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Multiple negative impacts of marine plastic pollution on tropical coastal ecosystem services, and human health and well-being

Carya Maharja [a,b,e], Radisti A. Praptiwi [a,c,*], Sainal Sainal [a], Prawesti Wulandari [a,b], Matthew Ashley [d], Kayleigh J. Wyles [e], Joyashree Roy [f,g], I Gede Hendrawan [h], Susan Jobling [i], Melanie C. Austen [d]

[a] Sustainability Research Cluster and Department of Biotechnology, Universitas Esa Unggul, Jakarta, 11510, Indonesia
[b] Yayasan Puspa Hanuman Indonesia, Bogor, 16113, Indonesia
[c] Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor KM 46, Cibinong, Bogor, 16911, Indonesia
[d] School of Biological and Marine Sciences, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, United Kingdom
[e] School of Psychology, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, United Kingdom
[f] SMARTS, Asian Institute of Technology (AIT), Pathumthani, Thailand
[g] Global Change Programme, Jadavpur University, Kolkata, India
[h] Department of Marine Science, Faculty of Marine Science and Fisheries, Udayana University, Bali, Indonesia
[i] The PISCES Partnership, Division of Environmental Sciences, College of Health, Life and Medical Sciences, Brunel University London, Uxbridge, UB8 3PH, United Kingdom

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ABSTRACT

There is limited empirical evidence showing the impacts of marine plastic pollution on ecosystem services or on human health and well-being in Global South countries. We aimed to estimate these impacts in the tropical archipelago of Indonesia, one of the top emitters of marine plastics globally, through an iterative Delphi survey, with an expert panel ($n = 42$) consisting of equal numbers of Indonesian scientists, policymakers, and practitioners. After two rounds of the survey, the analysis of interquartile ranges indicated that the experts reached a consensus in their predictions. The experts agreed that, over the next 10 years, plastics would be mainly accumulated in the coastal area of Java, the most densely populated island, and mostly in mangrove ecosystems. While all ecosystem services were harmed by plastic pollution, the most vulnerable services were food provisioning, genetic materials, nursery habitat, and recreation supplied by the highly vulnerable coastal ecosystems of, in descending order, mangrove, coral reef, seagrass, and sandy beach. These impacts on ecosystem services influenced different dimensions of human health and well-being and were dependent on the ecosystem types, as indicated in several statistically significant positive correlations (Spearman's rank), including those between the decline of mangrove ecosystem services and reduced household income, and between the decrease of coral reef ecosystem services and both deteriorating mental health and reduced household income. Overall, this study provides the first indication of Indonesian coastal ecosystems and ecosystem services to be prioritized for mitigation and monitoring efforts. The focus on impacts on human health and well-being also incentivizes ongoing efforts by policymakers, industry and commerce, the third sector, and the public in the country to address the contribution to global marine plastic pollution.

1. Introduction

1.1. Marine plastic pollution: sources and impacts

The versatility, durability, and competitive production cost of plastics have made these materials ubiquitous in consumer and industrial markets worldwide (Ren et al., 2020). Global production of plastics reached 368 million metric tons in 2019 and is predicted to double by 2039 (Lebreton and Andrady, 2019; Walker, 2021). Currently, about 40% of plastics are produced for short-lived single-use applications, chiefly as packaging, to be disposed of immediately after their use (Charles and Kimman, 2023). However, the used plastics often end up as

* Corresponding author. Sustainability Research Cluster and Department of Biotechnology, Universitas Esa Unggul, Jakarta, 11510, Indonesia.
E-mail addresses: radisti.ayu@esaunggul.ac.id, radisti_ayu@outlook.com (R.A. Praptiwi).

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wastes that enter the natural environment due to high production volume and inadequate end-of-life management, characterized by insufficient infrastructures, ineffective recovery techniques, and expensive recycling processes (Forrest et al., 2019; Ajibade et al., 2021).

Existing studies have indicated that a substantial amount of discarded plastics, ranging from 0.8 to 30 million metric tonnes, is released into the marine environment annually (Jambeck et al., 2015; Borrelle et al., 2020; Lau et al., 2020; Meijer et al., 2021). About 20% of the influx of plastics into the sea are estimated to be direct discharges from marine sources, such as fisheries and aquacultures, while the remaining 80% are generated inland (Li et al., 2016) and transported mainly through rivers (Lebreton et al., 2017; Schmidt et al., 2017). Although approximately 65% of plastics ever produced historically have positive buoyancy in seawater (Geyer et al., 2017), most plastics entering the sea from these marine and terrestrial sources will likely undergo a process of surface fouling (Póvoa et al., 2021) and degradation to microplastics, eventually causing them to be suspended in the water column or to sink into the seabed (Law, 2017; Pabortsava and Lampitt, 2020). Furthermore, recent modeling studies (Chenillat et al., 2021; Onink et al., 2021) suggest that as much as 93% of plastics released into the Earth's oceans are either beached or stranded in coastal ecosystems due to the combined effect of fouling, and regional oceanographic and meteorological conditions.

Despite the restricted transport in the sea, the accumulation of plastics in coastal areas can cause a variety of adverse social-ecological impacts. Studies have found that animal species feeding in coastal waters ingest higher quantities of plastics than other species feeding further away from the coast (Schuyler et al., 2013; Akhbarizadeh et al., 2018; Santos et al., 2021; Li et al., 2022). Once ingested, these plastics can damage digestive organs, potentially leading to mortality (Gall and Thompson, 2015), or act as vectors for toxic heavy metals and harmful organic pollutants (Rochman, 2015; Meñendez-Pedriza and Jaumot, 2020). Besides these impacts, plastics accumulated in coastal areas have been found to be colonized by invasive species (Kiessling et al., 2015; Arias-Andrés et al., 2018), to carry pathogenic microorganisms (Curren and Leong, 2019; Rodrigues et al., 2019), to cause physical harms due to entanglement (Høiberg et al., 2022), and to smother coastal sedimentary habitats leading to reduced gas exchange and respiratory failure of various benthic organisms (Green et al., 2015, 2016). In addition to these ecological impacts, plastic accumulation in coastal areas can lead to negative consequences for human societies, for instance through declining tourism and leisure activities (Hayati et al., 2020), economic loss to the fisheries sector (Antonelis et al., 2011), and disruption to maritime transportation (McIlgorm et al., 2011). These societal impacts may also extend into direct human health impacts, through, for instance, the ingestion of plastic particles from contaminated seafood (Danopoulos et al., 2020), with the consumed plastics potentially interfering with human's blood circulation system (Leslie et al., 2022).

Despite the emerging evidence, the majority of available research on marine plastic pollution still focuses on measuring the presence of plastics in marine biota and their distribution in a particular ecosystem, mainly on beaches (Villarrubia-Gómez et al., 2018; Haarr et al., 2022). As a result, there is only limited knowledge of the impacts of plastic pollution on the structure and function of coastal and marine ecosystems and the human societies that rely on them (Wang et al., 2023a; Yose et al., 2023). Through the processes inherent in them, these ecosystems produce a myriad of ecosystem services, crucial for human health and well-being (Barbier et al., 2011). Globally, the accumulation of plastics in these ecosystems has a high potential to cause a decline in the supply of ecosystem services, such as recreation opportunities and the provision of food, leading to substantial economic losses, ranging from USD 500 to USD 2500 billion annually (Beaumont et al., 2019). As such, it has been commented that future research on marine plastic pollution should attempt to gather knowledge on its impacts at the ascending analytical levels of ecosystem functions or processes, the ecosystem services they generate, and the resultant link to human health and well-being (Ladewig et al., 2021), all of which will differ according to the ecosystem types, such as mangrove or coral reef (Green, 2020). This research should also prioritize maritime areas with large influxes of marine plastics, such as Southeast Asia, where fewer studies have been performed compared to other regions with smaller influxes such as the North Atlantic and Pacific (Haarr et al., 2022).

Our study focused on Indonesia, the Earth's largest archipelagic country located in Southeast Asia, with its coastline spanning 81,000 km and 160 million people living in coastal areas (Adyasari et al., 2021). As indicated in modeling studies, the country is the second biggest emitter of plastics into the Earth's oceans after China (Jambeck et al., 2015; Meijer et al., 2021). Despite the rapid increase in its population and economic development, solid waste management in the country is still not adequately implemented, serving only about 47% of its population, mainly in urban areas (Lestari and Trihadiningrum, 2019). As a result, a large quantity of plastic waste is released into coastal waters from Indonesian islands, ranging from 0.2 to 1.73 million metric tonnes annually, based on estimates from current global models (Arifin et al., 2023). Most of these plastic leakages into the Indonesian seas remain within the country's exclusive economic zone (Onink et al., 2021), mainly stranded in coastal waters or washed ashore into the coastlines due to the region's intricate bathymetry and topography (Dobler et al., 2022).

The coastal areas of Indonesia where plastics accumulate are locations of high biodiversity, hosted within the world's largest expanse of mangrove, coral reef, and seagrass ecosystems (Burke et al., 2011; Giri et al., 2011; Unsworth et al., 2018). The ecosystem services from these natural environments are vital for the health and well-being of the predominantly coastal population of the country (Maharja et al., 2023a), many of whom form small-scale fishing communities and rely directly on coastal and marine ecosystems for their livelihoods (Teh and Pauly, 2018). Such reliance translates into significant economic value of the ecosystem services, which, for instance, can reach as high as USD 1 billion for the country's reef fisheries (Bartelet et al., 2024). Thus, the accumulation of plastics in the coastal and marine areas of Indonesia can negatively impact not only the country's maritime biodiversity but also both the Indonesian economy and the health and well-being of its residents.

Nonetheless, research on marine plastic pollution in Indonesia has only emerged and grown steadily from the year of 2013, predominantly emphasizing the most-densely populated island of Java (Vriend et al., 2021) and typically focusing only on the measurement and characterization of plastics stranded on the country's beaches (Purba et al., 2019). As such, there is a lack of empirical evidence on the social-ecological consequences of marine plastic pollution in Indonesia, particularly in relation to its impacts on ecosystem services (Omeyer et al., 2022). This is despite the growing awareness of the issue of marine plastic pollution amongst the general public of Indonesia and their demand for further research on the topic to inform mitigation efforts (Tyllianakis and Ferrini, 2021).

1.2. Research aim, questions, objectives, and strategy

This paper aims to estimate the impacts of marine plastic pollution on ecosystem services and human health and well-being in Indonesia, guided by the following research questions (RQs).

- RQ1: What geographical patterns of marine plastic accumulation will take place in Indonesia for the next 10 years?
- RQ2: How will plastic accumulation in Indonesian coastal waters influence ecosystem services provided by specific types of coastal ecosystems?
- RQ3: How will the accumulation of plastics in specific coastal ecosystems influence specific human health and well-being dimensions?

Considering the paucity of empirical studies performed on these topics, our research strategy was to engage Indonesian expert stakeholders in an exploratory study, through a process of iterative survey (a Delphi process), as further detailed in Section 2. The exploratory logic of our study necessitated that our focus was on identifying further areas where empirical evidence would be needed, instead of confirmatory testing of hypotheses (Nilsen et al., 2020). As such the following objectives were set out instead in our study: a) identifying Indonesian geographical regions and coastal and marine ecosystems where most plastics are perceived to accumulate over the next 10 years; b) predicting the impacts of the accumulation of these marine plastics on ecosystem services; and c) assessing how plastic accumulation in various coastal and marine ecosystems may influence multiple dimensions of human health and well-being. Our study thus acts as one of the first attempts to indicate the ecosystem service and human health and well-being consequences of marine plastic pollution in different types of tropical coastal ecosystems, using the ecologically diverse but largely polluted context of Indonesia. The results obtained can be used to inform future research studies, management measures, and mitigation efforts by revealing, through the consensus of experts, the Indonesian coastal ecosystems and associated ecosystem services that have to be prioritized in such undertakings.

2. Methodology

2.1. The Delphi process

The Delphi method is a technique applied to distill expert knowledge on a topic, typically using an iterative process based on a structured questionnaire (Diamond et al., 2014; Sourani and Sohail, 2014). The process of Delphi generally seeks a consensus on the queried topic from a group of experts in a data-scarce or highly uncertain situation (Hallowell and Gambatese, 2010). The Delphi process commonly involves anonymous and remote participation from the experts, hence its capability to transcend geographical boundaries and reduce biases arising from group dynamics, such as groupthink and domineering opinions, found in more-direct group elicitation techniques (McMillan et al., 2016; Humphrey-Murto et al., 2016). The method has been widely applied in a range of disciplines, including the health and social sciences (Beiderbeck et al., 2021), with increasing uses in ecosystem service studies, for instance in assessing environmental management impacts (Lecegui et al., 2022), measuring the risk of environmental changes (Armstrong et al., 2019), and mapping marine ecosystem services (Belgrano et al., 2021).

The application and reporting of the Delphi process in this study followed existing best-practice guidelines (Belton et al., 2019; Diamond et al., 2014), stipulating the detailed documentation and descriptions of all key steps, including expert recruitment, statistical analyses, the number of survey iterations, and the completion time of each iteration. The transparent reporting of these details is essential to enable the evaluation of the trustworthiness of a Delphi study according to the two relevant criteria of credibility and dependability (McPherson et al., 2018). Such criteria are salient for a Delphi study since the process intrinsically relies on the judgments provided by the participating experts, who can produce biased results due to subjectivity and uninformed deliberations (Krueger et al., 2012). However, the iterative and anonymous nature of the Delphi process mitigates this risk of bias by providing opportunity for reflexive and careful ruminations about the issues being appraised (Donohoe 2011), with experimental studies demonstrating the content and face validity of Delphi results (Morgan et al., 2007; Huang et al., 2008; Sharkey and Sharples, 2001). Nonetheless, there is an inherent limitation on the use of Delphi to analyze complex systems characterized by emergent properties, such as ecosystem services and human well-being (Brueckner-Irwin et al., 2019). Accurate predictions on the behaviors of such systems have been argued to be impossible, due to the nonlinear and stochastic interactions amongst system elements (Bennett et al., 2016). As commented by Benitez-Capistros et al. (2014), the use of the Delphi process to study complex systems can only produce indications of the system elements and attributes that future studies can focus on, particularly in relation to the type of empirical data needed to validate the Delphi results. These considerations on the limitations of the Delphi process and the future studies our results suggest are further discussed in Section 4.3 (Limitations and further studies).

A recent systematic review reveals that the iterative survey applied in Delphi is normally set for two rounds (Niederberger and Spranger, 2020), as adding more rounds does not lead to a substantial increase or decrease in the consolidation of the group opinions (Belton et al., 2019). The iterative nature of Delphi enables the participating experts to consult the results of the first round, provided as an anonymized summary report for each expert, and to reconsider their answers if they deem necessary (Sourani and Sohail, 2014). This approach ensures that each expert can provide an appraisal informed by the judgment of fellow experts, which has been demonstrated to enhance the validity and reliability of estimates obtained through the Delphi process (Hasson and Keeney 2011).

This study applied a two-round Delphi process comprising five stages (Fig. 1), following the recommendation of Mukherjee et al. (2015). The first stage consisted of two concurrent processes of selecting the panel of experts (described in section 2.2) and structuring the questionnaire (described in Section 2.3). In the second stage, the questionnaire was made available to the experts for the first round of the Delphi survey (on October 18, 2022). The experts were given eight weeks, following Keeney et al. (2006), to fill out the questionnaire using Google Forms for those with internet connections or via telephone interviews for those without. The questionnaire answers from the first round were then analyzed in the next stage for central tendency (mean and median) and dispersion (standard deviation), which were then summarized in an anonymized report. The fourth stage began with the distribution of the report and the same questionnaire to the panel of experts (on March 23, 2023) who were instructed to evaluate the report and review the answers they gave in the first round. The duration for this stage was also eight weeks, with the experts eventually deciding to revise or maintain

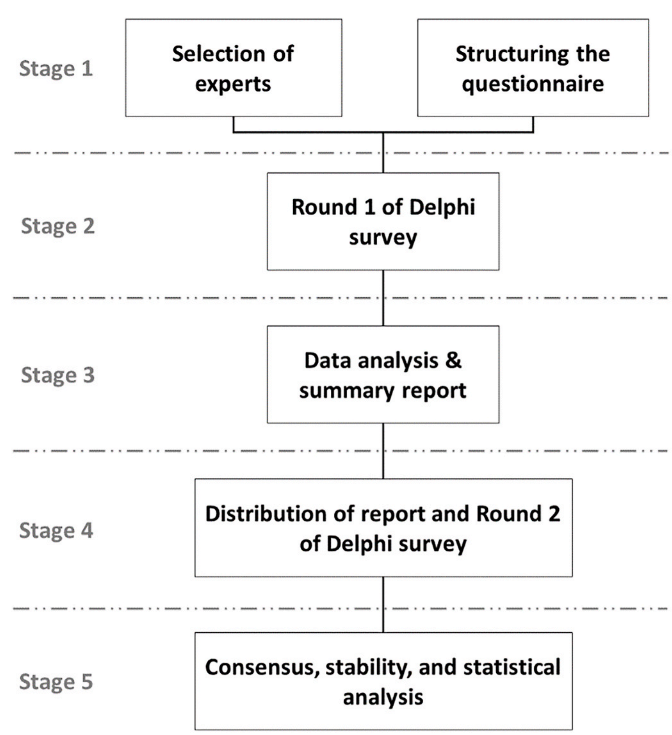

Fig. 1. The five-stage Delphi process applied in this study, including two rounds of survey.

the answers they already provided in the first round. The last stage consisted of the analysis of the second round of questionnaire results, including consensus and stability measurements, and further statistical analysis (described in Section 2.4). Ethics approval for this study was obtained from the Research Ethics Committee of Universitas Esa Unggul (No. 0922-06.014/DPKE-KEP/FINAL-EA/UEU/VI/2022 approved on June 14, 2022), with confirmations of informed consent provided by each expert before they participated in the Delphi surveys. Ethics approval and consent to participate are based on ensuring participant's anonymity and thus prevent publication of particular types of identifying data, including names and organizational affiliations of the experts.

2.2. Selection of experts

In a Delphi study, an expert is defined as an individual who, through their experiences, has gathered specialized knowledge related to the issue being investigated (Sourani and Sohail, 2014). The panel of experts in a Delphi study should consist of at least 15 individuals (McMillan et al., 2016) from two or three groups of heterogeneous expertise types (Avella, 2016) to ensure that the estimates generated through the Delphi process reflect the variety of expert perspectives, enhancing the accuracy and plausibility of Delphi results (Bolger and Wright, 2011; Spickermann et al., 2014). A Delphi study recruits its panel of experts purposively based on pre-determined criteria of expertise and their availability and willingness to participate in the Delphi process (Devaney and Henchion, 2018).

The experts involved in this study consisted of scientists, policymakers, and practitioners, with specific expertise criteria for each group. For scientists, the expertise criteria included records of relevant peer-reviewed publications in international or Indonesian scientific journals (a minimum of one as the first author), presentations at scientific conferences (a minimum of one), and their faculty roles or departmental positions (as a tenured faculty member). For policymakers, the criteria included years of experience (at least three years), and employment in Indonesian government bodies identified in a previous study to be responsible for overseeing the decentralized and polycentric governance of coastal and marine areas, including legislators, regional planning agents, and various ministerial representatives (Fortnam et al., 2022). For practitioners, the criteria consisted of years of experience (at least three years) and leading roles in community, private, or non-governmental organizations working on marine conservation or the mitigation of marine plastic pollution in Indonesia. Based on these criteria, a list of experts encompassing the coastal geography of Indonesian regions, as delineated according to the Indonesian government (The Ministry of National Development Planning/National Development Planning Agency, 2020), was prepared with an equal distribution amongst the three expert groups. Each category of expert was characterized with a particular type of knowledge accrued through pertinent professional experiences (Table 1). The experts were contacted individually to explain the purpose of this study and request their participation. All of the 42 contacted experts (Fig. 2) agreed to participate voluntarily in the Delphi process conducted in this study (100% response rate).

Table 1
The types and sources of knowledge for each category of experts participating in this study.

Category of experts	Knowledge types and sources
Scientists	Scientific knowledge gathered through first-hand experience in performing research studies in marine natural and social sciences.
Policymakers	Substantive and regulatory knowledge based on day-to-day engagement with political processes to set targets and mobilize resources for issues related to marine conservation and marine pollution mitigation.
Practitioners	Practice-based knowledge gathered from community engagement and empowerment activities, and from implementation of local interventions to address marine conservation and pollution issues, including through the establishment of marine protected areas, beach clean-ups, and waste bank initiatives.

2.3. Questionnaire format

The questionnaire used in this study (**Appendix A**) was formulated and developed through a co-design workshop and consultation held in Indonesia on May 23rd, 2022 involving research scientists from the fields of systems thinking, marine ecology, environmental psychology, economics, environmental economics, oceanography, and social-ecology. The questionnaire was further refined by consulting existing literature on questionnaire development and quantitative studies on ecosystem services and human well-being (e.g., Dick et al., 2018; Lindert et al., 2015; Oosterveld et al., 2019). The resulting questionnaire was structured to contain five sections asking the experts to provide their answers related to: 1. the future 10-year trend of marine plastic accumulation in existing Indonesian geographical regions (Fig. 2) and coastal and marine ecosystems (five-point Likert scale of -2 = large decrease to 2 = large increase), 2. the impacts of plastic accumulation in the ecosystems on ecosystem services (five-point Likert scale of -2 = large decrease to 2 = large increase), 3. the impacts of plastic accumulation in each ecosystem on human health and well-being dimensions (five-point Likert scale of -2 = large decrease to 2 = large increase), 4. The expertise profile (five-point Likert scale of 1 = not-at-all aware to 5 = high expertise), and 5. the background demographic profile of the expert (age, gender, level of education, and years of experience). The questionnaire was preceded with a background section detailing the definitions of each specific ecosystem service and human health and well-being dimension, and providing a visual representation of each coastal and marine ecosystem where plastics may accumulate. The participating experts could also provide comments relating to their answers in a text box provided at the end of the questionnaire.

The category of ecosystem services and the coastal and marine ecosystems that provide them were adapted from a study by Hattam et al. (2021), which assessed and mapped the potential of these ecosystems in supplying ecosystem services in Southeast Asia, where Indonesia is located. The coastal and marine ecosystems consisted of mangrove, sandy beach, seagrass, coral reef, subtidal sediment, and pelagic sea, with the ecosystem services they supply comprising provisioning ecosystem services (food provisioning, energy supply, and genetic materials), regulating ecosystem services (waste assimilation, erosion control, flood protection, nursery habitat, and climate regulation), and cultural ecosystem services (recreation, traditional ceremonial practices, creative activities, and knowledge-based activities). The multiple human health and well-being dimensions were derived from a typology created by the OECD (2020), consisting of physical health, mental health, household income, housing conditions, education, social connections, governance participation, and community empowerment.

The questionnaire and the data collection process were piloted with ten scientists, policymakers, and practitioners who did not form the actual panel of experts. We sought feedback on the questionnaire structure and its items, the wording, and the user-friendliness of the data collection process. There were no major difficulties found during the pilot testing with only minor changes in wording to ensure clarity. Overall, the questionnaire could be completed in about 30 min, as optimal for a Delphi survey (Okoli and Pawlowski, 2004).

2.4. Data analyses

The level of consensus on the questionnaire answers provided by the experts after round two of the survey was measured using interquartile range (IQR), with IQR ≤ 1 for each of the five-unit Likert scale items

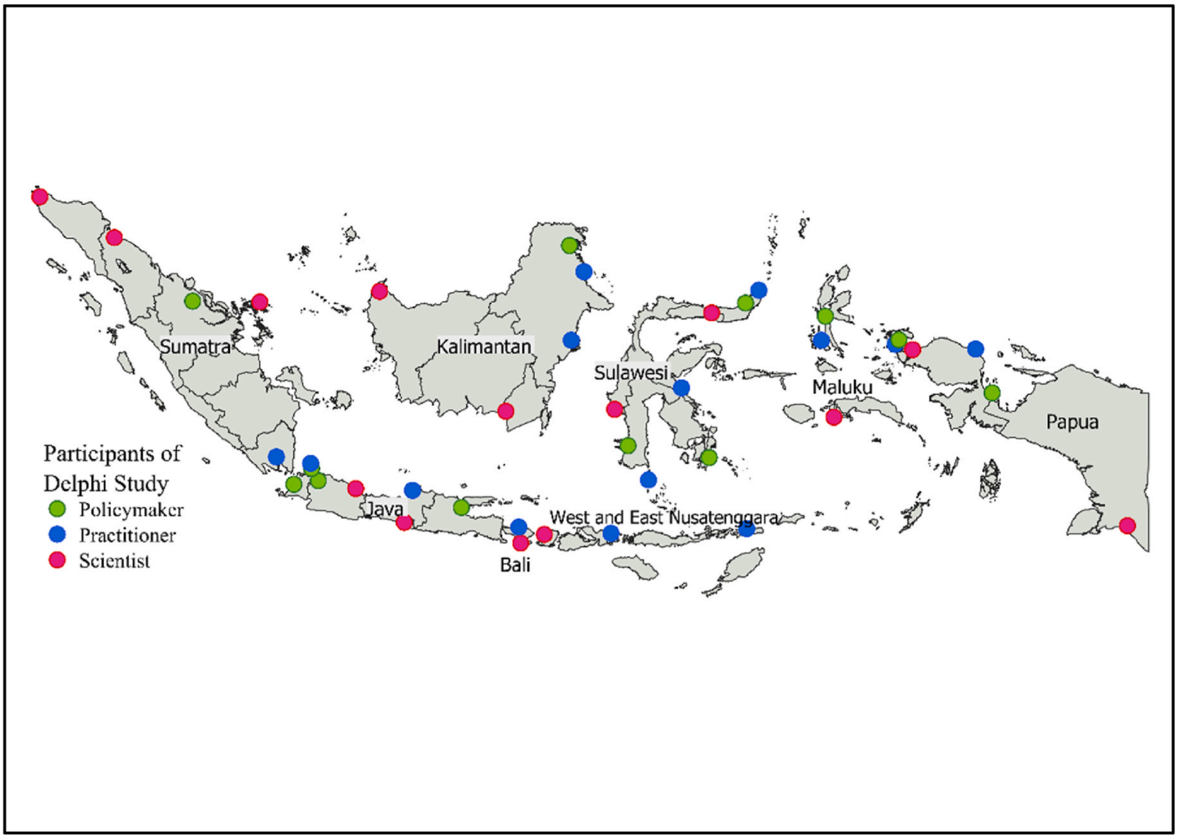

Fig. 2. The locations of each expert in Indonesia participating in the Delphi study, distributed to encompass the country's geographical regions.

indicating that consensus was achieved (von der Gracht, 2012). The stability of the answers provided was measured using Wilcoxon's matched-pairs signed-rank test, with $p > 0.05$ indicating the stability of responses (Beiderbeck et al., 2021). All estimates provided by the experts were averaged and reported as mean impact scores, with the five-unit Likert scales treated as interval data (Ameyaw et al., 2016).

The obtained data from round two of the survey were also tested for normality using Shapiro-Wilk tests. As the data were not normally distributed, non-parametric Kruskal-Wallis tests were performed to compare the differences across the Indonesian geographical regions, across the type of ecosystems, across the category of ecosystem services, and across the human health and well-being dimensions. Pairwise comparisons were then performed using Mann-Whitney U tests to identify which specific regions, ecosystems, ecosystem services, and health and well-being dimensions significantly differed, adjusted for post-hoc Bonferroni corrections. The vulnerability of each ecosystem towards plastic pollution was approximated and represented in a vulnerability matrix by calculating vulnerability scores (Matthews et al., 2014; Ricaurte et al., 2017), obtained by multiplying the ecosystem service potential scores of each ecosystem (Hattam et al., 2021) with the mean impact scores of the statistically significant ecosystem services and the predicted plastic accumulation trend in each ecosystem obtained in this study. Lastly, Spearman's rank correlations were used to analyze the relations between the mean impact scores for each specific ecosystem service and each dimension of human health and well-being, with significant results reported at $p < 0.05$ and correlation coefficients (r_s) categorized as weak ($0 < r_s \leq \pm 0.3$), moderate ($\pm 0.4 \leq r_s \leq \pm 0.6$), and strong ($\pm 0.7 \leq r_s < \pm 1$) (Dancey and Reidy, 2007). The statistical analyses performed in this study were conducted using Stata 18.0.

The future 10-year trend of marine plastic accumulation was also visually spatialized using ArcGIS according to the estimates provided by the participating experts. As the estimates represented the predicted accumulation trend in the coastal areas of Indonesia, the produced maps were color-coded by assigning the predicted estimates as specific values to the pixels surrounding Indonesian islands. The maps produced were also overlaid with secondary data on the population density and gross domestic product (GDP) of each region (Badan Pusat Statistik, 2023, 2024), two known correlates of plastic emissions into the natural environment (Amadei et al., 2022; Mai et al., 2023).

3. Results

3.1. Expert profile

The panel of experts consisted of 42 individuals, equally distributed amongst the three groups of scientists, policymakers, and practitioners. Descriptive statistics on the profile of experts (Table 2) revealed that they were composed mainly of men (69.05%), with half of the participating experts (50%) having, at least, a master's degree level of education. The experts had an average of 8.26 (±5.19) years of experience in their professions, with a mean age of 40.23 (±6.2) years old. In regard to the experts, the averaged self-ratings provided by them, and aggregated for each Indonesian region only for the experts located there, indicated that their expertise applied to the whole of Indonesia, with moderate expertise (scoring around 3 on the Likert scale) for each particular region, and that they were more than moderately aware of the issues of marine plastic pollution and coastal and marine ecosystem services. However, their expertise was mainly concentrated on the ecosystems of mangrove, sandy beach, seagrass, and coral reef, with their awareness of pelagic sea and subtidal sediment ecosystems scoring slightly below three (moderately aware). Such a relatively lower awareness in regard to the ecosystems of pelagic sea and subtidal sediment reflects the existing global knowledge gaps (Campagne et al., 2023). The first round of the survey involved all of the experts, with one participant dropping out in the second round, achieving a 98% completion rate. On the whole, the experts reached consensus for all

Table 2
The profile of experts participating in the Delphi survey.

	n (%)
Gender	
Woman	13 (30.95)
Man	29 (69.05)
Level of education	
College	2 (4.76)
Bachelor	19 (45.24)
Masters	16 (38.10)
Doctorate	5 (11.90)
	Mean (SD)
Years of experience	8.26 (5.19)
Age	40.23 (6.2)
Level of awareness[a]	
About marine plastic pollution	3.45 (0.59)
About coastal & marine ecosystem services.	3.48 (0.67)
Level of awareness regarding different types of ecosystems[a]	
Mangrove	3.70 (0.70)
Sandy beach	3.40 (0.70)
Seagrass	3.38 (0.80)
Coral reef	3.50 (0.80)
Pelagic sea	2.81 (0.77)
Subtidal sediment	2.98 (0.89)
Level of expertise for each Indonesian geographical region[a]	
Java	3.14 (0.97)
Bali	2.94 (0.12)
NTB & NTT	2.98 (0.65)
Sumatra	3.00 (0.89)
Kalimantan	2.93 (1.02)
Sulawesi	3.03 (1.03)
Papua & Maluku	3.02 (0.77)

[a] Note for measures on the level of awareness and expertise: 1 = not at all aware; 2 = slightly aware; 3 = moderately aware; 4 = very aware; 5 = high expertise.

items in the questionnaire (IQR $\leq$1) after round two of the surveys, as also indicated in the stability of answers ($p > 0.05$) provided in the questionnaire (**Appendix B**).

3.2. Marine plastic accumulation trend in Indonesia

We conducted Kruskal-Wallis tests to determine if the future 10-year trend of plastic accumulation, as estimated by the experts, significantly differed across the Indonesian geographical regions and across coastal and marine ecosystems in the country. The differences across the Indonesian geographical regions were statistically significant, H (6, n = 278) = 11.35, $p = 0.005$, with a similar result obtained for differences across Indonesian coastal and marine ecosystems, H (5, n = 241) = 8.35, $p = 0.03$. Pairwise Mann-Whitney U tests (Table C.1 and C.2 in Appendix C) showed that the differences were mainly observed when comparing the coastal area of Java with other geographical regions ($p \leq 0.002$, after Bonferroni correction) and when comparing mangrove ecosystem with pelagic sea, seagrass, and subtidal sediment ecosystems ($p \leq 0.003$, after Bonferroni correction). Visual representations of the estimates (Fig. 3) revealed that, on average, the experts predicted the coastal area of Java and mangrove ecosystem in the country to be the locations with the highest level of plastic accumulation over the next 10 years, with the coastal area of Kalimantan and the pelagic sea ecosystem accumulating the least amount of marine plastics. Nevertheless, the estimates provided by the experts ranged between 1 (moderate increase) and 2 (large increase) on the Likert scale, thus predicting a more than moderate increase in the accumulation of marine plastics across the whole of Indonesian regions and coastal and marine ecosystems over the next decade. Spatial visualization of these estimates indicates strong overlaps between areas with projected high levels of marine plastic accumulation and geographical regions with high GDPs and population densities (Fig. 4).

3.3. The impacts of marine plastic accumulation on ecosystem services and human health and well-being in Indonesia

Kruskal-Wallis test results (Table C.3 in Appendix C) revealed statistically significant differences ($p < 0.05$) in the impacts of plastic accumulation on several ecosystem services, consisting of food provisioning, genetic materials, erosion control, flood protection, nursery habitat, and recreation, and some human health and well being dimensions, consisting of physical health, mental health, household income, and housing conditions. Pairwise comparisons using Mann-Whitney U test (Table C.4 in Appendix C) showed that these differences were found mainly for the ecosystems of mangrove, coral reef, seagrass meadow, and sandy beach. As indicated by the mean impact scores for the statistically significant ecosystem services and health and well-being dimensions (Fig. 5), marine plastics were estimated to cause higher negative impacts when accumulated in these ecosystems. Nevertheless, all of the ecosystem services were negatively impacted by plastic accumulation across the different types of ecosystems. The highest reductions in ecosystem services were estimated for recreation from sandy beach, nursery habitat from seagrass, nursery habitat from mangrove, and recreation from coral reef. Furthermore, for human health and well-being dimensions, the expert panel saw plastic accumulation to have the greatest negative impact on household income, specifically due to plastic accumulation in coral reef ecosystem. Yet, the accumulation of plastic in other ecosystems was still perceived to lead to negative health and well-being consequences, but to a lesser extent (scoring between −0.05 and −1.01).

However, each of these ecosystems has different capacities for supplying ecosystem services due to the particular biotic structures and the ecological processes inherent in each. Thus, each ecosystem has specific capacity for resilience and degree of vulnerability in response to the risk of ecosystem service reduction caused by anthropogenic stressors (Doney et al., 2020). Calculating the vulnerability scores of the statistically significant ecosystem services and summarizing them in a vulnerability matrix (detailed in Section 2.4), revealed that the ecosystems and the ecosystem services they provided had different vulnerabilities to plastic pollution (Fig. 6). The ecosystem services most vulnerable to plastic pollution consisted of food provisioning (from mangrove forests), genetic materials (from seagrass meadows and coral reefs), nursery habitat (from mangrove forests, seagrass meadows and coral reefs), and recreation (from mangrove forests, sandy beach, and coral reefs). Based on the number of ecosystem services with higher vulnerability scores (the darker shaded cells in Fig. 6), it can be seen that, in descending order, highly vulnerable ecosystems consisted of mangrove, coral reef, seagrass, and sandy beach. These ecosystems were generally more vulnerable to plastic pollution than the ecosystems of pelagic sea and subtidal sediment.

Measurement of Spearman's rank correlations for the mean impact

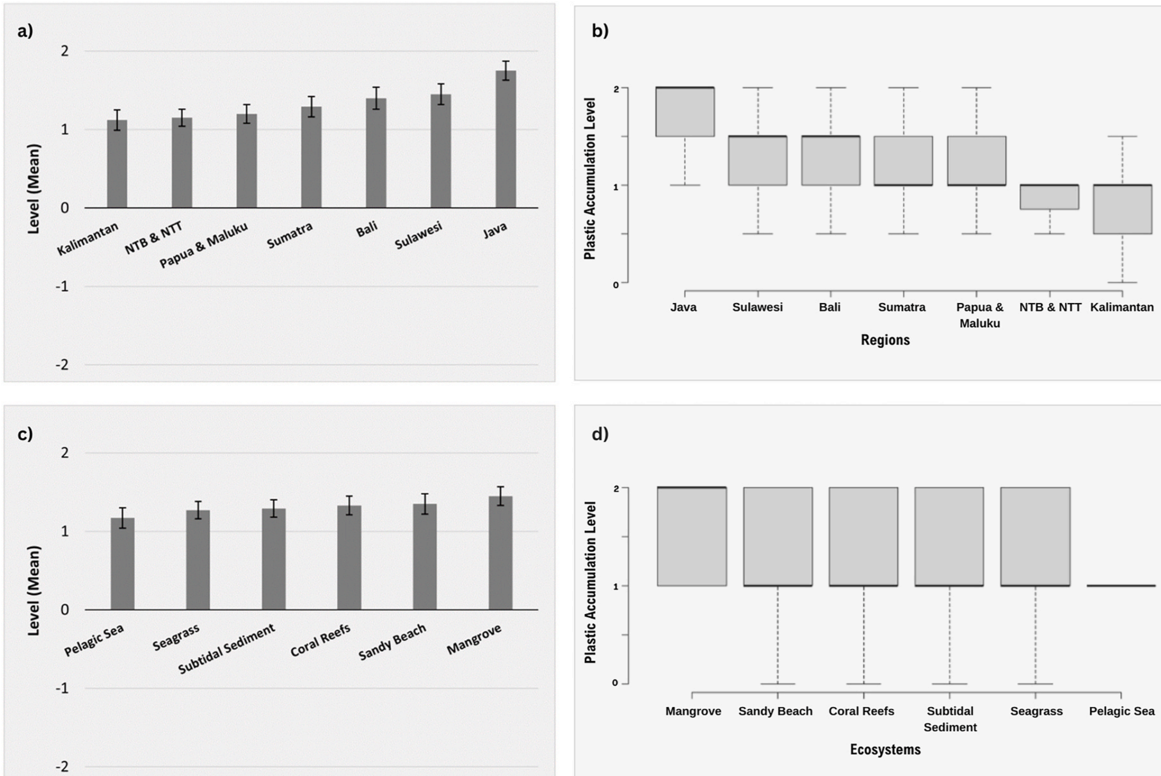

Fig. 3. The predicted future 10-year trends of marine plastic accumulation, based on expert judgments and consensus after two rounds of surveys, in Indonesian geographical regions (as a bar chart in 3a and as a boxplot in 3b), and Indonesian coastal and marine ecosystems (as a bar chart in 3c and as a boxplot in 3d) (scale ranged from −2 = large decrease, −1 = moderate decrease, 0 = no change, 1 = moderate increase, 2 = large increase); error bars represent standard errors.

scores of plastic accumulation, as estimated by the participating experts, revealed that the decline of ecosystem services was associated with a decrease in all human health and well-being dimensions (Appendix D). It is important to note that these findings are correlational, hence any causal inferences must not be made, particularly in the context of complex social-ecological interactions between ecosystem services and human well-being. Nonetheless, the patterns of correlation were especially pronounced when focusing on ecosystem services and human health and well-being dimensions with statistically significant mean impact scores (Fig. 7). The decline of mangrove ecosystem services due to plastic accumulation, as estimated by the experts, had weak to moderate positive correlations with reduced household income (r_s ϵ 0.34–0.54, $p < 0.05$), while plastic-induced decrease of coral reef ecosystem services had moderate positive correlations with deteriorating mental health (r_s ϵ 0.41–0.55, $p < 0.05$) and weak to moderate positive correlations with reduced household income (r_s ϵ 0.36–0.55, $p < 0.05$). In general, plastic accumulation in coastal and marine ecosystems was associated with reduced household income mainly through the decline in food provisioning from these ecosystems (weak to moderate positive correlations of r_s ϵ 0.33–0.62, $p < 0.05$). Furthermore, the adverse impacts of plastic accumulation on physical health would be mostly associated with the decrease of food provisioning from coral reef (moderate positive correlation of $r_s = 0.6$, $p < 0.001$), while deteriorating mental health was mainly associated with reduced ecosystem service of recreation supplied by all ecosystems apart from pelagic sea and seagrass (moderate positive correlation of r_s ϵ 0.34–0.51, $p < 0.05$). The influence of plastic accumulation on housing condition was most strongly associated with impacts on several ecosystem services from sandy beach (genetic materials, nursery habitat, and recreation), as indicated by the highly significant correlations (moderate positive correlations of r_s ϵ 0.54–0.56, $p < 0.001$). Lastly, the declining supply of the ecosystem service of erosion control from seagrass was correlated with a general decrease across the health and well-being dimensions (moderate positive correlations of r_s ϵ 0.46–0.52, $p < 0.05$).

4. Discussion

4.1. The predicted impacts of marine plastic pollution in Indonesia

This study assessed the impacts of marine plastic pollution on ecosystem services and human health and well-being through an iterative Delphi survey, focusing on the tropical archipelago of Indonesia. After two rounds of the survey, the panel of experts reached a consensus in the estimates they provided, indicating the Indonesian regions and ecosystems where marine plastics will likely accumulate over the next decade and the impacts of the accumulation. Existing systematic reviews demonstrate that, despite a growing body of research documenting plastic accumulation in coastal and marine ecosystems in Indonesia, there is a lack of empirical evidence on its impacts on ecosystem services and human health and well-being (Purba et al., 2019; Vriend et al., 2021). Thus, the results of this Delphi study provide the first indication of these impacts that can inform policymaking, further research, and mitigation efforts related to the issue of marine plastic pollution in Indonesia, with relevance for the wider region of Southeast Asia and other tropical countries in the Global South, which share similar social-ecological characteristics and challenges.

The panel of experts in this study agreed that the coastal area of Java would receive the highest amount of accumulating marine plastics over the next 10 years in Indonesia. The island of Java is the most densely populated Indonesian region with the fastest population growth and economic development (Adyasari et al., 2021). Increasing population, living standards, and gross domestic product (GDP) of a region have been linked to the proliferation of plastic waste emissions into the natural environment (Barboza et al., 2018; Sur et al., 2018; Isobe and Iwasaki 2022). Hence, the island of Java is also the likely source of plastics accumulating in the coastal waters surrounding the island, as

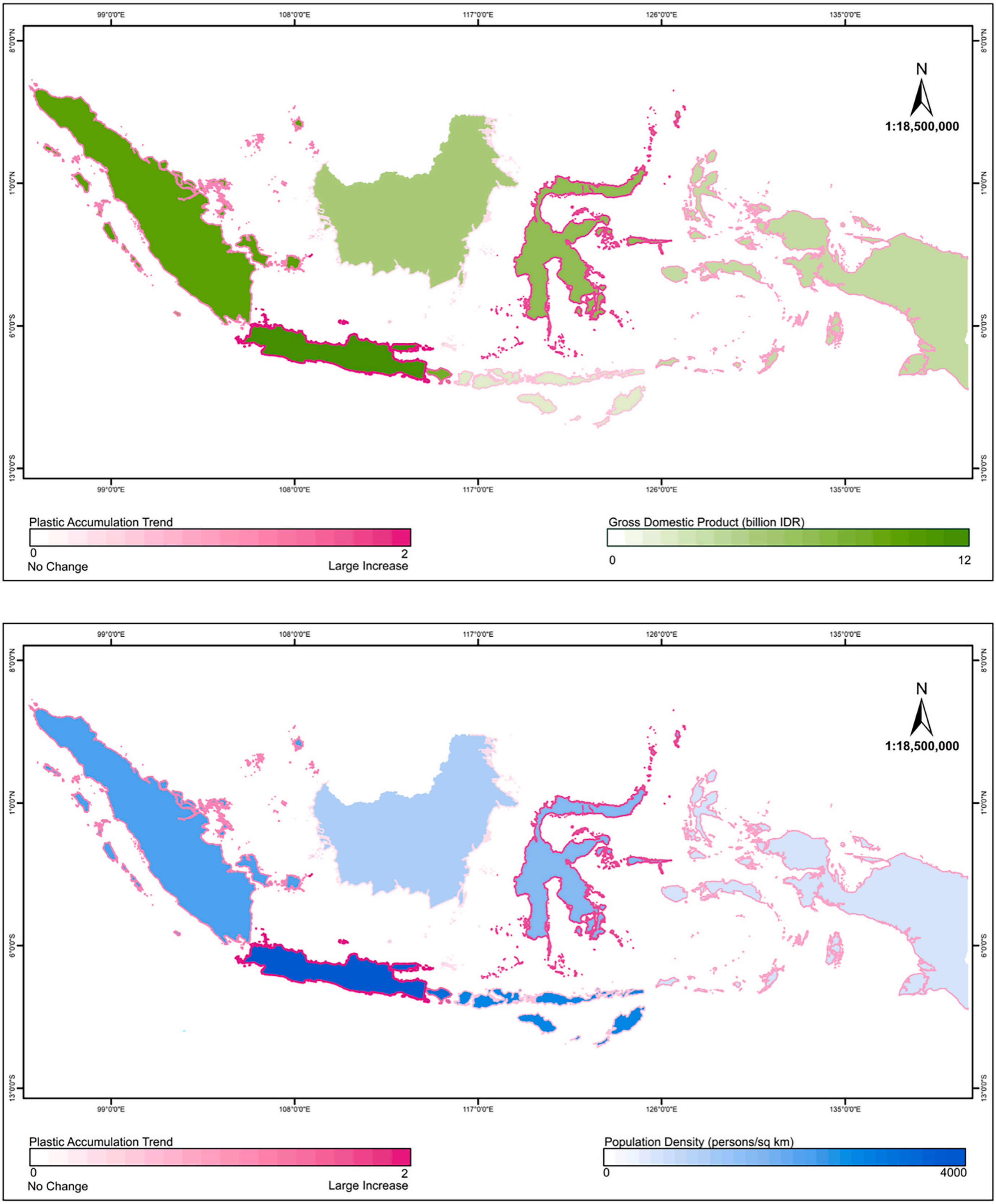

Fig. 4. Map of plastic accumulation in coastal areas of Indonesia, based on the future 10-year trend prediction by the Delphi experts, overlaid with: a) the regional gross domestic product of each geographical region, and b) the population density of each geographical region.

		Ecosystems					
		Mangrove	Sandy Beach	Seagrass	Coral Reef	Pelagic Sea	Subtidal Sediment
Ecosystem Services	Food Provisioning*	-1.37 (1.01)	-0.80 (0.93)	-1.41 (0.92)	-1.38 (0.88)	-0.95 (1.09)	-0.82 (0.79)
	Energy Supply	-0.73 (0.88)	-0.61 (0.74)	-1.20 (0.95)	-1.17 (0.95)	-0.69 (0.99)	-1.05 (0.79)
	Genetic Materials*	-1.10 (0.97)	-0.92 (0.76)	-1.32 (0.99)	-1.36 (0.85)	-0.97 (0.82)	-1.17 (0.84)
	Waste Assimilation	-1.04 (1.03)	-1.03 (0.97)	-1.27 (1.01)	-1.24 (0.99)	-0.86 (0.94)	-1.17 (0.90)
	Erosion Control*	-0.90 (0.94)	-0.87 (0.89)	-1.28 (0.97)	-1.07 (0.98)	-0.44 (0.78)	-0.84 (0.86)
	Flood Protection*	-1.07 (1.04)	-0.97 (0.82)	-0.76 (0.49)	-0.89 (0.88)	-0.32 (0.91)	-0.60 (0.90)
	Nursery Habitat*	-1.51 (0.90)	-1.12 (0.91)	-1.56 (0.79)	-1.46 (0.81)	-0.94 (0.76)	-1.20 (0.76)
	Climate Regulation	-1.00 (1.00)	-0.89 (1.02)	-1.10 (1.03)	-1.20 (1.00)	-0.72 (1.00)	-0.81 (0.99)
	Recreation*	-1.24 (1.14)	-1.57 (1.22)	-1.00 (1.03)	-1.51 (1.07)	-0.44 (1.07)	-0.39 (0.63)
	Traditional Ceremonial Practices	-0.69 (1.05)	-0.82 (1.08)	-0.67 (0.90)	-0.70 (0.91)	-0.46 (0.90)	-0.51 (0.85)
	Creative Activities	-0.69 (0.99)	-0.78 (1.14)	-0.71 (1.09)	-0.71 (1.09)	-0.43 (0.96)	-0.56 (0.97)
	Knowledge-based Activities	-0.59 (1.17)	-0.65 (1.09)	-0.68 (1.19)	-0.61 (1.14)	-0.39 (1.10)	-0.42 (1.05)
Well-being Dimensions	Physical Health*	-0.83 (0.83)	-0.93 (0.79)	-0.72 (0.79)	-0.90 (0.69)	-0.46 (0.70)	-0.65 (0.74)
	Mental Health*	-0.74 (0.73)	-0.88 (0.75)	-0.67 (0.69)	-0.98 (0.60)	-0.46 (0.61)	-0.60 (0.67)
	Household Income*	-0.98 (0.97)	-1.01 (0.85)	-0.95 (0.95)	-1.34 (0.65)	-0.79 (0.77)	-0.88 (0.81)
	Housing Conditions*	-0.97 (0.71)	-0.90 (0.79)	-0.54 (0.82)	-0.61 (0.77)	-0.35 (0.69)	-0.61 (0.74)
	Education	-0.40 (1.01)	-0.29 (1.02)	-0.22 (1.04)	-0.38 (1.06)	-0.28 (1.00)	-0.22 (0.97)
	Social Connections	-0.17 (1.01)	-0.21 (1.00)	-0.13 (0.86)	-0.19 (0.89)	-0.25 (0.84)	-0.24 (0.79)
	Governance Participation	-0.19 (1.07)	-0.13 (1.04)	-0.21 (1.04)	-0.07 (1.05)	-0.08 (0.99)	-0.10 (0.89)
	Community Empowerment	-0.14 (1.14)	-0.10 (1.12)	-0.08 (1.16)	-0.05 (1.88)	-0.05 (0.99)	-0.09 (1.04)

*Statistically significant differences

-2 -1.5 -1 -0.5 0 0.5 1 1.5 2

Fig. 5. Mean impact scores (and standard deviations) of plastic accumulation on ecosystem services and dimensions of human health and well-being associated with specific coastal and marine ecosystems (−2 = large decrease, −1 = moderate decrease, 0 = no change, 1 = moderate increase, 2 = large increase), based on expert judgments.

Ecosystem Services	Ecosystems					
	Mangrove	Sandy Beach	Seagrass	Coral Reef	Pelagic Sea	Subtidal Sediment
Food Provisioning	-3.54	-1.00	-1.76	-2.76	-1.66	-0.62
Genetic Materials	-3.30	-0.92	-3.96	-4.08	-0.97	0
Erosion Control	-2.70	-1.74	-2.56	-2.14	0	-0.84
Flood Protection	-3.21	-1.94	-1.52	-1.78	0	-0.60
Nursery Habitat	-4.53	-2.24	-4.68	-4.38	-2.82	-1.20
Recreation	-3.72	-4.71	-1.00	-4.53	-1.32	0

0 -1 -2 -3 -4 -5 -6

Not vulnerable Most vulnerable

Fig. 6. Plastic pollution vulnerability matrix of the statistically significant ecosystem services provided by a variety of coastal and marine ecosystems.

also confirmed both by a recent study on plastic dispersion modeling in Indonesian waters (Kisnarti et al., 2024) and by the indications of positive correlational patterns between marine plastic accumulation and regional GDPs and population densities in the spatial visualization of our findings (Fig. 4). A recent modeling study (Lau et al., 2020) has projected a 2.6-fold increase in the amount of plastics that can accumulate in the Indonesian marine environment by 2040 if the rapid population and economic growth are not accompanied by policy changes and intensive investments in waste management infrastructure. Most of these plastics will likely enter the marine environment from rivers located on the island of Java (Lebreton et al., 2017; Meijer et al., 2021) and will then settle in the low-energy coastal waters surrounding the island (Enders et al., 2019; Harris et al., 2021b). Thus, as indicated by the results of this study and other existing research, the coastal area of Java is the region with the highest risk of continuing marine plastic pollution in Indonesia.

While existing marine plastic monitoring studies have focused their efforts on the coastal area of Java, they were mainly concentrated on measuring and characterizing stranded litter on beaches (Purba et al., 2019; Vriend et al., 2021). Yet, as agreed by the panel of experts in this study, mangrove ecosystem in Indonesia will see the highest accumulation of marine plastics over the next 10 years. Mangrove ecosystems existing outside Indonesia contain a higher amount of trapped plastics than other coastal and marine ecosystems (Zhou et al., 2020; Ouyang et al., 2022; Garcés-Ordóñez et al., 2023; Wang et al., 2023b). Such high accumulation of plastics in mangrove is primarily caused both by the proximity of the global mangrove ecosystem to river estuaries transporting plastics from inland areas (Harris et al., 2021b) and by

	Ecosystem Services	Well-being Dimensions			
		Physical Health	Mental Health	Household Income	Housing Conditions
Mangrove	Food Provisioning	0.37*	0.39*	0.43*	0.18
	Genetic Materials	0.40	0.28	0.37*	0.40*
	Erosion Control	0.27	0.31	0.54*	0.37*
	Flood Protection	0.23	0.30	0.44*	0.33*
	Nursery Habitat	0.12	0.29	0.34*	0.16
	Recreation	0.19	0.34*	0.39*	0.01
Sandy Beach	Food Provisioning	0.34	0.59**	0.51*	0.46*
	Genetic Materials	0.51*	0.31	0.54**	0.54**
	Erosion Control	0.19	0.18	0.11	0.18
	Flood Protection	0.10	0.16	0.07	0.29
	Nursery Habitat	0.55**	0.45*	0.64**	0.66**
	Recreation	0.19	0.51*	0.35*	0.55**
Seagrass	Food Provisioning	0.30	0.48*	0.62*	0.39*
	Genetic Materials	0.36*	0.26	0.47*	0.37
	Erosion Control	0.46*	0.52*	0.47*	0.49*
	Flood Protection	0.20	0.39*	0.31	0.29
	Nursery Habitat	0.39*	0.48*	0.45*	0.51*
	Recreation	0.11	0.11	0.27	0.41*
Coral Reef	Food Provisioning	0.60**	0.44*	0.46*	0.38*
	Genetic Materials	0.34*	0.46*	0.55**	0.39*
	Erosion Control	0.29	0.51*	0.38*	0.30
	Flood Protection	0.23	0.55**	0.36*	0.34*
	Nursery Habitat	0.39*	0.47*	0.52*	0.39*
	Recreation	0.25	0.41*	0.48*	0.27
Pelagic Sea	Food Provisioning	0.42*	0.18	0.45*	0.31
	Genetic Materials	0.30	0.00	0.34	0.17
	Erosion Control	0.34	0.13	0.33	0.25
	Flood Protection	0.31	0.26	0.21	0.27
	Nursery Habitat	0.42*	0.33	0.40*	0.34
	Recreation	0.39*	0.24	0.49*	0.53*
Subtidal Sediment	Food Provisioning	0.37*	0.36*	0.33*	0.21
	Genetic Materials	0.07	0.20	0.30	0.17
	Erosion Control	0.44*	0.34*	0.26	0.37*
	Flood Protection	0.31	0.32	0.15	0.33
	Nursery Habitat	0.55*	0.55*	0.48*	0.46*
	Recreation	0.37*	0.44*	0.24	0.42*

Fig. 7. Spearman's rank correlations between ecosystem services and human health and well-being dimensions (color-shaded cells are statistically significant correlations at $*p < 0.05$ and $**p < 0.001$), based on the estimates provided by the participating experts.

mangrove root structures, consisting of prop and aerial roots, that act as filters retaining the transported plastics and enabling their deposition in sediment due to reduced water flow (Martin et al., 2020; Duan et al., 2021b; Okuku et al., 2023). Existing monitoring studies performed in mangrove forests in Indonesia indicated that substantial quantities of plastic items are trapped both in the surface water and the sediment of Indonesian mangroves (Yona et al., 2019; Suyadi and Manullang, 2020; Winarni et al., 2022). However, further studies are still required to ascertain the rate and pattern of plastic accumulation in mangrove ecosystems across Indonesia (Luo et al., 2021), especially considering that the country harbors the largest and most biodiverse mangrove forests globally (Arifanti et al., 2022).

In terms of the impacted ecosystem services, this study also found that mangrove ecosystems throughout Indonesia could be considered the most vulnerable to marine plastic pollution compared to other ecosystem types. This finding is consistent with emerging evidence from studies with coastal communities in both Indonesia and other Global South countries, documenting a perceived sharp increase of plastic accumulation in mangrove ecosystems (Hamza et al., 2020; Massiseng et al., 2022; Requiron et al., 2023; Sumeldan et al., 2021). Coastal communities in these countries also linked plastic pollution in mangroves with the decline of provisioning ecosystem services they relied on for their livelihoods (McMullen et al., 2023; Requiron et al., 2023).

Recent field and laboratory studies indicate several possible mechanisms through which accumulating plastics may lead to the decreased supply of mangrove ecosystem services. Plastics accumulated in mangrove ecosystems can reduce tree growth, survival, and primary production by clogging root pores and covering leaves, which disrupt photosynthesis, potentially leading to mortalities (De et al., 2023). Such adverse impacts were confirmed by a recent field experiment in Indonesia demonstrating that plastics covering mangrove roots caused loss of leaves and tree deaths (van Bijsterveldt et al., 2021). The accumulated plastics can also block water currents and obstruct local hydrodynamic flows, preventing propagule settlement and regeneration of mangrove plants (Luo et al., 2022). This hydrodynamic obstruction can be compounded by the smothering of mangrove sediments by plastics, which can prevent the growth of tree saplings (Smith, 2012; Selvam et al., 2021) and smother microorganisms essential for nitrification (Chen et al., 2022), thus interfering with the nutrient cycles. Laboratory experiments indicated that these adverse effects arising from the physical entanglement of mangroves with plastics can be further exacerbated by the potential uptake of plastic particles by mangrove root systems (Ding et al., 2022; Maity and Pramanick, 2020). These penetrative plastic particles can potentially interfere with the biochemical systems of mangrove plants by causing the disruption of energy distribution within the trees and the alteration of leaf ionome (Chai et al., 2023). Furthermore, accumulated plastics can be ingested by fauna inhabiting mangrove ecosystems, such as juvenile fish (Naidoo et al., 2020) and crabs (Not et al., 2020), which can lead to physical morbidity and reduced growth (Watts et al., 2015; Naidoo and Glassom, 2019; Sultan et al., 2023). However, a systematic review by Luo et al. (2021) revealed the lack of robust empirical evidence establishing causal links between plastic pollution and declining mangrove ecosystem services. These causal links can only be established through further ecotoxicological experiments and long-term monitoring studies equipped with standardized environmental risk models (Ouyang et al., 2022).

Decreasing supply of mangrove ecosystem services can have broader ramifications at the level of human well-being. This study found that the well-being impacts could include reduced household income. The Indonesian mangrove ecosystem directly supports the livelihood of the largest concentration of mangrove fishers in the world, estimated to consist of 893,000 people (zu Ermgassen et al., 2020). Furthermore, as much as half of the earnings of a typical fisher household in Indonesia are obtained from selling products obtained from mangrove (Malik et al., 2015). As such, the economic conditions of many people in Indonesia are dependent on the integrity of mangrove ecosystem of the country. It has been shown that a 1% decrease in mangrove coverage can lead to a 10% decrease in the annual income of fisher households in Indonesia (Yamamoto, 2023). Such vulnerability indicates that plastic accumulation in Indonesian mangrove ecosystems is a source of enormous economic risk to the country through the potential adverse impacts on mangrove integrity and ecosystem services.

The results of this study also suggest that direct economic consequences of marine plastic pollution in Indonesia may not be limited only to those associated with declining mangrove ecosystem services, but also those linked to the reduction of coral reef ecosystem services and a general decrease of food provisioning from a variety of coastal and marine ecosystems. The Indonesian fishery sector is constituted mainly of small-scale fishers (Teh and Pauly, 2018), directly employing approximately three million people (Sari et al., 2021), who rely not only on mangrove, but also on other nearshore ecosystems, such as coral reef and seagrass, for their fishing grounds (Teh et al., 2013; Jones et al., 2022). Existing systematic reviews observe that there are very limited data documenting the impacts of plastic pollution on the structures and functions of these nearshore tropical ecosystems, hence significant knowledge gaps on their ecosystem service impacts (Huang et al., 2021; Li et al., 2023). However, recent field experiments and monitoring studies on coral reef ecosystems and laboratory experiments on several seagrass species indicate that plastics may generate adverse ecological impacts by increasing the risk of coral diseases (Lamb et al., 2018), causing significant loss of coral tissues (Ballesteros et al., 2018), inducing coral bleaching and tissue death (Mueller et al., 2022), preventing seagrass growth (Menicagli et al., 2021), and reducing seagrass photosynthesis (Molin et al., 2023) and biomass (Menicagli et al., 2022). Available monitoring results in Indonesia indicate that nearshore coral reef and seagrass ecosystems may act as sinks for marine plastics (Putra et al., 2021; Utami et al., 2021). Thus, further studies to understand the economic and food security risks of marine plastic pollution are crucial, particularly due to the potential decline of ecosystem services from these nearshore ecosystems.

Our expert elicitation study also found that the impacts of marine plastic accumulation may extend beyond the ecological aspects of the affected ecosystems and the material well-being dimensions of the people relying on them. Indeed, the results of our study revealed that the decrease in coral reef ecosystem services due to plastic accumulation could be linked to deteriorating mental health. Furthermore, the adverse mental health impacts of plastic accumulation were also correlated with a reduced supply of recreation ecosystem service from coral reef and also from other coastal ecosystems, including sandy beach. Although the link between the health of coral reef ecosystem and mental health is not fully elucidated yet, cross-sectional surveys in Australia indicated that coral reef degradation was associated with a feeling of grief amongst the adjacent coastal communities (Marshall et al., 2019) and that healthy coral reef ecosystems were perceived to be more important for quality of life than local economic conditions (Larson et al., 2015). In the Indonesian context, recreational activities performed in coral reef and other coastal ecosystems have been associated with good mental health conditions of local coastal communities (Maharja et al., 2023b). The supply and quality of recreation ecosystem service provided by these ecosystems can be compromised by marine plastic accumulation, potentially leading to reduced enjoyment and psychological benefits (Wyles et al., 2016; Hayati et al., 2020). As indicated in this study and the existing evidence, marine plastic accumulation may elicit non-material negative impacts through its effects on mental health. However, uncertainties remain on the specific mechanisms, pathologies, and geographies of the mental health impacts of marine plastic pollution (Yose et al., 2023).

4.2. Policy and management implications

The estimates provided by the experts in this study indicate that the accumulation of plastics in coastal and marine ecosystems in Indonesia may cause the decline of ecosystem services, potentially leading to multifaceted negative impacts on human health and well-being. The experts were also in agreement regarding the Indonesian geographical regions and ecosystems that would receive the highest amount of marine plastic accumulation, with further data analysis conducted in this study indicating the ecosystems most vulnerable to the negative impacts of plastic accumulation. The findings suggest that monitoring, mitigation, and policymaking efforts on marine plastic pollution in Indonesia should take into account the potential vulnerability of the ecosystems of mangrove, coral reef, seagrass, and sandy beach, with a particular emphasis on the coastal area of Java, and the negative impacts on their ecosystem services and the health and well-being of people benefiting from them.

Although further studies are needed to validate our findings (as detailed in Section 4.3), the experts in our study still predicted that once plastics reach various coastal ecosystems, the materials can accumulate and produce complex social-ecological consequences that would be difficult to disentangle. Such findings indicate that measures preventing plastics from entering coastal and marine environments should be prioritized over clean-up mitigations. These clean-up operations are not only expensive (Welden, 2020) and have low efficacies (Sugianto et al., 2023), but also rely on techniques and technologies that have considerable environmental footprints (Mankaa and Traverso, 2023) and can cause further ecological damages (Ballesteros et al., 2018; Spencer et al., 2023; Watts et al., 2017). Instead, preventive measures must reach beyond the downstream to encompass the whole lifecycle of plastic (Gündoğdu et al., 2024). Various case studies have indicated that other downstream measures, including the provision of waste management and recycling infrastructures, are not sufficient for reducing the leakages of plastics into the sea (e.g., Borongan and NaRanong, 2022; Harris et al., 2021a), highlighting the necessity of targeting the upstream productions of plastics to prevent the social-ecological harms of marine plastic pollution (Grabiel et al., 2022).

Nevertheless, efforts to implement preventive measures at the upstream level have been hindered by the complex landscape of marine plastic governance. Although various policies, laws, and regulations exist at multiple jurisdiction levels, all of these have been fragmented and dominated by soft-laws that are not legally binding (Bertolazzi et al., 2024; Kamaruddin et al., 2022; Stöfen-O'Brien et al., 2022), further compounded by the lack of funding mechanisms (Fauziah et al., 2021) and siloed approaches of the governing institutions (Maruf et al., 2024). As a result, despite the copious amounts of pertinent policies, laws, and regulations, none of these have been effective in mitigating marine plastic pollution (Arifin et al., 2023; Fadeeva and Van Berkel, 2021; Serra-Gonçalves et al., 2023).

Within this context, the impending Global Plastics Treaty and its further evolution into a COP (Conference of the Parties) can bypass these complexities through a unified, coordinated, and legally-binding approach to the governance of marine plastics (Aanesen et al., 2024). Negotiations on the Treaty must also acknowledge that human societies and ecological systems of the Global South would bear most of the externalities arising out of plastic production and uses (Karasik et al., 2023), as the findings in our study also suggest. Ultimately, these global efforts to mitigate the impacts of marine plastic pollution must engage a holistic range of stakeholders, involving the government, scientists, industry sectors, consumers, and the voices of communities directly impacted by plastic pollution (Lampitt et al., 2023). Only then solutions to the systemic problem of marine plastic pollution can be effectively devised and implemented to help ensure the sustainable future of ecosystems and human societies.

4.3. Limitations and further studies

The results of this study were obtained through a Delphi process, which produced a collection of estimates provided by the participating experts. Thus, the results were representative only of the purposively selected experts and were not generalizable to all scientists, policymakers, and practitioners in Indonesia or another assembled panel of experts consisting of different individuals. Such limitations also signify that the results obtained, for instance, those suggesting that the ecosystems of pelagic sea and subtidal sediment as the least vulnerable, might be an artifact of the expert composition, as indicated in the lower expertise they had regarding these two ecosystems - hence more studies on these ecosystems are needed.

Furthermore, our study also applied post-hoc Bonferroni corrections for statistical pairwise comparisons, which incurred trade-offs in terms of reduced probabilities for Type I errors and increased probabilities for Type II errors (Francis and Thunell, 2021). The increased risk of false negatives can have negative ethical implications, a salient issue in certain fields of study, such as medicine and epidemiology (Perneger, 1998). However, as argued in several studies (Khorozyan, 2021; Psaltopoulos et al., 2017; Witzig et al., 2020), the realm of environmental management and policymaking demands that decisions be based on knowledge with a low risk of false positives due to the pragmatic, albeit utilitarian, imperative for optimum allocation of limited resources. As such, our findings still represent valuable initial evidence that can inform policy, practice, and further research, particularly as it is one of the first to analyze the potential impacts of marine plastic pollution on ecosystem services and human health and well-being using expertise from a range of expert specialists.

Our study also did not ask the participating experts to provide particular estimates in relation to different plastic particle sizes, mainly to reduce cognitive burdens, hence improving the reliability of estimates provided through the iterative Delphi survey, as also demonstrated in experimental studies by Boulkedid et al. (2011) and Gnatzy et al. (2011). However, different sizes of plastic particles may pose specific risks to ecosystem services and human health and well-being (Landrigan et al., 2023). In the Earth's oceans, plastics with the radius size above 25 mm, termed as macroplastics, undergo fragmentation into smaller particles of mesoplastics (radius size between 5 and 25 mm), microplastics (radius size below 5 mm), and nanoplastics (radius size below 1 μm) (Agamuthu et al., 2019). The fragmentation of macroplastics in the marine environment is generally driven by the weathering of plastic materials due to solar radiation, biodegradation, and mechanical processes caused by abrasive contacts with sea waves and sand particles (Andrady et al., 2022; Duan et al., 2021a). Although future studies should consider the pertinent level of granularity for the identification of specific social-ecological impacts of marine plastic pollution, our Delphi study still indicates the general negative attributes of such impacts, particularly since the concentrations of smaller plastic particles in oceanic compartments have been positively correlated with the presence of macroplastics (Bohdan, 2022).

Further studies should attempt to evidence the findings obtained in this study, for instance through conducting surveys or qualitative studies to understand the human health and well-being impacts of marine plastic pollution, which would be site-specific, and by performing field experiments and laboratory studies to elucidate the mechanisms by which marine plastics can affect the supply of ecosystem services. These studies are urgently required in coastal and marine areas with severe accumulations of marine plastics and high supplies, demands, and uses of ecosystem services. These more focused empirical studies involve greater resources and investment, and our study helps to highlight which ecosystem services and well-being dimensions to prioritize. Further monitoring studies describing the occurrence, distribution, and accumulation rate of marine plastics in coastal and marine ecosystems in Indonesia also remain essential, as field monitoring data are still lacking in the country, particularly those that include analysis of the meteorological and oceanographic factors influencing the hydrodynamic dispersion and distribution of marine plastics (Eriksen et al., 2023). Further research on the dynamics of marine plastic pollution will also have to include considerations on ecosystem types and their benthic communities, as also underlined by the emerging evidence on pelagic sargassum as a potential vector for the accumulation of plastic particles (Graham, 2023). In general, holistic knowledge of the sources, sinks, and impacts of marine plastics is still scarce both in Indonesia and globally, hindering policy responses and the formulation of best practices (Ladewig et al., 2021; Landrigan et al., 2023), thus this study acts as a crucial initial step to advance both the science and the solutions for marine plastic pollution.

Efforts to mitigate plastic pollution must also acknowledge that the risks associated with plastics interact with other stressors, such as climate change, organic pollution, overfishing, and urbanization, producing cumulative impacts that threaten the flourishing of humans and the functioning of oceans (Fleming et al., 2024). Research studies have revealed that the combination of marine plastics and rising sea temperature may increase the frequency, extent, and duration of harmful algal blooms (Ben-Haddad et al., 2024; do Prado Leite et al., 2022; Karalija et al., 2022), and intensify the rate of ocean acidification (Manno et al., 2022; Romera-Castillo et al., 2023). However, considerable uncertainties still predominate in the existing evidence on the interacting effects of cumulative marine stressors, particularly in relation to potential feedback mechanisms, non-linearities, thresholds for regime shifts, and the scale of the impacts, which can be gradual, abrupt, chronic, or acute (Defeo and Elliott, 2021; Gill et al., 2023; Simeoni et al., 2023; Trégarot et al., 2024). Further studies could address the potentially synergistic impacts of marine plastic pollution with other stressors by using complex systems methodologies (Alava et al., 2023) to enable cumulative impact assessment as a basis for decision-making for the sustainable use and equitable protection of coastal and marine ecosystems (Foley et al., 2017; Ota et al., 2022).

5. Conclusion

This study estimated the 10-year future trend of marine plastic pollution in Indonesia and its impacts on ecosystem services and several dimensions of human health and well-being. The estimates presented in this study were obtained through a Delphi process involving an expert panel consisting of 42 individuals, equally divided into the three expertise groups of Indonesian scientists, policymakers, and practitioners. The experts agreed that the coastal area of Java and mangrove ecosystem existing in the country would receive the highest amount of marine plastics over the next decade (RQ1). Our analysis further revealed that the ecosystems had different levels of vulnerability, with mangrove as the most vulnerable, followed by coral reef, seagrass, and sandy beach (RQ2). The highly vulnerable ecosystem services consisted of food provisioning, genetic materials, nursery habitat, and recreation supplied by the aforementioned ecosystems (RQ2). The impacts of marine plastic pollution on ecosystem services were also associated with the decline of several human health and well-being dimensions, with adverse mental health impacts mostly associated with reduced supplies of coral reef ecosystem services and recreational ecosystem services from a variety of coastal and marine ecosystems (RQ3). Furthermore, reduced household income had positive correlations with declining mangrove and coral reef ecosystem services, and a general decline of food provisioning from other coastal and marine ecosystems (RQ3).

Overall, the results of our study indicate that marine plastic pollution can have wide-ranging multifaceted consequences, not only limited to adverse ecological impacts but also extending to negative effects on human health and well-being. Further empirical studies are required to evidence these impacts and elucidate the causal mechanisms both at the level of ecosystems and human societies. Nonetheless, the results of this study provide one of the first indications for the prioritization of such undertakings, especially in the Indonesian context.

CRediT authorship contribution statement

Carya Maharja: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Radisti A. Praptiwi:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Sainal Sainal:** Validation, Investigation, Data curation. **Prawesti Wulandari:** Validation, Investigation. **Matthew Ashley:** Writing – review & editing, Methodology. **Kayleigh J. Wyles:** Writing – review & editing, Methodology. **Joyashree Roy:** Writing – review & editing, Methodology. **I Gede Hendrawan:** Methodology. **Susan Jobling:** Writing – review & editing, Funding acquisition. **Melanie C. Austen:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107423.

Data availability

Anonymized data from the Delphi surveys will be available publicly in Figshare at [DOI: 10.17633/rd.brunel.25690275], Repositori Ilmiah Nasional (RIN), and UK Data Service following a one-year embargo from the date of publication to allow for further analysis and its publications by the research team. The links to the deposited anonymous data will be made available after the embargo period (https://1drv.ms/f/s!Ap5PBD9dJGq-aaxN9YecJHQvVDE?e=rEoKGD). The anonymized data will also be made available upon request.

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