Priorities to inform research on marine plastic pollution in Southeast Asia

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Priorities to inform research on marine plastic pollution in Southeast Asia

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Abstract

Southeast Asia is considered to have some of the highest levels of marine plastic pollution in the world. It is therefore vitally important to increase our understanding of the impacts and risks of plastic pollution to marine ecosystems and the essential services they provide to support the development of mitigation measures in the region. An interdisciplinary, international network of experts (Australia, Indonesia, Ireland, Malaysia, the Philippines, Singapore, Thailand, the United Kingdom, and Vietnam) set a research agenda for marine plastic pollution in the region, synthesizing current knowledge and highlighting areas for further research in Southeast Asia. Using an inductive method, 21 research questions emerged under five non-predefined key themes, grouping them according to which: (1) characterise marine plastic pollution in Southeast Asia; (2) explore its movement and fate across the region; (3) describe the biological and chemical modifications marine plastic pollution undergoes; (4) detail its environmental, social, and economic impacts; and, finally, (5) target regional policies and possible solutions. Questions relating to these research priority areas highlight the importance of better understanding the fate of marine plastic pollution, its degradation, and the impacts and risks it can generate across communities and different ecosystem services. Knowledge of these aspects will help support actions which currently suffer from transboundary problems, lack of responsibility, and inaction to tackle the issue from its point source in the region. Being profoundly affected by marine plastic pollution, Southeast Asian countries provide an opportunity to test the effectiveness of innovative and socially inclusive changes in marine plastic governance, as well as both high and low-tech solutions, which can offer insights and actionable models to the rest of the world.

Keywords: environmental governance, marine debris, marine ecosystems, marine litter, plastic debris, waste management

1. Introduction

Southeast Asia consists of 11 countries, namely Brunei Darussalam, Cambodia, Indonesia, Laos (the only land-locked country), Malaysia, Myanmar, the Philippines, Singapore, Timor-Leste, Thailand, and Vietnam. The region includes almost 150,000 km of coastline and over 25,000 islands. It is a richly biodiverse region, hosting approximately 34% of the world’s coral reefs (Burke et al., 2002; Tun et al., 2005) and 25-33% of global mangrove forests (Spalding et al., 2010), and where most tropical marine biota has its greatest species richness (Briggs, 1999; Tittensor et al., 2010). Over 80% of the region’s reefs, however, are currently at risk from numerous threats, including overfishing, coastal development, marine pollution, aquaculture and agriculture, and climate change (Burke et al., 2002), resulting in significant species declines (Yamakita et al., 2017).

Alongside its extensive biodiversity, Southeast Asia is the third most populated geographical region in Asia, with over three quarters of its majority urban human population living in coastal communities (PEMSEA, 2015). The coastal and riparian orientation of human settlement in Southeast Asia has been accompanied by rapid economic growth, urbanisation, and globalisation. These are all factors that generate wide-ranging environmental effects, while exposing a large proportion of the population to climate change impacts, extreme weather events, and recurring urban flooding episodes (Brahmasrene and Lee, 2017; Khan, 2019; Kurniawan and Managi, 2018; Miller et al., 2018).

Furthermore, Southeast Asia has among the highest levels of marine plastic pollution globally, with Indonesia (10%), the Philippines (6%), Vietnam (6%), Thailand (3%), and Malaysia (3%) estimated to cumulatively contribute almost a third (30%) of marine plastic pollution to the world’s oceans (Jambeck et al., 2015). Ecosystem services, defined as the benefits people obtain from nature (Liquete et al., 2013), are negatively impacted by the presence of plastic pollution (Figure 1), causing considerable environmental, social, and economic impacts, with cascading implications for human health, wellbeing, and livelihoods in coastal communities (Abalansa et al., 2020; Beaumont et al., 2019; Thushari and Senevirathna, 2020)

The impacts of marine plastic pollution in Southeast Asia have been reviewed several times (Curren et al., 2021; Lyons et al., 2020, 2019), highlighting knowledge gaps which need to be addressed to inform more effective solutions. For example, research on microplastics, defined as particles which range from 0.1 µm to 5 mm in size (SAPEA, 2019), is especially limited from Cambodia, Laos, and Timor-Leste (Curren et al., 2021). To increase our understanding of the impacts and risks of plastics to marine ecosystems and their services, as well as to support the development of mitigation measures, an interdisciplinary, international network of experts established a research agenda for marine plastic pollution in the region, providing in-depth knowledge of marine plastics associated with identified research priorities and highlighting areas for further research in Southeast Asia. Research questions were grouped using an inductive method into five non-predefined key themes, which: (1) characterise marine plastic pollution in Southeast Asia; (2) explore its movement and fate across the region; (3) describe the biological and chemical modifications marine plastic pollution undergoes; (4) detail its environmental, social, and economic impacts; and (5) target regional policies and possible solutions. While applicable to other parts of the world, each question is discussed within the context of Southeast Asia.

2. Material and methods

The process followed for the writing of this review is detailed below and summarised in Figure 2. Authors engaged in active collaborative work to interpret and reframe the research design and guiding the questions, providing their in-depth knowledge of marine plastic pollution in answering the developed priority research questions, ranging from conservation to molecular biology, within a Southeast Asian context.

Between February and March 2021, a horizon-scanning exercise was conducted to gather suggestions for priority research questions for marine plastic pollution with a particular focus on Southeast Asia. Authors were selected from their involvement in the four projects funded by "Understanding the Impact of Plastic Pollution on Marine Ecosystems in Southeast Asia", Southeast Asia Plastics (SEAP) programme, an initiative co-funded by the Natural Environment Research Council (United Kingdom) and the National Research Foundation (Singapore).

In a preliminary survey established by the joint-lead and senior authors, other invited authors identified what they thought were the top three to five research priorities for marine plastic pollution in the region, targeted at expanding our understanding of the scale of the problem and the potential solutions and policy drivers. We employed respondent-driven sampling to ensure quality and diversity in author representation (Newing, 2010). This purposive sampling approach requests those directly contacted to recruit additional authors among their colleagues and peers involved in the SEAP programme. Most authors of this review participated in the first survey (n = 55) from countries including Australia, Indonesia, Ireland, Malaysia, the Philippines, Singapore, Thailand, the United Kingdom, and Vietnam.

The answers from the horizon-scanning exercise were categorised using an inductive approach. After the initial reading of all the suggestions (n = 214), the entire set of priority research questions was coded, forming the basis of repeated patterns (themes) across all the author survey responses (Braun and Clarke, 2006). Summary themes were identified through the process of directly examining the survey responses instead of having pre-defined categories (Elo and Kyngäs, 2008). Seven broad summary themes emerged (1. Description of plastic pollution; 2. Movement & fate; 3. Biological & chemical modifications; 4. Environmental impacts; 5. Socio-economic impacts; 6. Possible solutions; and 7. Regional policy), with an average of 32 (range: 24-39) suggestions within each theme. This process was repeated once within each theme to establish three priority research questions, consolidating similar suggestions or repeated keywords and concepts together, forming standalone questions. These resulted in a consolidated list of 21 research questions, across seven themes, which were further refined according to readability, with the support of two authors.

Individuals from the first survey were grouped and assigned questions based on their expertise identified during the first survey, for which authors contributed explanatory narratives drawing from their research knowledge, particularly regarding the Southeast Asian region. Two follow-up surveys were then sent to these authors between April and May 2021 to acquire feedback on the themes, question formulations, and author group assignations. This feedback loop facilitated the reduction of themes from seven to five, which, in turn, improved the clarity of the review. Specifically, sections on environmental and socio-economic impacts were combined, as were sections on possible solutions and regional policy. Author groups, each comprising between three and seven members, subsequently wrote short narratives supporting the importance of each question, forming the basis of this review. An additional five authors were identified during this process due to their expertise, who participated in the writing.

3. Results – identified themes and priority research questions

Five non-predefined key themes emerged from the horizon-scanning exercise, with between three and six priority research questions under each theme (Figure 3, Table S1). These were established by an interdisciplinary, international network of experts, who brought their in-depth disciplinary and geographical knowledge to bear on complex marine plastic questions. While some questions are applicable to other parts of the world, each question is discussed within a Southeast Asian context, highlighting key areas for further research in the region.

3.1 THEME 1: Description of marine plastic pollution

3.1.1 Question 1: What are the origins of plastic pollution in the marine environment in Southeast Asia?

Although not unique to Southeast Asia, rising standards of living, fast growing economies, and the region's substantial tourism industry have seen an increased reliance on single-use plastics in multiple sectors (Chaerul et al., 2014; Sur et al., 2018), primarily as packaging (GAIA, 2019; Geyer et al., 2017; GIZ, 2018). This reliance on single-use plastic was exacerbated by the COVID-19 pandemic, with, for example, personal protective equipment accounting for 15-16% of collected debris at two river outlets into Jakarta Bay, Indonesia in 2020 (Cordova et al., 2021a). Macroplastics, defined as items or particles exceeding 5 mm in size (SAPEA, 2019), enter the marine environment in the region through direct littering (Jayasiri et al., 2013; Thushari et al., 2017a; WWF Philippines, 2020), marine dumping, which is the deliberate disposal of waste at sea (Peng et al., 2019; Richardson et al., 2017; WWF Philippines, 2020), from aquaculture/agriculture facilities (Lee et al., 2006), and from accidental loss from shipping and fishing activities (Richardson et al., 2017; Valderrama Ballesteros et al., 2018). For example, in a survey of six coral reefs in Malaysia, approx. 70% of collected plastics were single-use items derived from marine dumping and a quarter of items were related to fishing activities, including derelict fishing gear and fishing lines (Santodomingo et al., 2021). Secondary micro- and nanoplastics, the latter being defined as particles smaller than 0.1 µm in size (SAPEA, 2019), enter Southeast Asia's oceans through international ocean flows and domestic sources (Praveena et al., 2021) and are derived from plastic fragmentation. In addition to the marine plastic waste generated within Southeast Asia, developing countries in the region that are major recipients of waste exporting countries, such as the European Union, the United States of America, and China, often experience leakages from overflowing landfills and overburdened waste processing facilities into the surrounding coastal and marine environment (Marks et al., 2020). For example, Thailand receives several hundreds of thousands of tons of plastic waste imports annually, while an estimated 70% of the country's domestic waste is being mismanaged (Marks et al., 2020). Of the country's waste produced in 2018, over a quarter was disposed of improperly, with mismanagement leading to waste entering canals or leaking onto beaches during heavy flooding events (Marks et al., 2020). As the amount of plastic waste entering the marine environment remains unclear in Southeast Asia (Cordova et al., 2021b), data-driven research is required to better understand the origins of plastic pollution.

3.1.2 Question 2: What are the main plastic entry points into the marine environment in Southeast Asia?

Rivers are a major transport pathway for plastic pollution to enter the marine environment in Southeast Asia (Figure 1b; Jambeck et al., 2015; Lahens et al., 2018; Lebreton et al., 2017; Lechthaler et al., 2021; Meijer et al., 2021). Of the predicted global top 50 plastic emitting rivers, over half (58%, n = 29) are in Southeast Asian countries (Meijer et al., 2021; Figure 4), although the linkages between freshwater and marine plastic pollution across the region remain critically under-examined. Plastic debris also leaks into the marine environment from densely populated coastal regions, port facilities, and industrial estates – e.g. Greater Jakarta, Indonesia (Cordova and Nurhati, 2019) and East Java, Indonesia (Lestari and Trihadiningrum, 2019) – including landfill sites (Nurhasanah et al., 2021; Sulistyowati et al., 2022) and beaches (Figure 1d; Jeyasanta et al., 2020; Kunz et al., 2016; Nguyen et al., 2020). Knowledge of debris entry points is key to developing waste management strategies aimed at reducing leakages, the methods for which depend on factors such as source, plastic debris polymer type, and size (Schmaltz et al., 2020). Quantitative data can be obtained through *in-situ* sampling of the region's waters. Surface macroplastics within a river plume have also been identified in optical satellite data covering a region close to Da Nang, Vietnam (Biermann et al., 2020). Biases, however, can arise in certain environments, such as rural catchments, which are less frequently investigated, as highlighted in Indonesia (Phelan et al., 2020). Novel observing platforms, such as drones (e.g. Martin et al., 2021), will make it possible to better evaluate entry points into the marine environment in the region. Furthermore, particle backtracking simulations (e.g. Cyprus: Duncan et al., 2018; Indonesia: Iskandar et al., 2021; Australia: Reisser et al., 2013; Arctic: Strand et al., 2021), which model the movement and spatial positioning of plastic particles backwards in time, could be used to help determine potential sources of observed marine plastic pollution in the region.

3.1.3 *Question 3: What are the most appropriate methodological approaches to characterise marine plastic pollution?*

There has been a recent increase in research into the identification and quantification of marine plastic pollution in Southeast Asia (Lyons et al., 2020; Vriend et al., 2021). Numerous methods exist to identify polymers which comprise plastics, however, most studies use Fourier Transform InfraRed (FTIR) or Raman spectroscopy (Hidalgo-Ruz et al., 2012; Kundu et al., 2021; Renner et al., 2018). Although it is often difficult to distinguish pure polymers from polymer blends, these two techniques provide sufficient information on the functional groups present on the polymer backbone. For example, FTIR and Raman spectroscopy were used to show that polypropylene and polyethylene were the most common polymers in Indonesia (Vriend et al., 2021), while polystyrene, polyethylene terephthalates, polyethylene-polypropylene copolymer, and polyacrylates were also detected in sediments in the Gulf of Thailand and Straits of Johor (Malaysia) (Matsuguma et al., 2017). Variations on these techniques, such as µ-Raman and attenuated total reflectance FTIR, have also been used to identify microplastic polymers in the remote mid-west Pacific Ocean (Wang et al., 2020) and coastal sites around Bintan Island, Indonesia (Syakti et al., 2018), respectively. While these techniques are all suitable to characterise plastics in the region, the scarcity of research equipment in Southeast Asia is currently hampering progress, which could be alleviated through international collaboration among research organisations. Ensuring that standardised protocols are used for the collection, identification, and monitoring of microplastics will enable better data comparison among studies, both within Southeast Asia and globally (Isobe et al., 2019; Koelmans et al., 2020; Kooi and Koelmans, 2019; Michida et al., 2019).

3.2 THEME 2: Movement and fate

3.2.1 Question 4: What drives dominant movement patterns and dispersal pathways of plastic in Southeast Asia?

The movement of plastic waste through the marine environment is mainly driven by ocean currents, but is mediated by coastal, sea-surface, and seabed interactions, as well as the specific characteristics of plastic pollution (Kaiser et al., 2017; Kooi et al., 2017; Long et al., 2015; ter Halle et al., 2016). Additionally, plastic particles can be redistributed organically within faecal pellets of marine organisms (Cole et al., 2016, 2013; see section 3.4.1). The

Indonesia Through Flow (Figure 4) is the major current between the Pacific and Indian Oceans (Sprintall et al., 2009), and its stratified profile interacts with the region's complex bathymetry (Gordon and Fine, 1996; Sprintall et al., 2009), strong internal tides (Nugroho et al., 2018), seasonal surface-currents (Lee et al., 2019), and currents from the South China Sea (Wang et al., 2019). As such, the complex bathymetry and topography of Southeast Asia, combined with the abundance of 'plastic-trapping' mangrove (Figure 1a, c), coral (Figure 1e), and seagrass habitats, present a major modelling challenge (Huang et al., 2020; Smith, 2012). Three-dimensional, high-resolution ocean models that explicitly include (i) tides and their topographic interactions, (ii) freshwater inputs, (iii) wave and wind dynamics, (iv) baroclinic flows, and (v) extreme weather events are necessary to sufficiently describe the mechanisms driving plastic movement in the region. As highlighted in previous reviews (e.g. van Sebille et al., 2020), addressing the heterogeneity of plastics and parameterising aggregation (see section 3.2.2), fragmentation (see section 3.3.3), and/or biofouling processes (see section 3.3.1) will be essential to accurately characterise plastic waste in these transport models.

3.2.2 Question 5: Which habitats act as major accumulation zones in Southeast Asia?

High densities of sessile biota in mangrove, seagrass, and coral habitats, which are widespread in coastal and shallow waters in Southeast Asia, directly lead to plastic accumulation by snagging (Figure 1; Valderrama Ballesteros et al., 2018; van Bijsterveldt et al., 2021), filtering (Chavanich et al., 2020; Martin et al., 2019a; Thushari et al., 2017b), and adhesion (Goss et al., 2018; Martin et al., 2019b). They also indirectly influence accumulation by affecting local hydro- (de Smit et al., 2021; Fonseca et al., 2019) and sediment- (Martin et al., 2020) dynamics. The fate of plastics in these habitats depends on: (1) the morphology and the hydrodynamics of the coastal environment (Cordova et al., 2019; Utami et al., 2021; see section 3.2.1), (2) the trapping efficiency of these habitats (Cozzolino et al., 2020; de los

Santos et al., 2021; de Smit et al., 2021; Harris et al., 2021; Huang et al., 2020; Sanchez-Vidal et al., 2021; Valderrama Ballesteros et al., 2018), and (3) the characteristics of plastic particles, in particular their size (Cozzolino et al., 2020; de los Santos et al., 2021; de Smit et al., 2021; Mohamed Nor and Obbard, 2014). Connectivity between coastal habitats and marine environments, however, can lead to the export of accumulated plastics, particularly in tidal-dominated systems (Harris et al., 2021) or those exposed to extreme events (see section 3.2.3), resulting in an underestimated abundance of plastic pollution among these habitats. Considering the abundance of these habitats in Southeast Asia, further research is required to better quantify the volume of plastics currently stored in mangrove, seagrass, and coral habitats, and to understand their environmental impacts and consequences for the coastal and riverine communities that depend on them in the region (see section 3.4.2-3.2.4).

3.2.3 Question 6: How will extreme weather events influence source-sink dynamics in Southeast Asia?

Temporal variability is a key factor in determining the transport between sources and sinks of plastics across Southeast Asia (Kurniawan and Imron, 2019; Xia et al., 2021), although extreme weather events may alter the volume of plastic at sources, as well as temporally change sinks to become sources. Seabed sediments are generally considered a sink for micro- and nanoplastics. However, monsoon seasonal typhoons, which are common in Southeast Asia and cause extreme wind and wave conditions (Nakajima et al., 2022) and other extreme weather events such as storm surges, have the potential for large-scale resuspension and subsequent dispersal of micro- and nanoplastics from accumulation zones (Ivar do Sul et al., 2014; R. Li et al., 2020; Lo et al., 2020; Xia et al., 2021). Seasonal changes in rainfall rates (Singh and Qin, 2020) are reflected in fluctuations in monthly river plastic emissions in Southeast Asia (Figure 1b; Cordova and Nurhati, 2019; Lebreton et al., 2017). Extreme precipitation events linked to climate change (Singh and Qin, 2020) will exacerbate this issue and compound the impacts (Ford et al., 2022; Roebroek et al., 2021). The continuous rise in global mean sea levels (Dangendorf et al., 2019) at a current estimated average rate of 3.1 mm per year (Cazenave et al., 2018), coupled with likely changes in the magnitude and frequency of extreme events (Easterling et al., 2000), could lead to present day plastic repositories becoming future sources of marine plastic pollution (Ford et al., 2022). Knowledge of the impact of mean sea level rise and the probability distributions of extreme weather events (likely changes in the magnitude and frequency) is crucial for understanding how extreme weather events influence source-sink dynamics when simulating the future within regional transport models (see section 3.2.1).

3.3 THEME 3: Biological and chemical modifications

3.3.1 Question 7: What are the assemblage and ecological driving forces of plastisphere biofilms?

The composition and functional capacity of the plastisphere (the microbial community found on plastic pollution; Zettler et al., 2013) is influenced by the size and chemical composition of plastics and the surrounding environment (Tu et al., 2020). Micro- and nano-plastics are not necessarily found as independently-floating particles in the environment, but rather can agglomerate and form larger particulate material, somewhat akin marine snow (Summers et al., 2018), becoming readily available for consumption by small organisms and filter feeders (see section 3.4.1). Microbial colonisation is enabled by the initial adsorption of various organic molecules to the plastic surface, forming an ecocorona (Galloway et al., 2017; Lynch et al., 2014), which provides an additional source of carbon and energy and drives the initial attachment of microorganisms (Figure 1f; Galloway et al., 2017; Rahman et al., 2021; Wright et al., 2020). While there have been numerous studies exploring the composition and diversity of biofilms on various types of plastics (Delacuvellerie et al., 2019; Dussud et al., 2018; McCormick et al., 2016; Miao et al., 2019; Oberbeckmann et al., 2018; Zettler et al., 2013), few studies have focused on the ecological functions of these microorganisms (Amaral-Zettler et al., 2020), and even fewer studies have been conducted in Southeast Asia. A recent study conducted in the Maludam River, Malaysia identified different gene expression profiles among communities present on microplastics from those expressed in the surrounding waters, including key genes involved in carbon, nitrogen, and sulphur cycling (Rahman et al., 2021). In addition, an increase in genes associated with metal homeostasis and the metabolism of aromatic and chlorinated compounds was observed on microplastics, suggesting potential mechanisms of detoxification or remediation within the plastisphere (Rahman et al., 2021). Similar studies within Southeast Asian marine waters are required to fully understand the functional diversity and metabolic capacity of plastisphere communities in the region, considering the spatio-temporal variation in community-assembly on plastisphere biofilms at both regional and global scales (Amaral-Zettler et al., 2020). However, whether there exists a core plastisphere that is significantly different from non-plastic biofilms remains a contentious issue (Oberbeckmann and Labrenz, 2020; Wright et al., 2020), although a recent meta-analysis suggests that this is the case (Wright et al., 2021).

3.3.2 Question 8: What is the potential for marine plastic pollution to transport pollutants and create hotspots of antimicrobial resistance?

Persistent organic pollutants (POPs), heavy metals, and microorganisms all bind to marine plastic debris (Hossain et al., 2019; W. Li et al., 2020; Wang et al., 2020; see section 3.3.1), which may accumulate and transport these pollutants (Jianlong Wang et al., 2021; T. Wang et al., 2020). As over 80 POPs have been detected in the coastal waters of Singapore (Zhang et al., 2015) and several known harmful algal bloom-forming species have been recorded in the

Philippines (Onda et al., 2020), the potential sorption of co-pollutants, microorganisms, and invasive species to marine plastic pollution represents a significant threat to ecosystem health in Southeast Asia (Borja et al., 2020; Karbalaei et al., 2018; Pariatamby and Kee, 2016). The implementation of international regulations, such as the Stockholm Convention, will likely reduce the impact of POPs in signatory countries in the region, but legacy effects will continue due to their persistence in the marine environment (UNEP, 2014). In addition, this combination of microorganisms and pollutants can also cultivate the development of antibiotic resistance genes (ARGs) on marine plastic pollution (Liu et al., 2021). The co-presence of heavy metals also increases ARG expression due to the joint loci of ARGs and metal resistance genes in bacteria (Li et al., 2017; Poole, 2017; Yang et al., 2019), which allows for the enrichment of ARGs on plastic specifically (Guo et al., 2020). However, there is no evidence to support the pathogenic activity of antibiotic resistant microorganisms on marine plastic pollution (Delacuvellerie et al., 2022; Oberbeckmann et al., 2021). It has also been argued that micro- and nanoplastics pose no more risk of harbouring potential pathogens than natural particles (Oberbeckmann and Labrenz, 2020) and that there is little to no proof of pathogenicity to humans or animals from organisms transported on plastics thus far (Jacquin et al., 2019; Lamb et al., 2018). The limited number of published studies on plastics as surfaces for developing and disseminating antimicrobial resistance, however, underpins the importance of more research into this area, particularly in Southeast Asia (reviewed by Liu et al., 2021), where high mean sea surface temperatures (28.9°C in the coral triangle; McClanahan et al., 2020), which have been increasing at an average rate of 0.2°C per decade (Peñaflor et al., 2009), might be altering the microbial community structure and favouring the proliferation of pathogens (le Roux et al., 2015; Tout et al., 2015).

3.3.3 *Question 9: What is the pattern of fragmentation and degradation of plastic pollution?*

Most of the known polymer degradation in the environment follows free radical mechanisms, where polymer structure, traces of catalysts, and defects along the polymer backbone contribute significantly to accelerate degradation (Gewert et al., 2015; Muthukumar and Veerappapillai, 2015; Singh and Sharma, 2008). Biodegradation is enacted by microorganisms (Shah et al., 2008), however, abiotic environmental factors, such as ultraviolet radiation, temperature, oxygen, salinity, molecular weight distribution of polymers, and the presence of additives are known to enhance degradation (Pariatamby, 2018). Biofilm formation on the surface of plastics, often facilitated by the polar groups and surface morphology, is the first step of biodegradation, followed by enzymatic degradation of the polymers (see section 3.3.1). Bioplastics with low molecular weight tend to be more susceptible to microbial enzymatic hydrolysis and degradation accelerates in tandem with decreasing crystallinity of the bioplastics (Adhikari et al., 2016; Tabasi and Ajji, 2015). Members of the bacteria phyla Proteobacteria, Actinobacteria, Chloroflexi, and Firmicutes have regularly been linked to plastic degradation (Curren and Leong, 2019; Gong et al., 2019; Liao and Chen, 2021; Roager and Sonnenschein, 2019; Rüthi et al., 2020). Although results to date are in line with global trends, studies on biodegradation of plastics by microbes remain in nascent stages and confined to particular localities across the region (e.g. Auta et al., 2017), as do studies on marine fungi or bacteria (Nurdhy, 2020; Onda et al., 2020). Despite the importance of enhancing our understanding of plastic debris fragmentation and degradation, thorough standardised testing methods have yet to be developed that allow for full elaboration of the plastic polymer environmental degradation pathways.

3.4 THEME 4: Environmental, social, and economic impacts

3.4.1 Question 10: What are the impacts of plastic pollution on marine organisms?

Plastic ingestion can cause injury and obstruction to the digestive tract of marine organisms (Roman et al., 2019). In most cases, it leads to sublethal effects, such as reduced feeding efficiency (Savinelli et al., 2020; Watts et al., 2015), plastic-induced satiety (Santos et al., 2020), and suboptimal health conditions (Pedà et al., 2016; Senko et al., 2020), the effects of which may be amplified by the ecotoxicology of ingested plastics (Anbumani and Kakkar, 2018). In Southeast Asia, plastic ingestion (ranging from macro- to microplastic) has been documented in sea turtles, whales, and sharks (Abreo et al., 2019a, 2019b, 2016a, 2016b; Coram et al., 2021; Garay et al., 2019; Haetrakul et al., 2009), as well as fish (Azad et al., 2018; Karbalaei et al., 2019; Paler et al., 2021; Rochman et al., 2015), bivalves (Argamino and Janairo, 2016; Nam et al., 2019; Rochman et al., 2015; Shauib Ibrahim et al., 2016; Thushari et al., 2017b), and zooplankton (Amin et al., 2020). Publications for seabirds are lacking altogether from Southeast Asian countries, although plastic ingestion has been recorded in red-footed boobies (*Sula sula*) collected from Yongxing Island, South China Sea (Zhu et al., 2019). Plastic ingestion in zooplankton (Botterell et al., 2019), which form the base of the food chain, is concerning because of the potential trophic transfer up the food chain (e.g. Chagnon et al., 2018; Farrell and Nelson, 2013; Furtado et al., 2016; Hammer et al., 2016), having particular implications for the degradation of species for human consumption (see section 3.4.6). Additionally, entanglement in plastic debris is recognised as a global threat to marine species (Stelfox et al., 2016) by causing severe wounds and restricting movement and breathing (Colmenero et al., 2017; Franco-Trecu et al., 2017), with examples reported from Southeast Asia (Chim, 2014; Chim et al., 2015; Valderrama Ballesteros et al., 2018; Yeo, 2014). Life-histories, behaviours, and morphologies of species likely affect the extent and type of plastic interactions (e.g. Baak et al., 2020; Reichert et al., 2018; Suckling, 2021). As the impacts of marine plastic pollution are multi-faceted, species-specific, and spatially variable, there is a need for a greater understanding of these impacts on marine organisms in Southeast Asia, particularly those endemic to the region (Lyons et al., 2019).

3.4.2 Question 11: What are the impacts of plastic pollution on key marine habitats in Southeast Asia?

Macroplastics can become trapped by biological structures, such as mangrove forests, seagrass beds, and coral reefs (Figure 1; see section 3.2.2), while micro- and nanoplastics can eventually precipitate to the seafloor and become incorporated into sediments (Chavanich et al., 2020; Cordova et al., 2021; Cordova and Wahyudi, 2016; Y. Huang et al., 2021; Ivar do Sul et al., 2014; Riani and Cordova, 2021). Plastic pollution negatively impacts these marine habitats by mechanical and chemical means, and by altering microbial and macrofaunal communities and their associated traits. High macroplastic concentrations can smother and damage mangrove roots and cause leaf loss, decreasing tree survival and primary production, which in turn affect dependent aquatic ecologies, such as fish and shrimp nurseries (Luo et al., 2021; van Bijsterveldt et al., 2021). Additionally, entanglement by marine plastic waste, particularly fishing gear, can damage important habitat-forming organisms, such as coral reefs (Abu-Hilal and Al-Najjar, 2009; Chiappone et al., 2005; Gilardi et al., 2010; Valderrama Ballesteros et al., 2018). Despite mangrove forests and seagrass beds being globally essential carbon stores (Duarte et al., 2013), studies on how micro- and nanoplastics affect the biogeochemistry of their associated substrata remain small-scale and confined to specific areas of Southeast Asia (Cordova et al., 2021b; Manalu et al., 2017; Mohamed Nor and Obbard, 2014; Tahir et al., 2019). In addition, micro- and nanoplastics have been shown to alter microbial and planktonic community compositions, which may in turn influence the regulation of oceanic carbon cycles (Galgani and Loiselle, 2021; Ladewig et al., 2021; Jiao Wang et al., 2021). Future research should build on, and expand the geographical scope of, emerging studies into the incorporation of micro- and nanoplastics into sediments and their effects on microbial communities (e.g. Putri and Patria, 2021; Sawalman et al., 2021), and thus, the permanency of carbon stores in the region (Y. Huang et al., 2021).

3.4.3 Question 12: What are the impacts of plastic pollution on marine ecosystem services in Southeast Asia?

The marine environment provides a wealth of ecosystem services, many of which are particularly vulnerable to the deleterious effects of plastic pollution. In Southeast Asia, such negative effects are well documented for marine ecosystems (Curren et al., 2021) and are predicted to increase (Chen et al., 2021). There is evidence that these impacts will, in turn, affect the extent of ecosystem service provision (Beaumont et al., 2019), with the potential to decrease the wellbeing of humans across the globe, owing to the loss of food security, livelihoods, income, and good health (see section 3.4.4). For example, Southeast Asia's tuna industry, worth an estimated US$7 billion annually (Hasnan, 2019), is severely threatened by marine plastic pollution (Warren and Steenbergen, 2021; and see section 3.4.6). Ecotourism, which creates employment and generates products sustainably from locally important resources, is another major industry for most countries in Southeast Asia. Yet, unsustainable practices related to tourism in Southeast Asia generate significant levels of marine plastic pollution, with the ten most common types of litter collected during coastal clean-up campaigns being linked to leisure activities (SEA Circular, 2019). The consequences of plastic polluting behaviours upon such high-value ecosystem services, as well as those provided by mangrove forests, seagrass meadows, and coral reefs in Southeast Asia (see section 3.4.2), however, remain poorly understood and should be a priority for future research.

3.4.4 Question 13: What are the relationships between marine plastics, livelihoods, and poverty alleviation in Southeast Asia?

The costs of marine plastic pollution in Southeast Asia are unequally distributed across countries and populations, with the livelihoods of physically proximate coastal communities particularly impacted (Beaumont et al., 2019), especially if they are reliant on marine food sources (Teh and Sumaila, 2013; see section 3.4.3). In both urban and rural contexts, numerous single-use plastic products (e.g. food and toiletry sachets) have been designed to aid poverty alleviation, as they can help increase hygiene and access to sanitary products, as well as reduce disease. Although this generates a waste problem, it is insignificant when compared with ecological footprints of Southeast Asia's burgeoning middle classes, who possess far greater purchasing power (Marks et al., 2020). Moreover, Southeast Asia's sizeable informal waste sector fills an important gap in effective state waste management systems as waste pickers sort, clean, and recycle large volumes of plastic debris (Visvanathan and Anbumozhi, 2018). Future research is urgently needed in collective efforts to nurture more ecologically sustainable behaviours which bridge existing gaps between sectors and across socioeconomic groups.

3.4.5 Question 14: How is the economic cost of pollution shared between polluter and polluted countries in Southeast Asia?

Some Southeast Asian countries are simultaneously primary producers of plastic waste and heavily impacted by marine plastic pollution. In a global context, however, developed countries are the highest producers of plastic waste (Liu et al., 2018) and can afford to offshore waste while pursuing domestic policies to meet global climate commitments by greening domestic economies. Plastic waste exports from the European Union, the United

States of America, and China to countries like Malaysia and Thailand for disposal (Gong and Trajano, 2019) mean that developing countries tend to bear the cumulative environmental, health, and socioeconomic burdens of ill-disposed waste. This is a complex problem for governments in developing countries because they are often the least prepared in terms of technologies and financial resources to deal with the negative externalities associated with landfill leakage into the marine environment (Bishop et al., 2020). A lack of international legislation to hold major polluters accountable perpetuates the transboundary nature of marine plastic pollution by reducing the incentive for any single country to take responsibility for these transgressive cross-border flows (Dauvergne, 2018; Raubenheimer and McIlgorm, 2017; see section 3.5.5). For example, abandoned, lost or otherwise discarded fishing gear is particularly challenging to monitor due to the difficulties of observing fishing fleets in both time and place and assigning recovered gear to fishing vessels (Gilman, 2015) especially considering the prevalence of small-scale artisanal fisheries in the region (Teh and Pauly, 2018). Similarly, litter from merchant shipping is increasing, including operational garbage, microplastics in grey water or ballasts, and wrecks (Ryan et al., 2019; Suaria et al., 2018), which is particularly relevant given the region's high level of shipping traffic and major ports. Preventing such littering and marine dumping will be difficult as it likely occurs in the high seas, where enforcing legislation is challenging. Pursuing marine polluters, such as the fishing and transport industries, will be costly and uncertain, whilst the persistence of marine plastic in the environment means that the benefits of abatement efforts in the present extend into the future. This problem has worsened since the onset of the COVID-19 pandemic, which, in Southeast Asia, has rolled back decades of recycling gains amidst the global spike in single-use plastics, while exacerbating illicit flows of leakage from landfills into the marine environment (Miller et al., 2022). Enforceable international legislation is needed to ensure that wealthy countries contribute more meaningfully towards the costs of mitigating the socioecological impacts created by the offshoring of domestic waste under the guise of environment sustainability (see sections 3.1.1, 3.1.3, and 3.5.1-6).

3.4.6 Question 15: What is the role of plastic debris in degrading seafood safety?

Plastic contamination of seafood, which tends to be established by investigating the plastic burden in digestive tracts of food species, has recently been identified as a major concern for global food security and human health (Danopoulos et al., 2020; Guillen et al., 2019; Mohamed Nor et al., 2021; Ragusa et al., 2021; Schwabl et al., 2019). In Southeast Asia, a high reliance on, and consumption of, seafood among dependent coastal communities could result in significant negative health consequences, such as endocrine disruption, through secondary plastic consumption (Barboza et al., 2018; Kirstein et al., 2016; Trujillo-Rodríguez et al., 2021; Wardrop et al., 2016). Micro- and nanoplastic concentrations in the digestive tract of contaminated seafood provide only limited knowledge about the possible risks to human health, especially for organisms in which the digestive tract is not consumed. However, the diverse range of human pathogens and antibiotic resistant bacteria present on marine micro- and nanoplastics, which may have the ability to enter the human food chain, are of concern (Bowley et al., 2021; Keswani et al., 2016; Moresco et al., 2021; Rodrigues et al., 2019; Yang et al., 2019; see section 3.3.2). For example, experiments in laboratory-reared catfish *Clarias gariepinus*, which are a major food source in Southeast Asia, showed that microplastics act as efficient shuttles to concentrate and transfer trace metals to individuals that ingest them, with accumulation levels significantly differing with tissue type (Jang et al., 2022). Additionally, biodegradable polylactic acid was found to transfer higher amounts of trace metals in this species, which suggests that biodegradable polymers could pose a greater environmental threat than more common polymers, such as polyamide 12 used in this study (Jang et al., 2022). As such, investigations into the impacts of marine plastic pollution on species for human consumption and how these may be translated into associated risks to human health are critically needed.

3.5 THEME 5: Regional policies and possible solutions

3.5.1 Question 16: How can we identify effective interventions in Southeast Asia?

Any integrated waste management approach to reduce marine plastic pollution must include effective collection, processing, and treatment systems (Winterstetter et al., 2021). Many parts of Southeast Asia currently lack technological solutions which are readily available to developed countries, such as Ocean Accounting, which consolidates data on stocks, flows, and output for accountability of economic activities and waste generation (Global Ocean Accounts Partnership, 2019), and the Plastic Pollution Prevention and Collection Technology Inventory (Schmaltz et al., 2020), which tracks and accesses innovations like digital technologies (e.g. citizen science mobile applications and virtual plastic waste currencies; Winterstetter et al., 2021) and enzymatic recycling (Knott et al., 2020; Winterstetter et al., 2021). As around 55% of Southeast Asia’s population lacks regular internet access, many societies remain reliant on traditional decision-making methods (UNESCAP, 2020). Although the waste ‘Interceptors’ and ‘River Trash Booms’ deployed in Jakarta and Bali (Indonesia) and the Klang River (Malaysia) have been described as success stories by preventing several tonnes of plastic waste from entering the marine environment daily (Brooijmans et al., 2019; Cordova et al., 2021a; Cordova and Nurhati, 2019; Fauziah et al., 2021), these water bodies remain amongst the most heavily polluted in the region (Koagouw et al., 2021; Zaki et al., 2021). In the Mekong River, which intersects five countries in Southeast Asia, plans to install a unit of interceptors (River Cleanup, 2020) will be similarly challenged by much larger pollution problems which have drastically reduced fish stocks, displacing riverine livelihoods and communities across the region. Furthermore, the large population size, lack of waste disposal infrastructures, and low official recycling rates are all factors which have resulted in a significant amount of plastic waste entering the marine environment (Glaeser and Glaser, 2010; Shuker and Cadman, 2018). Identifying and targeting these land-based leakage points (see section 3.1.3) represents one of several possible interventions (see section 3.5.4) to reduce marine plastic pollution from freshwater source points in the region.

3.5.2 Question 17: How can a circular economy of plastics be developed to benefit livelihoods in coastal communities in Southeast Asia?

To be cost-effective and socially viable, interventions need to engage the full range of business, government, and societal stakeholders into coordinated activities to reduce the amount of plastic entering the marine environment and to increase public awareness and participation (see section 3.5.3). Beyond the promise held by urban waste recycling movements across the region which have been led by eco-concerned consumers and informal waste pickers, there is still considerable room for improvement. Additionally, despite preliminary work done by Liu et al. (2009), the benefits of a circular economy of plastics, whereby plastic items are reused/repaired/recycled rather than thrown away and which can be used as an important tool for engaging with businesses and local communities to benefit livelihoods, has only entered policy circles relatively recently in Southeast Asia (Laurieri et al., 2020; Luqmani et al., 2017; Visvanathan and Anbumozhi, 2018). To implement viable solutions, the connection between local communities' behaviours, perceptions, and awareness, in addition to local government's environmental concepts, policies, and infrastructure should be improved to ensure public participation and support for plastic waste reduction (Du et al., 2018; Morren and Grinstein, 2016; Stuchtey et al., 2019). Notwithstanding, the justifiable critiques of the circular economy for failing to address the underlying problems inherent in capital-driven growth (Valenzuela and Böhm, 2017), this framework is worthy of further exploration for its incentive-based potential (Andriamahefazafy and Failler, 2021).

3.5.3 Question 18: How to design effective, comprehensive awareness, education, and monitoring programmes?

Grassroots environmental groups and mass media campaigns are crucial in increasing public awareness around environmental issues (Garcia et al., 2019; One Planet, 2021), while large scale scientific reports (e.g., Jambeck et al., 2015) aid understanding around the significance and severity of marine plastic pollution in Southeast Asia. To be effective, however, national governments would first need to reduce their heavy reliance on profitable but polluting industries. Environmental accountability and transparency in policy choices could be enhanced through the generation of environmentally relevant data (Chen, 2015), which should ideally be made available on open-access databases to ensure transboundary data sharing. Establishing long-term monitoring protocols which are compatible with international regulations will be essential to best design suitable strategies to tackle the issue of marine plastic pollution (Cheshire et al., 2009; OSPAR, 2010). Coastal clean-ups provide a valuable contribution to the monitoring of marine plastic pollution (e.g., Nelms et al., 2021; van Calcar and van Emmerik, 2019), while deepening stakeholder collaboration and promoting custodianship and responsibility of care to coastal communities (Hidalgo-Rus and Thiel, 2015; Hong et al., 2014). Initiatives that target an ‘all hands-on deck’ approach, involving multiple stakeholders (e.g., citizen, corporations, manufacturers), at local, (sub-)national, and regional scales are arguably the most suitable mechanisms to target marine plastic pollution, but these remain largely confined to fixed-term projects in Southeast Asia (Garcia et al., 2019).

3.5.4 Question 19: How effective are the major regional policy interventions to reduce plastic waste?

Recently, there has been considerable regional-scale plastic pollution policy action in Southeast Asia. For example, the Association of Southeast Asian Nations (ASEAN) Regional Action Plan for Combating Marine Debris in the ASEAN Member States (2021–2025) provides support for collaboration on 1) policy support and planning; 2) research, innovation, and capacity building; 3) public awareness, education, and outreach; and 4) private sector engagement (Lyons et al., 2020). Similarly, the Coordinating Body on the Seas of East Asia (COBSEA) strategic directions 2018-2022 (UNEP, 2020) has established a regional action plan to tackle land-based sources of marine plastic pollution (COBSEA, 2019, 2018). Nationally, interventions in the region have focused on isolated actions, such as bans of specific plastic items (Knoblauch et al., 2018), deposit-return schemes (Wardoyo, 2018), and biodegradable packaging (e.g., Avani, 2014; Evoware, 2017), rather than on systemic changes to reduce single-use plastics (Hermawan and Astuti, 2021; Marks et al., 2020; Maruf, 2019; Xuan Son, 2021). In a very limited way, some ASEAN countries are beginning to follow European counterparts in shifting responsibility and innovation to producers (e.g., extended producer responsibility; WWF Philippines, 2020), corporations (e.g., corporate social responsibility), and business operations (e.g., circular economy, see section 3.5.2), with the aim of implementing regional policy interventions which reduce plastic pollution entering the marine environment (see section 3.5.1), as shown by the recent EU-ASEAN GreenTech Dialogue and Innovation Mapping initiative (2021), currently piloted in the Philippines. National reforms to state waste management systems are also needed across the region to better deal with burgeoning domestic waste and the influx of plastic waste exports into Southeast Asia (see section 3.5.6). Above all, however, national cultures of consumption need to be reset along more sustainable development pathways, which can only be attained through multi-sectoral and multi-scalar efforts to change existing ecological behaviours in the longer term.

3.5.5 Question 20: What are the geopolitical roles of countries in exporting/transporting plastic waste in Southeast Asia?

Societal resentment among ASEAN member countries, particularly after China introduced its National Sword Policy banning plastic waste imports, completing its transition from a waste importing to a waste exporting country (Marks et al., 2020), has led some governments to refuse to import plastic waste (Global Alliance for Incinerator Alternatives, 2019a). However, a significant amount of plastic waste continues to both legally and illegally enter Southeast Asian countries. For example, investigations into recycling facilities in Thailand revealed that the lack of enforceability of regulations led to large amounts of plastic being smuggled and illegally processed in the country despite national restrictions on imports of recyclable goods (Sasaki, 2021). Similarly, almost one-third of waste imported into East Java, Indonesia was labelled as scrap paper despite being illegal scrap plastic (Marks et al., 2020), suggesting that such piecemeal bans on plastic waste imports could have counterproductive effects. Several countries, including Malaysia and the Philippines, have returned mislabelled waste, restricted or re-exported imports, and announced upcoming bans and regulations (Marks, 2019). Interstate initiatives and reforms to international legal frameworks are urgently needed to help address inequalities in the distribution of plastic waste between wealthy waste exporting countries and poorer waste importing countries. As part of this, enforceable (inter)national legislation is needed to make transnational corporations compliant with the safe and sustainable export and import of recyclable plastic waste. Analysis of the transnational plastic waste chain should thus take into account postcolonial histories as well as the challenges of global capitalism (Ronda, 2018), which are crucial to understanding the high degree of inequality in geopolitical relations between plastic exporting and importing countries. Multi-national companies with operations in ASEAN countries could contribute meaningfully to the reform of country-level industry practices by undertaking waste assessments, brand audits, and transitioning to ecologically safer and affordable packaging products (Global Alliance for Incinerator Alternatives, 2019b). This, in turn, promotes their participation in extended producer responsibility, which is gaining more traction in ASEAN countries, such as in the Philippines, which proposed to include this in their new policy on single-use plastics.

3.5.6 Question 21: What is the political framework of marine plastic governance and how can it be improved in Southeast Asia?

Transboundary governance of marine plastic pollution in Southeast Asia is failing for several reasons. Unlike climate change, there is as yet no global plastic agreement with binding targets and timelines to guide strong regional action (Borrelle et al., 2017). The development of international agreements has been more advanced for ocean-based than land-based sources of marine litter, which operate with relative impunity (Ferraro and Failler, 2020). Uncoordinated and fragmented national policies further undermine regional efforts (Dauvergne, 2018). In part, this political fragmentation is due to the close working relationship between state agencies and polluting fossil fuel and plastic industries which have successfully pushed back against policies to curb plastic consumption (Tabuchi et al., 2020) by emphasising the responsibility of consumers to deal with their own waste (Fuhr and Patton, 2019). Overall, governance of plastic is fragmented between sectors and spatial scales which undermines implementation at the national and subnational levels (Dauvergne, 2018; see section 3.5.4).

In March 2019, ASEAN adopted greater transboundary cooperation on marine plastic pollution, which is a critical starting point for collective action, although the Declaration now must be translated into actionable policies (ASEAN Secretariat, 2021). Such ASEAN-level commitments could open the political space and funding opportunities for innovative contributions at all scales of governance (Marks et al., 2020), as could the new United Nations Environmental Assembly resolution, adopted in March 2022 to end global plastic pollution, which is due to take legal effect by the end of 2024.

4. Conclusion

Although not unique to the region, the 21 priority research questions which guide and underpin this research agenda highlight the importance of better understanding the fate of marine plastic pollution, its degradation, and the impacts and risks it can generate across communities and different ecosystem services in Southeast Asia. Future research into these areas is needed to form a firm foundation for future policy development which currently suffers from transboundary problems relating to poor coordination, lack of responsibility and punitive measures for major polluters, and inaction to tackle the issue from its point source in the region. Being profoundly affected by marine plastic pollution, countries in Southeast Asia provide an opportunity to test the effectiveness of innovative and socially inclusive changes in environmental governance, as well as both high and low-tech solutions, which can offer insights and actionable models to the rest of the world.

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Figure 1. **Examples of plastic pollution in Southeast Asia:** a) after rainfall under the bridge of Sungai Ciluar, Bogor, Indonesia (photo credit: Muhammad Reza Cordova); b) in a mangrove forest in Carmen, Cebu, Indonesia (photo credit: University of San Carlos, SEAMaP team); c) in Rambut Island Wildlife Reserve, Jakarta Bay, Indonesia (photo credit: Muhammad Reza Cordova); d) on a beach in Tanah Merah, Singapore (photo credit: Tai Chong Toh); e) on a coral reef in Paiton, East Java, Indonesia during a coastal cleanup (photo credit: Ruly Istaful Khasana); and f) plastic bottles on the seafloor at Lazarus Island, Singapore (photo credit: Our Singapore Reef). – Please see online version of article for colour. Double column fitting image.

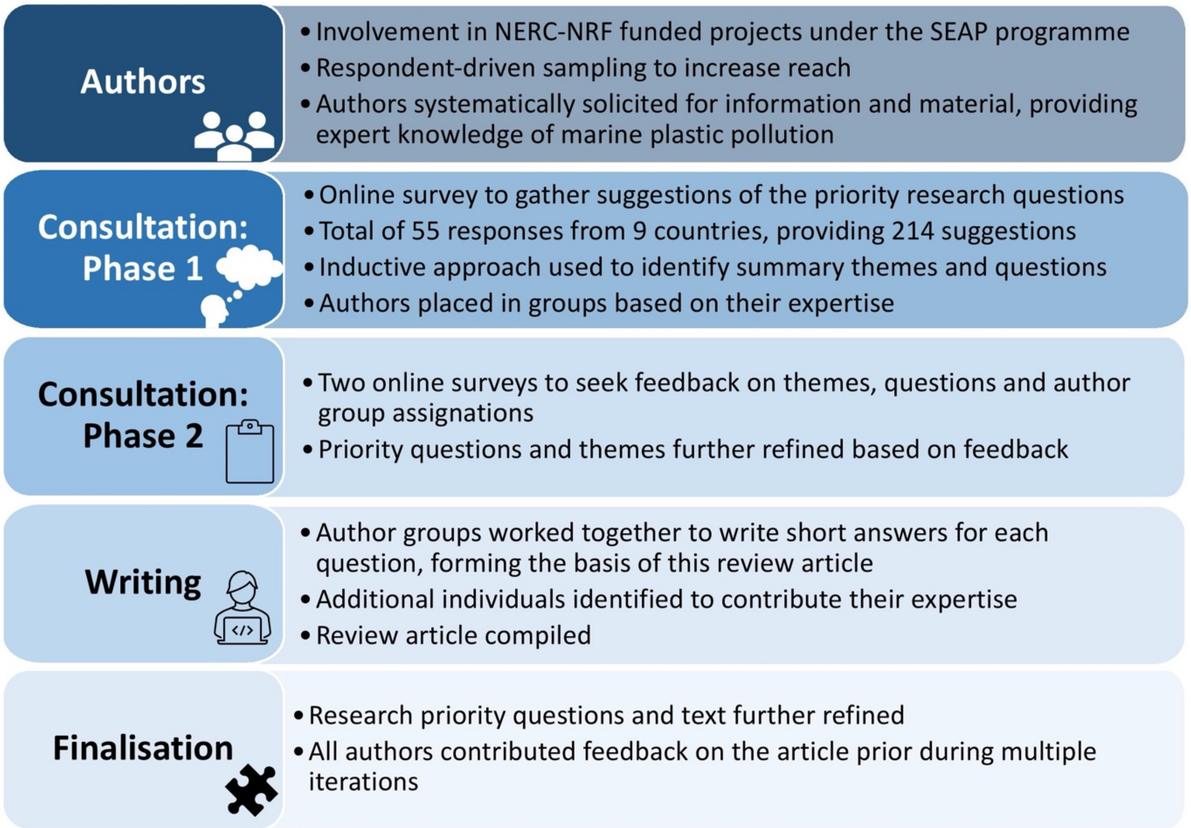


Figure 2. **Summary of horizon-scanning writing process**. – Please see online version of article for colour. Double column fitting image.

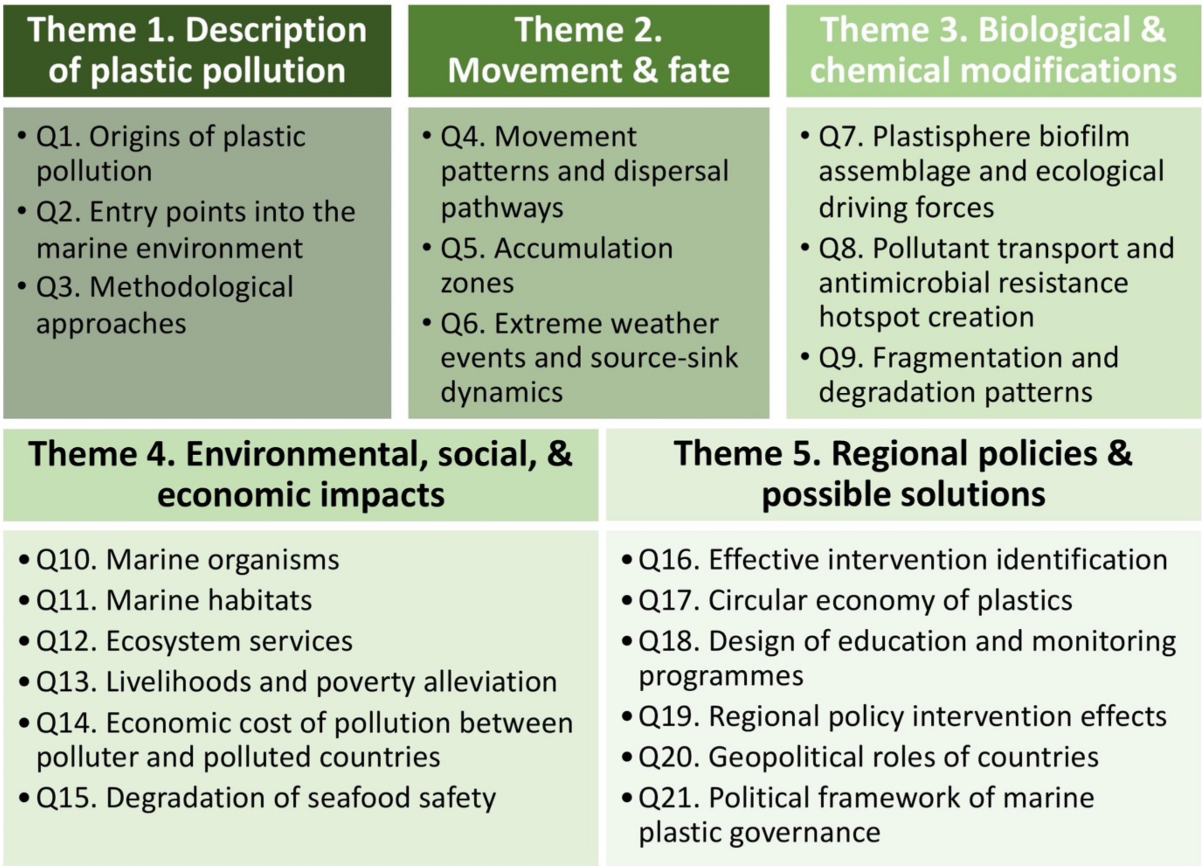


Figure 3. Summary of the five key themes covered in this review for the purpose of identifying research priorities for marine plastics in Southeast Asia. – Please see online version of article for colour. Double column fitting image.

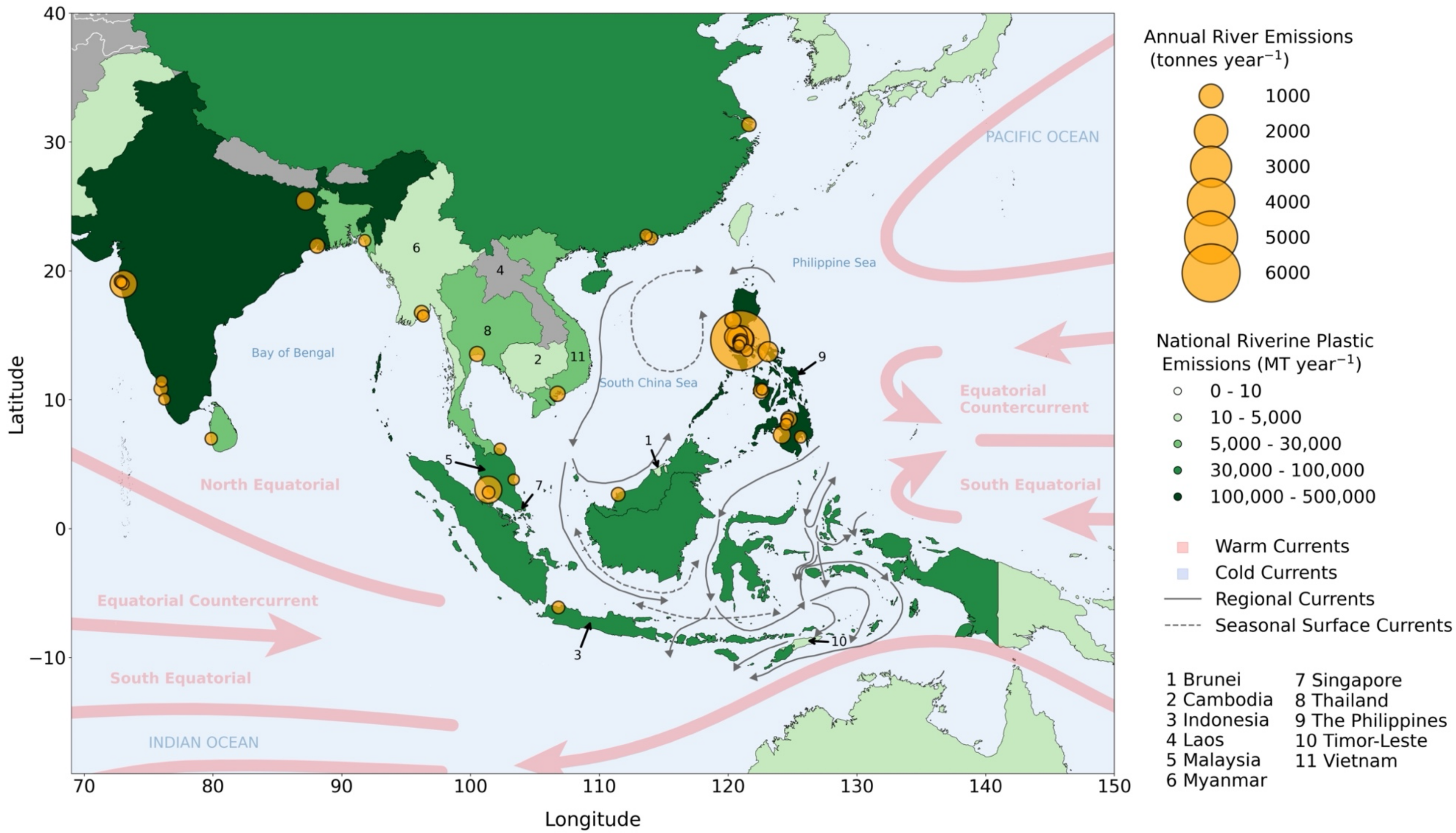
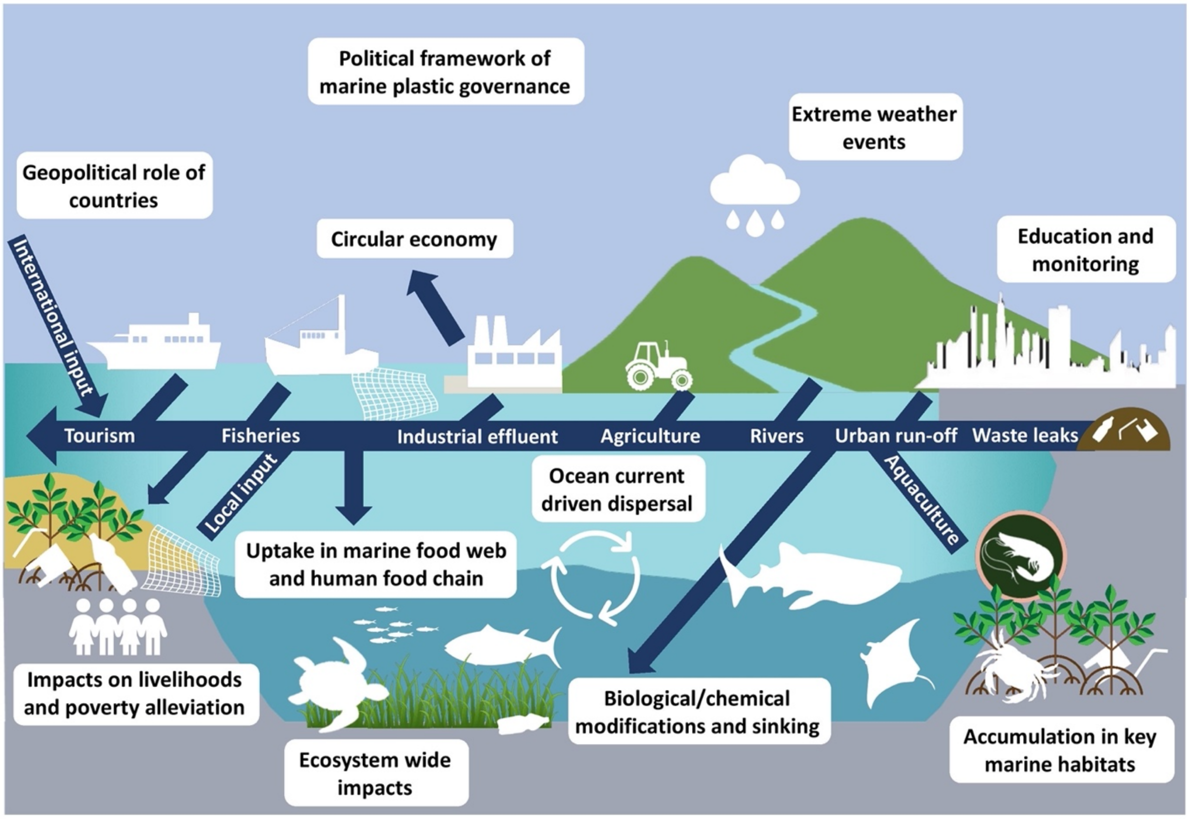


Figure 4. Map of Southeast Asia showing the principal ocean currents of the region and plastic emissions per country and river. The chloropleth map represents total plastic emitted into the ocean (millions of tonnes per year), while the scatter plot (orange) shows the geospatial distribution of the relative individual river emissions (tonnes per year). Global surface warm ocean currents are represented by the thick red arrows. Regional surface currents of the Indonesia Through Flow affecting the dispersal of marine plastic litter are represented with thin grey arrows. Data on plastic emissions from Meijer et al. (2021). – Please see online version of article for colour. Double column fitting image.

Highlights

- Established key research questions for marine plastic pollution in Southeast Asia
- Need to better understand fate, degradation and impacts of plastics regionally
- Suffers from transboundary problems, lack of responsibility and inaction
- Further research needed to support development of mitigation measures in the region

Graphical abstract



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Supplementary material

Table S1. Key research priority question to inform marine plastic pollution in Southeast Asia, their associated current knowledge and areas for further research.

Priority questions	Current knowledge	Areas for further research
Theme 1. Description of plastic pollution		
Q1. What are the origins of plastic pollution in the marine environment in Southeast Asia?	- Land-based sources from reliance on single-use plastics, exacerbated by COVID-19 pandemic - Sources of macroplastics: direct littering, marine dumping, aquaculture, and accidental loss from shipping and fishing activities - Sources of microplastics: plastic fragmentation, ocean circulation, and domestic sources - Leakage from overflowing landfills and over-burdened waste processing facilities as major producers/recipients of waste	- Quantify the amount of plastic waste entering the marine environment from each source
Q2. What are the main plastic entry points into the marine environment in Southeast Asia?	- Rivers are major transport pathways into the marine environment, with half of top 50 plastic emitting rivers predicted to be in Southeast Asia - Entry points include densely populated coastal regions, industrial estates, port facilities, landfill sites and beaches	- Understand the linkage between freshwater and marine plastic pollution - Identify important entry points for the development of waste management strategies - Combining in-situ sampling with novel technology and particle backtracking simulations could aid in determining potential sources
Q3. What are the most appropriate methodological approaches to characterise marine plastic pollution?	- Fourier Transform InfraRed (FTIR) or Raman spectroscopy mostly commonly used methods globally - Spatial variability in identified polymers from in-situ sampling	- International collaboration among research organisations to alleviate the scarcity of research equipment in Southeast Asia - Ensure use of standardised protocols for collection, identification, and monitoring to allow for regional and global comparisons
Theme 2. Movement and fate		

Q4. What drives dominant movement patterns and dispersal pathways of plastic in Southeast Asia?	- The Indonesia Through Flow (ITF) is the major current in the region, which interacts with the region's complex bathymetry and topography - Abundance of plastic-trapping habitats, such as mangroves, seagrasses, and coral reefs	- Develop three-dimensional, high-resolution models that explicitly include tides and their interactions, freshwater inputs, wave and wind dynamics, and extreme weather events - Address heterogeneity of plastics when parameterising aggregation, fragmentation and/or biofouling process in transport models
Q5. Which habitats act as major accumulation zones in Southeast Asia?	- Sessile biota in mangrove, seagrass and coral habitats directly accumulate plastic via snagging, filtering and adhesion, and indirectly influence local hydro- and sediment-dynamics - Connectivity between coastal and marine habitats can lead to the export of accumulated plastics	- Better quantify the volume of plastic pollution currently stored in mangrove, seagrass, and coral habitats - Understand the impacts and consequences for the coastal and riverine communities that depend on key habitats
Q6. How will extreme weather events influence source-sink dynamics in Southeast Asia?	- Temporal variability is a key factor in determining the transport of plastics and can be influenced by extreme weather events - Regionally, monsoon seasonal typhoons and storm surges, for example, have the potential to cause resuspension & dispersal of microplastics from accumulation zones	- Investigate impacts of sea level rise and probability distributions of extreme weather events on source-sink dynamics
Theme 3. Biological and chemical modifications		
Q7. What are the assemblage and ecological driving forces of plastisphere biofilms?	- Composition and functional capacity of plastisphere biofilms influenced by the size and chemical composition of plastics and the surrounding environment - Differences in gene expression profiles among communities present in microplastic biofilms	- Study the composition and ecological functions of microorganisms within biofilms in Southeast Asia - Understand the metabolic capacity of plastisphere communities - Contribute towards determining whether a core plastisphere exists that is significantly different to non-plastic biofilms

Q8. What is the potential for marine plastic pollution to transport pollutants and create hotspots of antimicrobial resistance?	- Potential sorption of co-pollutants, microorganisms and invasive species to marine plastic pollution represents a significant threat to ecosystem health - Combination of microorganisms and pollutants can cultivate the development of antibiotic resistance genes on marine plastic pollution	- Investigate the role of plastics as surfaces for developing and disseminating antimicrobial resistance in Southeast Asia - Explore the pathogenic activity of antibiotic resistant microorganisms on marine plastic pollution and the risk posed to humans and animals
Q9. What is the pattern of fragmentation and degradation of plastic pollution?	- Polymer degradation in the environment is influenced by abiotic factors and the presence of microorganisms - Members of several bacteria phyla have regularly been linked to plastic degradation	- Continue research on biodegradation of plastics by microbes in the region and in novel locations - Develop thorough standardised testing methods to enhance understanding of plastic fragmentation and degradation
Theme 4. Environmental, social, and economic impacts		
Q10. What are the impacts of plastic pollution on marine organisms?	- Plastic ingestion (ranging from macro- to microplastic) has been documented in numerous taxa in Southeast Asia - Reports of entanglement present for species and impacts of abandoned, lost, or otherwise discarded fishing gear on habitats such as coral reefs	- Investigate ingestion in seabirds in the region as publications are currently lacking entirely for this taxon - Explore trophic transfer, having implications for sea food safety - As the impacts of marine plastic pollution are multi-faceted, there is a need for a greater understanding of these impacts in Southeast Asia, particularly for endemic species
Q11. What are the impacts of plastic pollution on key marine habitats in Southeast Asia?	- Macroplastics become trapped by biological structures, while microplastics become incorporated into sediments - Plastic pollution negatively impacts marine habitats by mechanical and chemical means, altering microbial and macrofaunal communities - Micro- and nano-plastics alter microbial and planktonic community composition, influencing the regulation of oceanic carbon cycles	- Study how micro- and nanoplastics affect the biogeochemistry of their associated substrata more widely in Southeast Asia - Build on and expand the geographical scope of emerging studies into the incorporation of plastics into sediments and their effects on microbial communities

Q12. What are the impacts of plastic pollution on marine ecosystem services in Southeast Asia?	- Many ecosystem services are known to be particularly vulnerable to the deleterious effects of plastic pollution, in turn impacting the extent of ecosystem service provision - Unsustainable practices related to ecotourism in Southeast Asia generate significant levels of marine plastic pollution - The impact of plastic pollution on key fisheries species will have wide-ranging impacts due to the importance of this industry in Southeast Asia	- Better understand the consequences of plastic polluting behaviours upon high-value ecosystem services as well as those provided by important habitats in the region
Q13. What are the relationships between marine plastics, livelihoods, and poverty alleviation in Southeast Asia?	- Costs of marine plastic pollution unequally distributed across countries and populations - Single-use plastic products can help increase hygiene and access to sanitary products, as well as reduce disease - Sizeable informal waste sector fill an important gap in ineffective state waste management systems	- Explore how we can collectively nurture more ecologically sustainable behaviours which bridge existing gaps between sectors and across socioeconomic groups
Q14. How is the economic cost of pollution shared between polluter and polluted countries in Southeast Asia?	- Some Southeast Asian countries are both primary producers and heavily impacted by marine plastic pollution - Primary producers often not the countries impacted by marine plastic pollution due to exportation, meaning that developing countries tend to bear the cumulative environmental, health and socioeconomic burdens of ill-disposed waste	- Develop and enforce international legislation to hold major polluters accountable and reduce the incentive for any single country to take responsibility for transgressive cross-border flows - Ensure that wealthy countries contribute more meaningfully towards the costs of mitigating the socioeconomic impacts of domestic waste offshoring
Q15. What is the role of plastic debris in degrading seafood safety?	- High reliance on and consumption of seafood among dependent coastal communities in Southeast Asia could have significant negative health impacts	- Investigate the impacts of marine plastic pollution on species for human consumption and how these may be translated into associated risks to human health

	- Ability of diverse human pathogens and antibiotic resistant bacteria present on marine plastic to enter the human food chain through secondary consumption	
Theme 5. Regional policies and possible solutions		
Q16. How can we identify effective interventions in Southeast Asia?	- Many areas of Southeast Asia lack technological solutions readily available to developed countries - Waste interceptors in rivers in the region have successfully been trialled and prevented several tonnes of plastics from entering the marine environment	- Identifying and targeting land-based leakage points represents one of several possible intervention to reduce marine plastic pollution
Q17. How can a circular economy of plastics be developed to benefit livelihoods in coastal communities?	- The benefits of a circular economy of plastics have only entered policy circles relatively recently in Southeast Asia	- Develop viable solutions involving all stakeholders to ensure public participation and support for plastic waste reduction - Further explore the potential of a circular economy of plastics in the region
Q18. How to design effective, comprehensive awareness, education, and monitoring programmes?	- Grassroots environmental groups and mass media campaigns increase public awareness campaigns, while scientific reports aid understanding of the significance and severity of the problem - Coastal clean-ups provide a valuable contribution to the monitoring of marine plastic pollution, deepening stakeholder collaboration and promoting individual responsibility of care	- Strive to implement approaches targeting marine plastic pollution which involves multiple stakeholders at local, national, and regional scales - Establish long-term monitoring protocols, compatible with international regulations to develop regional policies on environmentally relevant data

Q19. How effective are the major regional policy interventions to reduce plastic waste?	- Considerable recent regional-scale plastic pollution policy action in Southeast Asia, which have focused on isolated actions, such as bans on specific items and biodegradable packaging, rather than on systemic change	- Develop and implement national reforms to state waste management systems to better deal with burgeoning domestic waste and the influx of plastic waste exports in Southeast Asia - Align national cultures of consumption along more sustainable development pathways, through multi-sectoral and multi-scalar efforts to change existing ecological behaviours in the longer term
Q20. What are the geopolitical roles of countries in exporting/transporting plastic waste in Southeast Asia?	- Following China's National Sword Policy, there has been some societal resentment among Southeast Asian countries with some governments refusing to import plastic waste - Illegally entry of significant amounts of plastic waste - Multi-national companies can contribute meaningfully to geopolitical relations through waste assessment and brand audits - Extended producer responsibility is gaining more traction in the region	- Implement interstate initiatives and reforms to international legal frameworks to help address inequalities in the distribution of plastic waste between exporting and importing countries - Enforce legislation (inter)nationally to make transnational corporations compliant with the safe and sustainable export of import of plastic waste
Q21. What is the political framework of marine plastic governance and how can it be improved in Southeast Asia?	- Transboundary governance failing for several reasons in the region - Uncoordinated and fragmented national policies undermine regional efforts, with plastic governance fragmented between sectors and spatial scales	- Continue the development of greater transboundary cooperation on marine plastic pollution which could open the political space and funding opportunities for innovative contributions at all scales of governance - Participate in discussions to develop a global agreement to tackle marine plastic pollution