes 16.1m foreign tourists in 2019, coronavirus clouds tourism outlook. *The Jakarta Post*. Accessed on 27-10-2020 via: https://www.thejakartapost.com/news/2020/02/03/indonesia-welcomes-16-1m-foreign-tourists-in-2019-coronavirus-clouds-tourism-outlook.html

Blettler, M. C., Abrial, E., Khan, F. R., Sivri, N., & Espinola, L. A. (2018). Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. *Water research*, *143*, 416-424.

Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., ... & Eriksen, M. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science, 369*(6510), 1515-1518.

Castro-Jiménez, J., González-Fernández, D., Fornier, M., Schmidt, N., & Sempéré, R. (2019). Macro-litter in surface waters from the Rhone River: Plastic pollution and loading to the NW Mediterranean Sea. *Marine pollution bulletin*, *146*, 60-66.

Conchubhair, D. Ó., Fitzhenry, D., Lusher, A., King, A. L., van Emmerik, T., Lebreton, L., ... & O'Rourke, E. (2019). Joint effort among research infrastructures to quantify the impact of plastic debris in the ocean. *Environmental Research Letters*, *14*(6), 065001.

Cordova, M. R., & Wahyudi, A. (2016). Microplastic in the deep-sea sediment of southwestern Sumatran Waters. *Marine Research in Indonesia*, *41*(1), 27-35.

Cordova, M. R., & Nurhati, I. S. (2019). Major sources and monthly variations in the release of land-derived marine debris from the Greater Jakarta area, Indonesia. *Scientific Reports*, 9(1), 1-8.

Cordova, M. R., Riani, E., & Shiomoto, A. (2020). Microplastics ingestion by blue panchax fish (Aplocheilus sp.) from Ciliwung Estuary, Jakarta, Indonesia. *Marine Pollution Bulletin*, 161, 111763. https://doi.org/https://doi.org/10.1016/j.marpolbul.2020.111763

Cordova, M. R., Nurhati, I. S., Riani, E., Nurhasanah, & Iswari, M. Y. (2021). Unprecedented plastic-made personal protective equipment (PPE) debris in river outlets into Jakarta Bay during COVID-19 pandemic. *Chemosphere*, 268, 129360. https://doi.org/https://doi.org/10.1016/j.chemosphere.2020.129360

Free, C.M., Jensen, O.P., Mason, S.A., Eriksen, M., Williamson, N.J., Boldgiv, B. (2014). High levels of microplastic pollution in a large, remote, mountain lake. *Marine Pollution Bulletin, 85*, 156-163.

Gall, S. C., & Thompson, R. C. (2015). The impact of debris on marine life. *Marine pollution bulletin*, *92*(1-2), 170-179.

DIVA-GIS (n.a.). Indonesia – Administrative areas. Accessed on 16-10-2020 via: http://www.diva-gis.org/gData

González-Fernández, D., & Hanke, G. (2017). Toward a harmonized approach for monitoring of riverine floating macro litter inputs to the marine environment. *Frontiers in Marine Science*, *4*, 86.

Hantoro, I., Löhr, A. J., Van Belleghem, F. G., Widianarko, B., & Ragas, A. M. (2019). Microplastics in coastal areas and seafood: implications for food safety. *Food Additives & Contaminants: Part A*, *36*(5), 674-711.

Hantoro, I., Widianarko, Y. B., & Retnaningsih, C. (2020). Protokol HW1-TP UNIKA: Metode Deteksi dan Identifikasi Mikroplastik dengan ATR-FTIR Mikroskopi pada Sampel Hasil Laut. Wahana Resolusi, Yogyakarta. *Unika Repository*.

Hastuti, A. R., Lumbanbatu, D. T., & Wardiatno, Y. (2019). The presence of microplastics in the digestive tract of commercial fishes off Pantai Indah Kapuk coast, Jakarta, Indonesia. *Biodiversitas Journal of Biological Diversity*, *20*(5).

Honingh, D., van Emmerik, T., Uijttewaal, W., Kardhana, H., Hoes, O., & van de Giesen, N. (2020). Urban river water level increase through plastic waste accumulation. *FrEaS*, *8*, 28.

Jang, Y. C., Hong, S., Lee, J., Lee, M. J., & Shim, W. J. (2014). Estimation of lost tourism revenue in Geoje Island from the 2011 marine debris pollution event in South Korea. *Marine Pollution Bulletin*, *81*(1), 49-54.

Khoironi, A., & Anggoro, S. (2018, March). The existence of microplastic in Asian green mussels. In *IOP Conference Series: Earth and Environmental Science* (Vol. 131, No. 1, p. 012050). IOP Publishing.

Koelmans, A. A., Nor, N. H. M., Hermsen, E., Kooi, M., Mintenig, S. M., & De France, J. (2019). Microplastics in freshwaters and drinking water: critical review and assessment of data quality. *Water research*, *155*, 410-422.

Koelmans, A. A., Besseling, E., Foekema, E., Kooi, M., Mintenig, S., Ossendorp, B. C., ... & Scheffer, M. (2017). Risks of plastic debris: unravelling fact, opinion, perception, and belief.

Kooi, M., & Koelmans, A. A. (2019). Simplifying microplastic via continuous probability distributions for size, shape, and density. *Environmental Science & Technology Letters*, *6*(9), 551-557.

Lau, W. W., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., ... & Thompson, R. C. (2020). Evaluating scenarios toward zero plastic pollution. *Science*, *369*(6510), 1455-1461.

Lasut, M. T., Weber, M., Pangalila, F., Rumampuk, N. D., Rimper, J. R., Warouw, V., ... & Lott, C. (2018). From coral triangle to trash triangle—how the hot spot of global marine biodiversity is threatened by plastic waste. In *Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea* (pp. 107-113). Springer, Cham.

Lebreton, L. C., Van Der Zwet, J., Damsteeg, J. W., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature communications*, *8*, 15611.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., ... & Noble, K. (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Scientific reports*, *8*(1), 1-15.

Lebreton, L., & Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Communications*, *5*(1), 1-11.

Lestari, P., and Trihadiningrum, Y. (2019). The impact of improper solid waste management to plastic pollution in Indonesian coast and marine environment. *Marine Pollution Bulletin*, *149*, 110505.

LI, W. C., Tse, H. F., & Fok, L. (2016). Plastic waste in the marine environment: A review of sources, occurrence and effects. *Science of the Total Environment*, *566*, 333-349.

Meijer, L. J. J., van Emmerik, T., Lebreton, L., Schmidt, C., & van der Ent, R. (2019). Over 1000 rivers accountable for 80% of global riverine plastic emissions into the ocean.

Michida, Y., Chavanich, S., Chiba, S., Cordova, M. R., Cozsar Cabanas, A., Glagani, F., et al. (2019). *Guidelines for Harmonizing Ocean Surface Microplastic Monitoring Methods*. Version 1.1. Chiyoda-ku, Tokyo, Japan: Ministry of the Environment Japan. https://doi.org/http://dx.doi.org/10.25607/OBP-867 URI

Nurhati, I. S., & Cordova, M. R. (2020). Marine plastic debris in Indonesia: baseline estimates (2010-2019) and monitoring strategy (2021-2025). *Marine Research in Indonesia*, *45*(2).

OSPAR Commission (2010). Guideline for monitoring Marine Litter on the Beachers in the OSPAR Maritime Area. London: OSPAR commission

Owens, K. A., & Kamil, P. I. (2020). Adapting coastal collection methods for river assessment to increase data on global plastic pollution: Examples from India and Indonesia. *Frontiers in Environmental Science*, *7*, 208.

Pawar, P.R., Shirgaonkar, S.S., Patil, R.B. (2016). Plastic marine debris: sources, distribution, and impacts on coastal and ocean biodiversity. *PENCIL Publication on Biological Sciences 3*(1), 40–54.

Petten, L., Schalekamp, J., Viool, V., Gupta, A. (2020). The price tag of plastic pollution – An economic assessment of river plastic. Deloitte. Accessed on 04-11-2020 via: https://www2.deloitte.com/nl/nl/pages/strategy-analytics-and-ma/articles/the-price-tag-of-plastic-pollution.html

Purba, N. P., Faizal, I., Cordova, M. R., Abimanyu, A., Afandi, N. K., Indriawan, D., & Khan, A. M. (2021). Marine Debris Pathway Across Indonesian Boundary Seas. *Journal of Ecological Engineering*, *22*(3), 82-98.

Rochman, C. M., Tahir, A., Williams, S. L., Baxa, D. V., Lam, R., Miller, J. T., ... & Teh, S. J. (2015). Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Scientific reports*, *5*, 14340.

Schmidt, C., Krauth, T., & Wagner, S. (2017). Export of plastic debris by rivers into the sea. *Environmental science & technology*, *51*(21), 12246-12253.

Shim, W. J., Hong, S. H., & Eo, S. E. (2017). Identification methods in microplastic analysis: a review. *Analytical Methods*, *9*(9), 1384-1391.

Spalding, M., Spalding, M. D., Ravilious, C., & Green, E. P. (2001). *World atlas of coral reefs*. Univ of California Press.

Statistics Indonesia. (2020). *International visitor arrival statistic 2019*. Catalog: 8401011. Publication Number: 06330.2003. ISSN: 2085-9309. xii+61 PP. Jakarta, Indonesia

Syakti, A. D., Bouhroum, R., Hidayati, N. V., Koenawan, C. J., Boulkamh, A., Sulistyo, I., ... & Wong-Wah-Chung, P. (2017). Beach macro-litter monitoring and floating microplastic in a coastal area of Indonesia. *Marine Pollution Bulletin*, *122*(1-2), 217-225.

Tomascik, T. (1997). *The ecology of the Indonesian seas*. Oxford University Press.

Uneputty, P., & Evans, S. M. (1997). The impact of plastic debris on the biota of tidal flats in Ambon Bay (eastern Indonesia). *Marine Environmental Research*, *44*(3), 233-242.

van Calcar, C. J., & Van Emmerik, T. H. M. (2019). Abundance of plastic debris across European and Asian rivers. *Environmental Research Letters*, *14*(12), 124051.

van Emmerik, T., & Schwarz, A. (2020). Plastic debris in rivers. *Wiley Interdisciplinary Reviews: Water*, *7*(1), e1398.

van Emmerik, T., Kieu-Le, T. C., Loozen, M., van Oeveren, K., Strady, E., Bui, X. T., ... & Schwarz, A. (2018). A methodology to characterize riverine macroplastic emission into the ocean. *Frontiers in Marine Science*, *5*, 372.

van Emmerik, T., Loozen, M., Van Oeveren, K., Buschman, F., & Prinsen, G. (2019). Riverine plastic emission from Jakarta into the ocean. *Environmental Research Letters*, *14*(8), 084033.

Vriend, P., Roebroek, C. T. J., van Emmerik, T. (2020). Same but different: A framework to Design and Compare Riverbank Plastic Monitoring Strategies. *Frontiers in water*, 2, 31.

Widyarsana, I. M. W., Damanhuri, E., Ulhusna, N., & Agustina, E. (2020). A Preliminary Study: Identification of Stream Waste Quantity and Composition in Bali Province, Indonesia. In *E3S Web of Conferences* (Vol. 148, p. 05005). EDP Sciences.

Willoughby, N. G. (1986). Man-made litter on the shores of the Thousand Island Archipelago, Java. *Marine Pollution Bulletin*, 17(5), 224-228.