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Assessing Age-Specific Variability in Microplastic Intake Through Seafood Consumption: A Case Study in Central Java, Indonesia

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ABSTRACT

Microplastics (MPs) are frequently detected in seafood. However, the extent to which seafood consumption contributes to MP intake remains uncertain. Previous studies on MP intake in humans did not consider interindividual variability in exposure. The present study aimed to identify which types of seafood contribute most to the long-term average MP intake of residents of Semarang city in Indonesia, and to determine which groups have the highest exposure level. We utilized published data on MP concentrations in locally caught seafood, where MPs were quantified by microscopy and polymer types were confirmed by μ-FTIR under strict analytical quality assurance measures. These data were then combined with seafood consumption data from questionnaires and 24 h dietary recalls in 982 respondents of various age groups. Estimates of microplastic intake were derived using a Monte Carlo simulation (10,000 iterations), with species-specific mean microplastic concentrations as fixed inputs and seafood consumption sampled from a lognormal distribution. Parameter importance was explored through a sensitivity analysis. Bivalves significantly contribute to MP intake, especially for adolescents (31%) and adults (26.4%). Crabs are the main contributor for toddlers (49.4%) and the elderly (32.7%). Shrimps also contribute substantially to children's MP intake (30.6%). Adolescents are the most exposed age group, with daily intakes at the 99.5th percentile reaching up to 427 particles per person. In contrast, children and toddlers, although consuming smaller per-person amounts, showed the highest intake of MPs per kilogram bodyweight ($MP \cdot kg^{-1} \cdot bw \cdot y^{-1}$), that is, 1.9 and 1.6 times higher than adults, respectively. Hence, children and toddlers are the most vulnerable groups in terms of exposure.

1 | Introduction

Plastic pollution has emerged as a critical global concern over the past decade (SAPEA 2019). Microplastics (MPs) are commonly defined as plastic particles less than 5 mm in size (Thompson et al. 2024). In the present study, we consider particles ranging in size from 1 µm to 5 mm as MPs (Frias and Nash 2019). MPs have diverse morphotypes, such as pellets, fragments, fibers, films, filaments, foams, and sponges, originating from common polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS),

[†]Jiaqi Wang passed away on July 29, 2024.

polyethylene terephthalate (PET), and polyvinyl chloride (PVC) (Frias and Nash 2019). MPs are widely spread in the environment, inevitably resulting in human exposure.

MPs may enter the human body via ingestion, inhalation, or dermal contact, which ingestion route recognized as the main route exposure pathway (Rahman et al. 2021). Many studies have detected MPs in various vital human tissues, organs, excrements, and biological fluids, including in human stool (Luqman et al. 2021; Ho et al. 2022), colectomy specimens (Ibrahim et al. 2020), placenta (Ragusa et al. 2021), blood (Leslie et al. 2022), lung tissue (Jenner et al. 2022), breast milk (Ragusa et al. 2022), and brain (Nihart et al. 2025). This prevalence highlights the need to better understand the exposure pathways and the potential health implications of MP exposure, as emphasized in recent assessments and reviews (WHO 2022; Li et al. 2024; Luo et al. 2025).

Given this predominance of ingestion as the primary exposure pathway, numerous studies have reported MPs in various foodstuffs, such as seafood, honey, salt, sugar, canned fish, beer (Toussaint et al. 2019), and drinking water sources (Koelmans et al. 2019). From the environment, MPs can enter the food chain, exposing humans through contaminated food and drink (Al Mamun et al. 2023).

Seafood has been extensively investigated for its level of MP contamination (Barboza et al. 2018; Dehaut et al. 2019; Hantoro et al. 2019; Walkinshaw et al. 2020) since the marine environment is one of the areas most affected by plastic pollution (Yu et al. 2020). Several recent global studies have confirmed that microplastics are now being detected in a wide variety of fish and fishery products from marine ecosystems and underscore the significant contribution of seafood to dietary microplastic exposure and potential human health concerns (Alberghini et al. 2023; Unuofin and Igwaran 2023; Woh et al. 2024). Previous studies stated that seafood is the main pathway for MPs to enter the human body (Danopoulos et al. 2020; Zhao and You 2024). A recent study across 109 countries found that 57% of MP intake came from aquatic products, especially seafood, in rapidly industrializing areas in Southeast Asia. This study indicated that Indonesians are estimated to have the highest MP intake, at 15 mg/month, with the primary exposure pathway being seafood consumption (Zhao and You 2024).

The presence of MPs in seafood raises concerns about its quality and safety, particularly in countries with high MP pollution, potentially impacting food security and human health (Barboza et al. 2018). This contamination creates a conflict between the nutritional benefits and the safety of seafood. Seafood is a vital protein source globally, contributing up to 17 percent of animal protein intake in 2019 (FAO 2022). In Indonesia, seafood is essential for addressing malnutrition, as reflected in the national food and nutrition action plan for 2020–2024, which aims to increase fish consumption from 50.7 kg·capita^{-1}·y^{-1} in 2020 to 95.2 kg·capita^{-1}·y^{-1} in 2024 (National Development Planning Agency/Bappenas 2021). As one of the top five global producers of fishery and aquaculture products, Indonesia produced 5.2 million tonnes in 2020, with projections of 6.6 million tonnes by 2030. Additionally, Indonesia ranked second in marine capture in 2019 and 2020, following China (FAO 2022). However, Indonesia is also the third-largest contributor to marine plastic pollution (Cottom et al. 2024). Therefore, there is an urgent need to assess the risks of MP exposure in Indonesia to ensure the safety of seafood consumption for better diets.

Previous studies have detected MPs in various seafood species from Indonesian waters (Rochman et al. 2015; Rahmatin et al. 2024), but the significance of seafood as an exposure pathway remains unclear, especially in regions with high MP contamination and seafood consumption. To address this gap, this study focuses on Semarang, a densely populated coastal city in Central Java with active small-scale coastal fisheries (Malik et al. 2021) and documented MP contamination in nearby coastal waters and commercial seafood (Khoironi et al. 2018; Hantoro et al. 2024; Natasya and Nugroho 2025). Semarang combines rapid population growth, intensive coastal development, with inadequate waste management, and increasing levels of riverine and urban pollution. It is facing increasing pressure from plastic pollution, while seafood is promoted as an affordable source of protein nationally. These conditions are typical of many mid-sized tropical coastal cities in Asia, yet remain insufficiently studied. Hence, this makes Semarang a relevant and broadly representative case study for assessing MP exposure through seafood.

Although numerous studies assessing MP exposure exist, most rely on survey-based approaches and provide only population-averaged estimates (Barboza et al. 2024; Irnidayanti et al. 2025; Shufol et al. 2025). Previous studies rarely integrated locally measured MP concentrations with age-specific consumption patterns within a probabilistic modeling framework. To address this gap, our study combines empirical data on MP concentrations from commonly consumed seafood species in Semarang with detailed consumption patterns across age groups, quantified through Monte Carlo simulations. This approach allows us to estimate inter-individual variability in long-term exposure, providing a more realistic characterization. This study can serve as a model for similar coastal cities with similar environmental profiles and demographic structures.

Exposure assessment is an important component of the risk assessment process for MPs. Factors influencing the level of human exposure to MPs are not only determined by the exposure sources and pathways but also by population characteristics, such as age-dependent dietary consumption patterns. Different populations can have varying levels of exposure. Considering variability within the population, performing exposure assessment is vital for protecting vulnerable groups (Hore et al. 2024). Thus, identifying the types of seafood contributing most to MP contamination and the groups with the highest exposure is crucial for reducing MP exposure.

This study aimed to assess long-term average MP exposure from seafood consumption among Semarang residents across different age groups, to identify seafood types that contribute most to MP intake, and to determine which age group is most exposed. Such insights will deepen the understanding of interindividual exposure variability and of exposure routes that contribute most to MP intake from seafood.

TABLE 1 | MP concentrations (MP·g^{-1} ww) in tissues of different types of seafood collected from Semarang (Hantoro et al. 2024; Adidharma 2019; Angganararas 2019; Sudianto 2019).

Seafood	Tissue analyzed	MP concentration (MP·g^{-1}·ww) (Mean value)	Median
Milkfish	Digestive tract	0.04 ± 0.03	0.03
Shrimp	Skin and soft tissues	2.07 ± 1.85	1.58
Cockle	Soft tissues	14.18 ± 6.15	13.56
Mussel	Soft tissues	34.12 ± 28.85	26.20
Crab	Digestive tract	9.16 ± 4.93	8.23
Squid	Soft tissues	15.25 ± 443.33	0.52

2 | Materials and Methods

2.1 | Study Area

Semarang is located on the northern coast of Central Java province and is known as the fifth-largest city in Indonesia. It has approximately 1.7 million inhabitants (Badan Pusat Statistik Kota Semarang 2018) and is divided into 16 districts. In terms of administrative levels, under districts, there are villages, followed by community units (*Rukun Warga*, RW) and neighborhoods (*Rukun Tetangga*, RT).

2.2 | Calculation of MP Intake

The total intake of MPs from seafood was estimated by adding up the MP intake from different types of seafood, after first calculating the MP intake for each type of seafood by multiplying the measured MP concentration in each food type by its intake rate (Equation 1):

$$I_{\mathrm{MP-Seafood}} = \sum_{i=1}^{i=n} (C_i \cdot I_i), \tag{1}$$

where $I_{\mathrm{MP\text{-}Seafood}}$ is the intake of MPs from seafood (MP·d^{-1}); i is the index number to identify the type of seafood (i.e., 1 = shrimps, 2 = milkfish, etc.); C_i is the number of MPs in seafood type i (MP·$^{g-1}$·wwt); I_i is the intake of seafood type i (g·wwt·d^{-1}).

We considered six types of seafood, that is, milkfish (*Chanos chanos*), blood cockle (*Anadara granosa*), green mussel (*Perna viridis*), white shrimp (*Litopenaeus vannamei*), crab (*Scylla* spp.), and squid (*Loligo sp.*). Data on the number of MPs per type of seafood were obtained from our previous studies (Table 1), which also characterized particles based on size, shape, and polymer type. In the current intake assessment, we used these data as the basis for exposure modeling. Detailed information on the microplastic analysis of the seafood samples and contamination prevention steps were provided in Supporting Information Materials 1 of the original publication (Hantoro et al. 2024).

In brief, the particles detected in seafood were mostly dominated by fragments and fibers in the size range of 50 µm to 1000 µm for bivalves and 100 to 5000 µm for milkfish, which mostly consisted of rubber, styrene copolymers, cellulose, polyamide, and polyethylene as reported in our previous study (Hantoro et al. 2024). Data on seafood intake were gathered through a location-specific food dietary survey.

2.3 | Dietary Survey

A dietary survey was conducted among people living in Semarang to gather location-specific data on the intake of different types of seafood. The dietary survey consisted of a seafood consumption questionnaire (SCQ) to determine the frequency of seafood consumption, and a 24 h dietary recall (24HR), which was conducted three times on nonconsecutive days in a week to quantify the amount of seafood consumed (Zhao et al. 2016). Five different age classes were distinguished, that is, toddlers (2–≤5 years), children (>5–≤13 years), adolescents (>13–≤18 years), adults (>18–≤64 years), and elderly (>64 years). Five types of seafood were covered, that is, fish, shrimp, bivalves, crab, and squid. The survey methodology used in this study was carefully reviewed and approved by the Review Team of the Institute for Research and Community Service, Soegijapranata Catholic University. In accordance with institutional regulations, formal ethical committee approval was not required for this type of research.

The SCQ and 24H instruments were refined using a structured expert panel (Delphi-type) approach. A panel of experts reviewed SCQ and 24HR's draft questions regarding relevance and validity. Six experts with at least 5 years of professional experience in nutrition or food technology independently evaluated each question using a 5-point Likert-type scale (Zhang et al. 2022). Items receiving a score of 2 or below were flagged for revision and subsequently discussed until consensus was reached. For low-scoring items, experts also provided brief written comments to clarify their concerns and suggest improvements. Based on this process, the wording, structure, and grouping of several questions were revised, and a final version of the SCQ and 24HR instruments was produced.

The SCQ was designed to collect information from the respondents, including basic information, such as the type of seafood consumed, its frequency, and habits in handling seafood. Respondents were asked to fill out the Indonesian SCQ in their residence and were supported by trained Indonesian assistants. The SCQ took an average of 15 min to complete. For toddlers and children, the SCQ was answered by their mothers or people who helped prepare their food at home.

To ensure data quality and reproducibility, several quality assurance procedures were implemented during survey implementation. All field assistants underwent training on how to guide respondents in completing the SCQ and 24HR questionnaires, techniques for extracting information without introducing bias, and the use of food models to accurately estimate portion sizes. Field supervisors routinely monitored data collection activities and checked the completed questionnaires for completeness and readability. Any unclear or missing responses were clarified with respondents as soon as possible.

In the 24HR, respondents were asked to recall the seafood, or food containing seafood, they had consumed over the last 24 h. Respondents were asked to fill out the 24HR for three nonconsecutive days in a week, that is, two weekdays and one weekend day. To support accurate estimation of the amount of seafood consumed, respondents were provided with "food models" and household measuring instruments. Food models were provided as visual aids in the form of pictures of various seafood groups printed in actual size; either whole-size or as pieces of seafood. Each type of seafood was provided in several size classes as available in the market. The weight of each size class was determined and used as a reference for calculating the amount of seafood consumed.

A multistage random sampling design was used to select respondents across districts, villages, and community units of Semarang (Levy and Lemeshow 1999). Each district in Semarang was assigned a numeric code, and five districts were selected using a random number generator, resulting in the selection of Semarang Timur, Semarang Barat, Banyumanik, Gajah Mungkur, and Gayamsari. A similar process was performed to select two villages and two community units from each of the selected districts (Table S2). Respondents were then selected from the household level in the neighborhoods of the chosen community units using a convenience sampling method (Wu et al. 2019).

Trained field assistants visited selected households, explained the study objectives, and invited eligible individuals to participate voluntarily. Only people who were willing to complete both the SCQ and three 24H recalls were included; people not consuming seafood at all were excluded.

The number of respondents needed for the dietary survey was determined by performing a preliminary 24HR survey involving 40 individuals across all age groups. Based on the results from this preliminary 24HR, the minimum sample population required for each age group was determined using Equation (2):

$$n = \left(\frac{z.\sigma}{E}\right)^2, \quad (2)$$

where "n" denotes the sample size, "Z" represents the critical value corresponding to the desired confidence level (i.e., 1.96 for a 95% confidence level), "σ" stands for the standard deviation of seafood consumption of the population, and "E" signifies the margin of error. In determining the sample population, it is necessary to establish the margin of error (MOE) based on several considerations. First, seafood is not consumed routinely, and there is considerable variability in its consumption patterns. Second, the study is exploratory. Therefore, a 10% MOE was used (Australian Bureau of Statistics 2022; Althubaiti 2023). The margin of error used to determine sample size ranged from 8.77 to 19.95, which was derived from the average seafood consumption resulting from the preliminary survey that involved 40 individuals (Walpole et al. 2009).

Ultimately, 985 respondents were included in the survey. Informed consent was obtained from all participants. Three respondents were excluded from the results since they did not eat seafood at all. The remaining 982 individuals were distributed over the different age groups as follows: 193 toddlers, 199 children, 195 adolescents, 200 adults, and 195 elderly.

2.4 | Simulating Variability

We applied a Monte Carlo simulation to quantify the interindividual variability in the long-term average daily intake of MPs via seafood consumption for each age class (Mohamed Nor et al. 2021). In a Monte Carlo simulation, variable or uncertain input parameters are represented by frequency distributions. Subsequently, values are sampled from each input distribution, and the outcome is calculated. By repeating this process many times (i.e., the number of iterations of the simulation), a picture of the variation in the output emerges, which can be attributed to the variation in the input values.

In this particular case, we're interested in the interindividual variability in the long-term MP intake of the different age groups. This implies that the variation in MP concentration per seafood type can largely be ignored. After all, the incidental consumption of a piece of seafood with a relatively high MP concentration is likely to be compensated over time by the consumption of a piece with a relatively low MP concentration. An exception would apply if the seafood consumed always originates from the same location. Still, considering that most seafood is sold through markets where seafood from different origins is mixed, we think this situation is unlikely. We therefore assumed that the MP concentration per seafood type is constant and can be represented by its average value. The only exception is squid, where we used the median to reduce the impact of one extreme measurement in a relatively small dataset.

The interindividual variability in the amount of seafood consumed was assessed for each seafood type separately based on the results of the dietary survey (SCQ and 24HR). This dataset contains different sources of variation, that is, temporal variability (e.g., day-to-day variation in the amount consumed), interindividual variability (some people eat more of the seafood type than others), and uncertainty (due to the limited number of measurements). Since we're only interested in interindividual variability, that is, the variation in the long-term average daily consumption of a seafood type between individuals, we created four bins for each seafood type and age class. Each bin was characterized by a probability (of eating that specific seafood type over 0, 1, 2, or 3 days) and the average amount of that type of seafood consumed over these days. We then determined the average and standard deviation of the amounts consumed

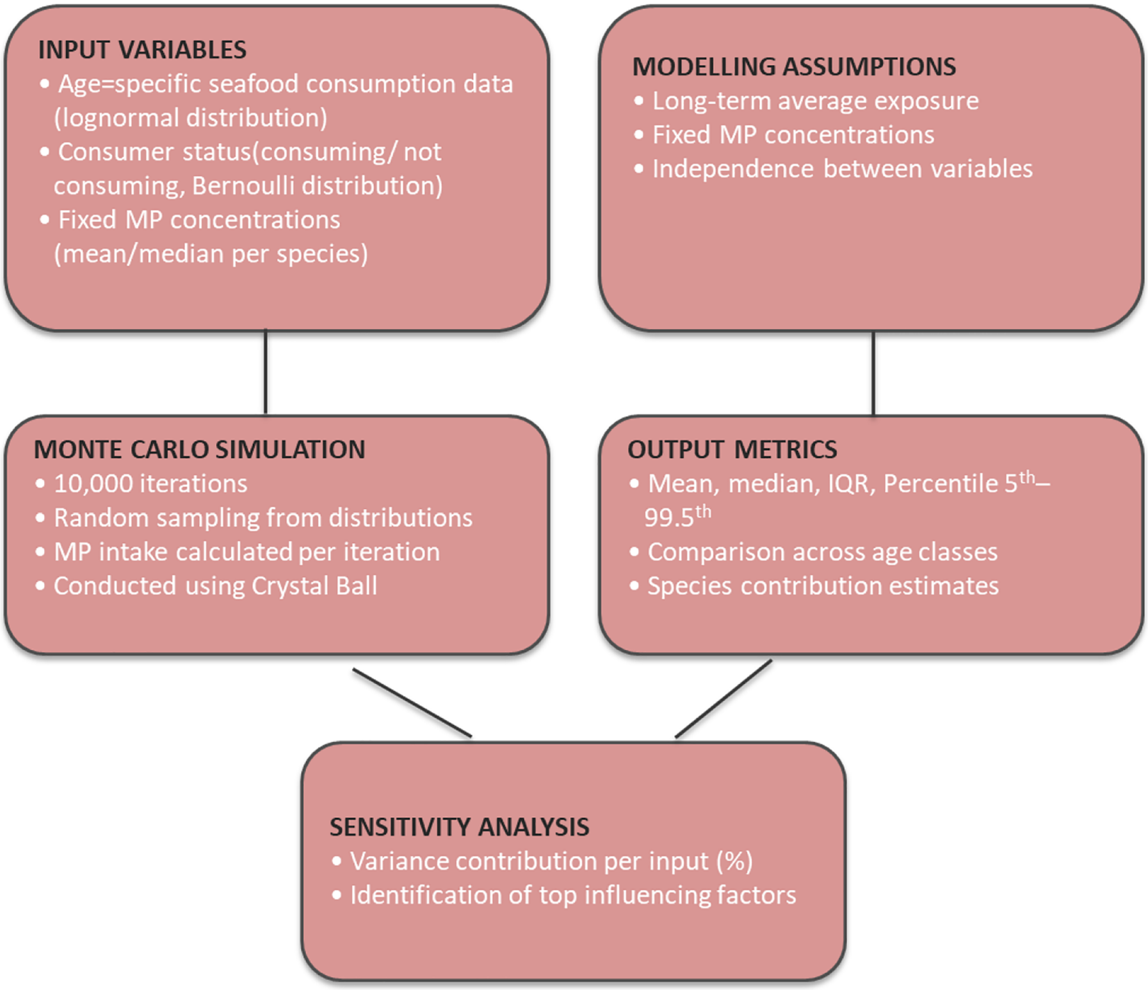


FIGURE 1 | Monte Carlo simulation framework.

over the four bins and used these to parameterize a lognormal distribution, which was assumed to reflect the long-term consumption of each seafood type for each age class. In the ultimate simulation, explicit nonconsumers of each seafood type were included through nested simulation, that is, by first determining whether somebody is a consumer or not by drawing from a Bernoulli (binary) distribution and subsequently sampling the amount of seafood consumed from the lognormal distribution for consumers (Table S3). Monte Carlo simulations were performed in Excel with Crystal Ball, Version 11.1.3.0.000 (Oracle, Inc., USA), with 10,000 iterations for every run. Sensitivity analysis was performed to identify parameters that contribute most to the variance in the output. The Monte Carlo framework is presented in Figure 1.

3 | Results and Discussion

3.1 | Seafood Consumption

This study reveals that most of the population of Semarang prefers consuming seafood. Figure 2 shows the proportion of consumers and nonconsumers for each type of seafood and for each age group. Almost all respondents from all age groups consumed fish (96.9%–99.5%). The proportion of people consuming shrimp and squid in the elderly group was lower compared with other age groups, namely 75.9% and 64.1%, respectively. The percentage of respondents consuming bivalves and crabs was less than that of the other types of seafood, especially for the age groups 2–≤5 years and >64 years.

The reasons respondents provided for not consuming certain types of seafood were quite varied, e.g. "because it is expensive" (234 individuals), "don't like it" (177 individuals), "don't like the smell of it" (134 individuals), "don't know how to process it" (108 individuals), "impractical to consume" (95 individuals), "allergic to it" (73 individuals), and "ever got sick after eating it" (31 individuals). Ninety-five respondents chose "other reasons", and half of them indicated that they considered this type of seafood dirty, especially in the case of bivalves. Twenty-four respondents indicated not to eat certain types of seafood for health reasons, especially related to high cholesterol content. Few respondents (9 people) indicated they did not eat a certain type of seafood because of its toxin content.

The consumption pattern, dominated by fish followed by shrimp, squid, crabs, and bivalves, aligns with national trends (Soselisa et al. 2021; Badan Pusat Statistik 2023; Partelow et al. 2023). Market availability explains this prevalence. Figure 3 shows which three specific seafood species within each type of seafood

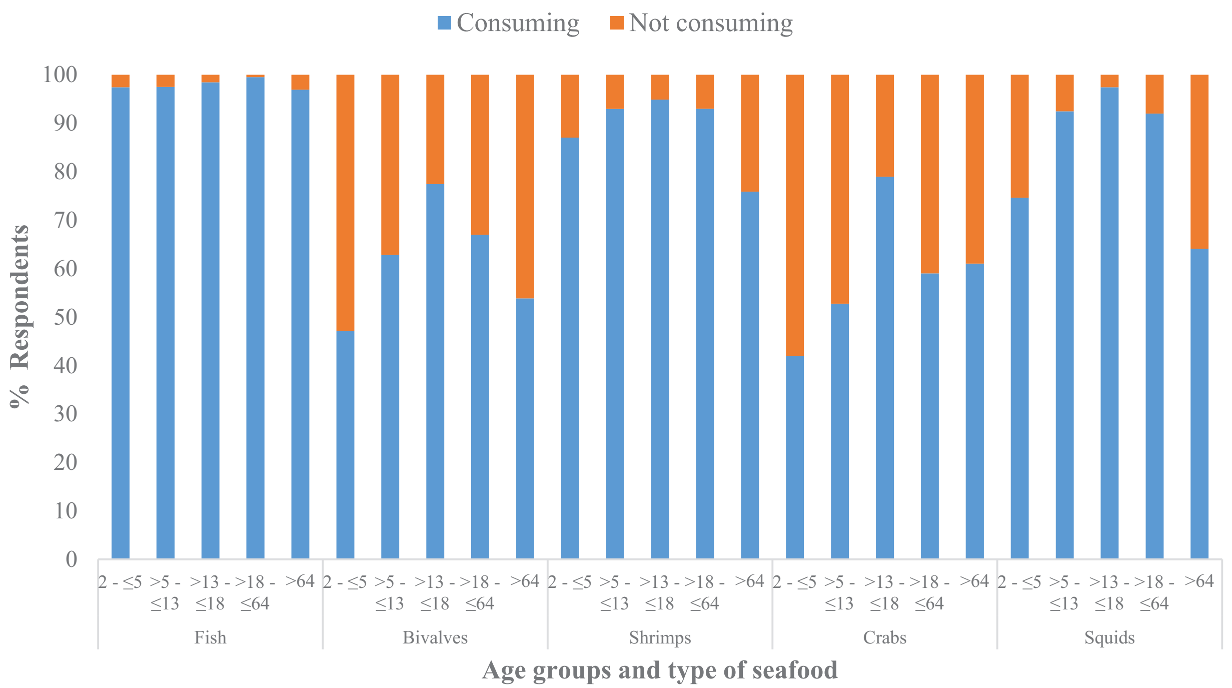


FIGURE 2 | The proportion of respondents who consumed and did not consume particular types of seafood.

TABLE 2 | Seafood consumption (g·capita^{-1}·d^{-1}) of Semarang inhabitants based on age classes.

Seafood type	Mean value of seafood intake (g·capita·d^{-1})				
	2–≤5 y	**>5–≤13 y**	**>13–≤18 y**	**>18–≤64 y**	**>64 y**
Fish	16.4 ± 11.8	25.4 ± 16.8	18.4 ± 13.1	24.2 ± 17.1	26.1 ± 17.4
Shrimp	2.9 ± 2.8	5.1 ± 4.2	5.8 ± 3.8	4.4 ± 3.5	4.1 ± 3.4
Cockle	0.7 ± 1.6	1.2 ± 2.3	1.1 ± 3.0	1.5 ± 2.9	0.8 ± 1.9
Mussel	0.1 ± 0.7	0.1 ± 0.9	0.6 ± 2.8	0.4 ± 2.1	0.7 ± 3.0
Crab	0.8 ± 2.2	2.0 ± 4.5	1.5 ± 4.5	1.5 ± 3.5	1.8 ± 4.6
Squid	1.1 ± 2.0	4.4 ± 6.0	3.9 ± 7.2	2.2 ± 4.1	3.9 ± 5.8
Total	22.0	38.2	31.4	34.1	37.3

were most often consumed over the last 30 days. All age groups ate almost the same variety of seafood. Milkfish, blood cockle, banana shrimp, mud crab, and Indian squid were the most common species of seafood that the respondents consumed.

Quantitative intake further underscores the dominance of fish (16.4 ± 11.8 to 26.1 ± 17.4 g·capita^{-1}·d^{-1}) than other types of seafood for all age groups (Table 2). All ages also consumed shrimp and squid, but in relatively low amounts, that is, 2.9 ± 2.8 to 5.8 ± 3.8 g·capita^{-1}·d^{-1} and 1.1 ± 2.0 to 4.4 ± 6.0 g·capita^{-1}·d^{-1}, respectively. Consumption of the other three types of seafood for all ages was very low, ranging from 0.7 ± 1.6 to 1.5 ± 2.9 g·capita^{-1}·d^{-1} (cockles), 0.1 ± 0.7 to 0.7 ± 3.0 g·capita^{-1}·d^{-1} (mussels), and 0.8 ± 2.2 to 2.0 ± 4.5 g·capita^{-1}·d^{-1} (crabs).

Among respondents in Semarang, children exhibited the highest total daily seafood consumption, namely, 38.2 g·capita^{-1}·d^{-1}, followed by the elderly, adults, and adolescents with magnitudes of 37.3, 34.1, and 31.4 g·capita^{-1}·d^{-1}, respectively. The consumption of seafood in the toddler group was the lowest compared with the others, that is, 22.0 g·capita^{-1}·d^{-1}, which may reflect parental caution, since seafood is a common allergen and often introduced later in the diet (Sicherer and Sampson 2018). Despite these differences, seafood intake across age groups was relatively similar, except for lower levels observed in toddlers.

When converted to annual estimates, seafood consumption in Semarang ranged from 8 to 14 kg·capita^{-1}·y^{-1}, assuming a regular daily intake. The estimated seafood consumption from this study is consistent with the data on fish consumption by the residents of Semarang City in 2023, released by the National Food Agency of Indonesia, which amounts to 14.3 kg·capita^{-1}·y^{-1}. However, these data include marine and inland fisheries products (Badan Pangan Nasional 2023). Per capita seafood consumption in Semarang was notably lower than Indonesia's national average, which increased from 54.6 kg in 2020 to 56.5 kg in 2022 (Kementerian Kelautan dan Perikanan 2023). At the global level, Indonesia ranked 17th

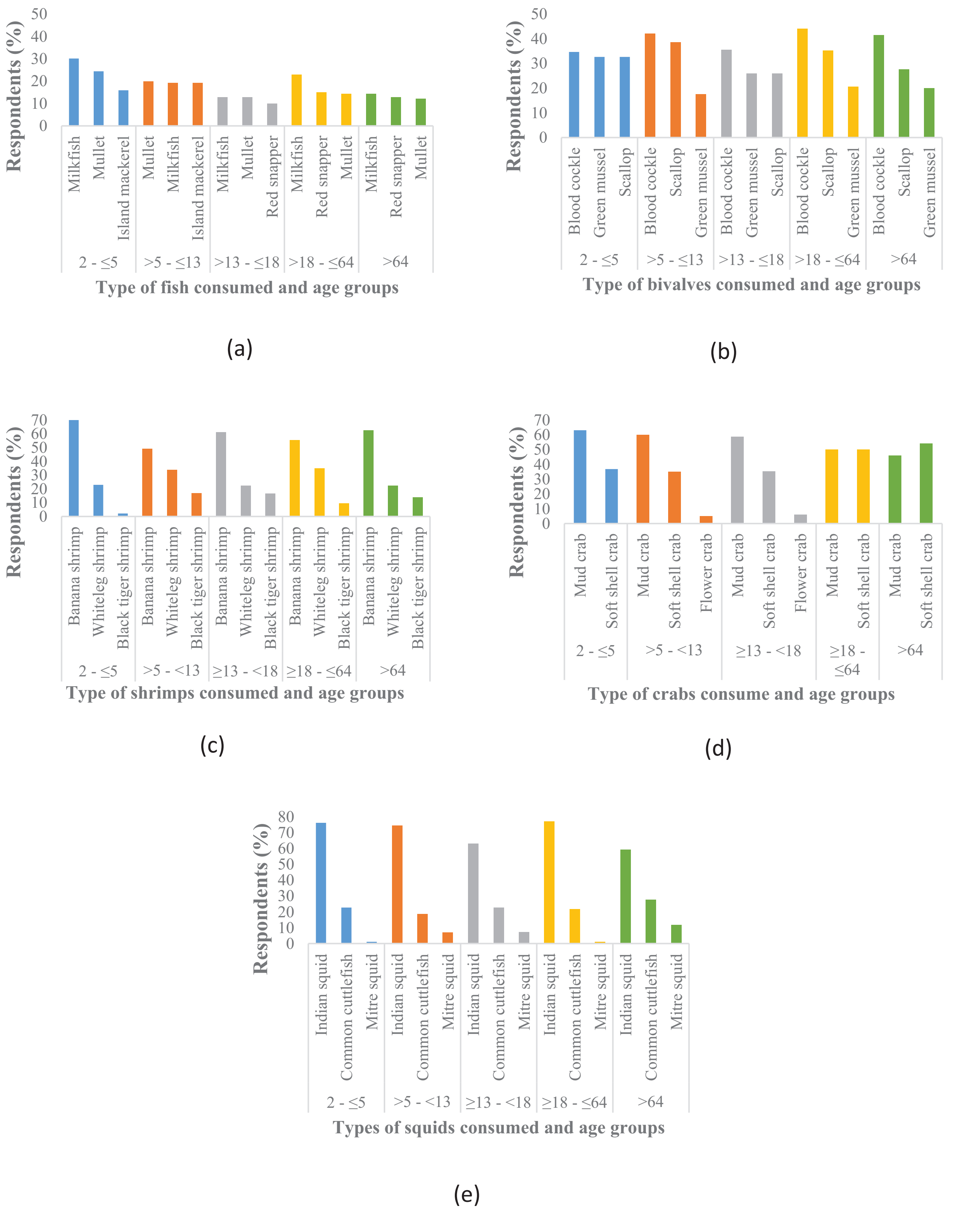


FIGURE 3 | Specific species of (a) fish, (b) bivalves, (c) shrimps, (d) crabs, and (e) squids that are most often consumed by various age categories during the last 30 days.

in 2020, with a per capita intake of 44.7 kg, more than double the world average of 20.2 kg (FAO 2023).

The amount of seafood consumption found in this study is still much lower than the average annual seafood consumption of the Indonesian population. There are several factors that could explain this discrepancy. First, the national seafood consumption data released by the Ministry of Marine Affairs and Fisheries is based on calculations of marine fish consumption, other marine products, brackish water fish, freshwater fish, and various processed fishery products (Hutagalung and Sitanggang 2017). In contrast, this study focuses on marine seafood consumption only. Second, during the 24HR recording, there is still a possibility that respondents may have missed recording the consumption of processed products containing seafood. Third, seafood consumption levels vary across regions in Indonesia (Soselisa et al. 2021). Residents in Java were reported to have lower fish consumption compared with other regions in Indonesia due to marine pollution concerns (Anyanwu et al. 2023).

3.2 | MPs Intake via Seafood Consumption and Factors Affecting Exposure

The highest daily intake of MPs through seafood consumption was found for adolescents (>13–≤18 years) with a total of 47.7 ± 76.6 MP·capita^{-1}·d^{-1}, followed by adults and children (Table 3). The average MP intake through seafood in adolescents was 1.1 to 2.9 times higher than for other age groups. In the adolescent group, 5% is estimated to ingest more than 133.9 MP·capita^{-1}·d^{-1} via seafood (the 95th percentile), with the 99.5th percentile reaching 426.7 MP·capita^{-1}·d^{-1}, almost 10 times the average intake. In the adult group, there were also cases showing a high daily MP intake with a 95th percentile MP intake of 119.2 MP·capita^{-1}·d^{-1} and a 99.5th percentile MP intake of 387.5 MP·capita^{-1}·d^{-1}. In contrast, daily MP intake was lower among the elderly and toddlers, at 17.7 ± 30.8 MP·capita^{-1}·d^{-1} and 16.6 ± 32.3 MP·capita^{-1}·d^{-1}, respectively.

Differences in exposure are influenced by consumption patterns and physiological characteristics. Children with high exposure generally consume blood cockles, crabs, and shrimp, while adolescents consume more mussels, blood cockles, and crabs, which are commodities with relatively high concentrations of MP. Moreover, because children and adolescents are in an active growth phase and have lower body weight, portion sizes relative to body weight tend to be larger.

The simulated distribution of MP intake was highly skewed to the right, reflecting irregular seafood consumption patterns. Many respondents reported not consuming certain types of seafood on the days of the 24 h recall, while a small proportion consumed relatively large portions. This combination resulted in many zero intake values alongside occasional high intakes, driving the elevated upper percentiles observed across age groups.

For several seafood-age group combinations, the median MP intake was zero or close to zero, indicating infrequent seafood consumption, and, for these specific combinations, at least half the population had no detectable daily MP intake from these seafood types. The interquartile range (IQR) values for most seafood commodities were low, indicating that daily MP exposure for the majority of individuals was relatively consistent and low. Greater variability was observed in certain age groups, particularly for the consumption of cockle and crab. Extreme variability was only observed among consumers with high intakes, as reflected in the 95th and 99th percentiles. Although mean MP intake values were influenced by extreme consumption events, the narrow 95% confidence intervals, resulting from numerous iterations in the Monte Carlo simulation, indicate a high degree of precision in the estimates of mean exposure for each group.

Table 4 summarizes MPs intake estimates from previous studies covering different geographical regions, including Europe, East and Southeast Asia, Indonesia, and several global-scale exposure assessments. Because these studies use different exposure scenarios and, in some cases, different units, the comparisons presented here should be interpreted as relative rather than as fully standardized quantitative estimates. Intake values reported in these studies vary from approximately 10^1 to >10^5 MP·capita^{-1}·y^{-1}, reflecting differences in contamination levels across seafood species and underlying consumption assumptions. The range of annual microplastic exposure through seafood estimated for Semarang in this study, 6.1 × 10^3 to 1.7 × 10^4 MP·capita^{-1}·y^{-1} (Table 4), is in line with the range reported globally, despite differences in species consumed, dietary habits, and contamination levels.

Although Table 4 includes a comparison of MP intakes on a global scale, narrative comparisons with Asian studies are emphasized because these studies provide the regional contrasts most relevant to Indonesia. For example, the MP intake estimates in our study are significantly higher (by a factor of 22 to almost 600 times and 10 to 30 times, respectively) than those presented in the studies by Cho et al. (2019, 2021), largely due to lower MP contamination levels in Korean seafood and smaller daily shellfish intake (4.0 g person^{-1}). Other studies also show relatively low MP levels in bivalves, resulting in relatively low MP exposures for the humans who consume them (Everaert et al. 2018; Daniel et al. 2021; De-La-torre et al. 2022; Ding et al. 2022; Ferreira et al. 2023; Barboza et al. 2024; Tunçelli and Erkan 2024).

In contrast, several Indonesian studies reported significantly higher intake estimates from seafood than our study (Rubio-Armendáriz et al. 2022; Irnidayanti et al. 2023; Irnidayanti et al. 2025; Rahmatin et al. 2024). In particular, Irnidayanti et al. (2023) estimated MP intake from the consumption of green mussels in Indonesia, while Rahmatin et al. (2024) focused on cockles. According to these studies, the annual MP intake could be 3.4 times higher (Rahmatin et al. 2024) and 24 times higher (Irnidayanti et al. 2023) than our findings. This discrepancy is primarily due to methodological rather than environmental factors. The previous studies assumed very high seafood consumption levels, such as the EFSA recommendation (15.6 kg y^{-1}) or the national average (55,370 g capita^{-1} y^{-1}), which do not reflect actual consumption patterns in Semarang. Although MP concentrations in seafood species were comparable, the assumption that all seafood contained equivalent contamination to highly contaminated species (e.g., green mussels, blood cockles) likely inflated exposure estimates.

TABLE 3 | Estimated intake of MPs (MP·capita^{-1}·d^{-1}) via the consumption of different types of seafood by different age classes of the population in Semarang city, Indonesia.

Seafood type	Age (year)	MPs intake (MP·capita^{-1}·d^{-1})									
		Mean ± SD	5th	25th	50th	75th	95th	99th	99.5th	IQR	95% CI for the mean
Fish	2–≤5	0.6 ± 0.5	0.0	0.3	0.4	0.7	1.4	2.4	2.9	0.5	(0.6, 0.6)
	>5–≤13	1.0 ± 0.7	0.0	0.6	0.8	1.3	2.3	3.4	4.0	0.7	(1.0, 1.0)
	>13–≤18	0.7 ± 0.5	0.0	0.4	0.6	0.9	1.7	2.6	3.1	0.5	(0.7, 0.7)
	>18–≤64	1.0 ± 0.7	0.1	0.5	0.8	1.2	2.3	3.5	4.0	0.7	(1.0, 1.0)
	>64	1.0 ± 0.7	0.0	0.5	0.8	1.2	2.2	3.3	3.9	0.7	(1.0, 1.0)
Shrimp	2–≤5	5.4 ± 5.7	0.0	1.9	3.8	6.9	15.6	26.8	32.8	5.0	(5.2, 5.5)
	>5–≤13	10.1 ± 8.6	0.0	4.7	7.9	12.9	26.2	42.9	51.9	8.3	(9.9, 10.3)
	>13–≤18	11.5 ± 8.0	0.0	6.2	9.6	14.6	26.5	39.6	46.0	8.4	(11.3, 11.6)
	>18–≤64	10.4 ± 7.5	0.0	5.5	8.6	13.2	24.2	37.1	42.6	7.7	(10.2, 10.5)
	>64	2.5 ± 2.6	0.0	0.9	1.9	1.4	7.4	12.0	14.3	2.5	(2.5, 2.6)
Cockle	2–≤5	5.3 ± 21.7	0.0	0.0	0.0	4.3	22.5	67.4	93.3	4.3	(4.9, 5.8)
	>5–≤13	11.3 ± 26.7	0.0	0.0	3.3	11.5	48.7	113.9	147.5	11.5	(10.8, 11.8)
	>13–≤18	12.2 ± 33.4	0.0	0.5	3.3	10.8	49.5	140.0	217.0	10.4	(11.5, 12.8)
	>18–≤64	13.7 ± 31.2	0.0	0.0	4.3	14.3	56.2	141.5	193.9	14.3	(13.1, 14.3)
	>64	4.5 ± 14.6	0.0	0.0	0.4	3.5	20.8	60.4	84.2	3.5	(4.2, 4.8)
Mussel	2–≤5	2.1 ± 18.4	0.0	0.0	0.0	0.6	7.4	33.1	52.8	0.6	(1.7, 2.4)
	>5–≤13	1.7 ± 18.2	0.0	0.0	0.1	0.5	5.4	24.9	43.3	0.5	(1.3, 2,0)
	>13–≤18	10.6 ± 56.5	0.0	0.1	1.2	6.0	40.0	153.6	228.0	5.9	(9.5, 11.7)
	>18–≤64	8.9 ± 48.2	0.0	0.0	0.7	4.4	35.0	132.7	271.8	4.4	(8.0, 9.9)
	>64	0.0 ± 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(0.0, 0.0)
Crab	2–≤5	2.9 ± 14.6	0.0	0.0	0.0	1.6	12.2	42.2	71.3	1.6	(2.6, 3.2)
	>5–≤13	9.8 ± 30.3	0.0	0.0	1.1	8.3	44.2	118.5	162.9	8.3	(9.2, 10.3)
	>13–≤18	10.7 ± 33.6	0.0	0.3	2.4	8,7	43.5	132.6	202.4	8.3	(10.1, 11.4)
	>18–≤64	8.6 ± 25.6	0.0	0.0	1.7	7.7	37.3	100.0	131.6	7.7	(8.1, 9.1)
	>64	8.2 ± 26.4	0.0	0.0	0.9	6.6	36.2	104.1	158.7	6.6	(7.7, 8.8)
Squid	2–≤5	0.4 ± 0,9	0.0	0.0	0.2	0.4	1,6	3.9	5.1	0.4	(0.4, 0.4)
	>5–≤13	2.1 ± 3.1	0.0	0.6	1.2	2.5	7.0	13.9	18.7	2.0	(2.1, 2.2)
	>13–≤18	2.0 ± 3.8	0.0	0.4	0.9	2.2	7.1	16.5	22.5	1.8	(1.9, 2.1)
	>18–≤64	1.0 ± 1.9	0.0	0.2	0.5	1.1	3.9	8.9	12.0	1.0	(1.0, 1.1)
	>64	1.5 ± 3.0	0.0	0.0	0.6	1.7	6.0	12.9	17.5	1.7	(1.4, 1.5)
Total MP intake	2–≤5	16.6 ± 32.3	0.5	5.6	10.2	18.3	46.7	110.0	172.7	12.7	(16.0, 17.3)
	>5–≤13	36.0 ± 45.6	3.2	15.0	24.5	41.7	97.1	196.2	257.0	26.7	(35.1, 36.9)
	>13–≤18	47.7 ± 76.6	4.7	19.4	30.9	51.0	133.9	292.1	426.7	31.6	(46.2, 49.2)
	>18–≤64	43.6 ± 63.1	3.2	17.4	29.0	49.8	119.2	258.7	387.5	32.4	(42.4, 44.8)
	>64	17.7 ± 30.8	0.6	5.3	9.8	19.0	57.5	132.8	187.1	13.7	(17.1, 18.3)

Abbreviation: IQR, interquartile range.

Compared with European studies, the daily MP consumption from seafood in our study is lower than in the study by Rubio-Armendáriz et al. (2022). The MP intake from shellfish was 212.0 MP·capita^{-1}·d^{-1}, 5 to 13 times higher than this study, and from fish was 410 MP·capita^{-1}·d^{-1}, 9 to 25 times higher. These differences are due to the higher seafood consumption levels used in the calculations, which are based on European consumption rates, and are generally higher at 25.8 kg·capita^{-1}·y^{-1}. Furthermore, the fish species used as a reference for calculations in the previous study were collected from the Charleston Harbor estuary, which has extremely high MP levels (Rubio-Armendáriz et al. 2022).

TABLE 4 | Comparison of MP intake through seafood from various studies.

No.	Reference	Seafood	MP Intake (MP·capita^{-1}·y^{-1})
1	Van Cauwenberghe and Janssen (2014)	Shellfish	1.1×10^4
2	Everaert et al. (2018)	Bivalves	*3.8×10^3*
3	Cho et al. (2019)	Mussels	2.9×10^1
		Bivalves	2.1×10^2
		Shellfish	2.8×10^2
4	Cho et al. (2021)	Coastal wild bivalves	5.9×10^2
5	Daniel et al. (2021)	Shellfish (shrimps, crabs, and squids)	1.3×10^1
6	Senathirajah et al. (2021)	Shellfish	*6.5×10^3*
7	Ding et al. (2022)	Mollusk	*9.1×10^1*
8	De-La-torre et al. (2022)	Bivalvia	4.8×10^1
9	Rubio-Armendáriz et al. (2022)	Crustaceans and mollusks	7.7×10^4
		Fish	1.5×10^5
10	Irnidayanti et al. (2023)	Green mussels	*4.1×10^5*
	Irnidayanti et al. (2025)	Green mussels	*2.7×10^5*
11	Lam et al. (2023)	Clams	1.4×10^4
12	Ferreira et al. (2023)	Mussels	*2.5×10^3*
13	Barboza et al. (2024)	Mussels	
		Children	*5.6×10^2*
		Adolescents	*6.5×10^2*
		Adults	*1.3×10^3*
		Elderly	*8.6×10^2*
		High consumers	*2.1×10^3*
14	Tunçelli and Erkan (2024)	Mussels	*4.0×10^3*
15	Rahmatin et al. (2024)	Cockles	*5.7×10^4*
16	This study	Seafood	
		Toddler	6.1×10^3
		Children	1.3×10^4
		Adolescent	1.7×10^4
		Adult	1.6×10^4
		Elderly	6.5×10^3

Note: All numbers in italics represent the geomean annual MP intake, derived from the minimum and maximum values from each study.

Figure 4 shows the relative contribution of seafood to total MP intake. Eating cockles contributed 32.1%, 31.4%, and 31.5% to MP intake in toddlers, children, and adults, respectively. Shrimp (32.2%) and crabs (46.4%) were the major contributors in the toddler and elderly groups, respectively. Shrimp eating also had a large impact on children's MP intake (32.2%), although it had a smaller impact on other age groups (14.3%–28.17%). A relatively high contribution of mussel consumption to MP intake was found in adolescents (22.3%) and adults (20.5%). In contrast, consumption of fish and squid contributed relatively little to the total MP intake in all age groups (1.5%–5.4% and 2.4%–8.4%, respectively).

Bivalves, especially blood cockle, are the main contributors to MP intake in Semarang, even though they are less consumed than other seafood. Their disproportionate contribution is partly explained by the vulnerability of bivalves to exposure to microplastics, which is consistent with their role as filter feeders that process large amounts of water (Ta et al. 2022), and by the fact that humans commonly eat the entire soft tissue of bivalves (Ding et al. 2022). Several studies have confirmed the presence of MPs in bivalves, suggesting a considerable human intake (Cho et al. 2019; Irnidayanti et al. 2023; Lam et al. 2023; Barboza et al. 2024; Rahmatin et al. 2024).

Crabs are a type of shellfish that serves as a major pathway for MP intake, in addition to bivalves and shrimp, across all age groups, especially among the elderly. This is attributed to the high contamination of MPs in crabs found in Semarang. Crabs, as benthic organisms, have omnivorous–scavenging behavior; they are frequently exposed to and ingest microplastics through their feed and close contact with contaminated sediments (Gopal et al.

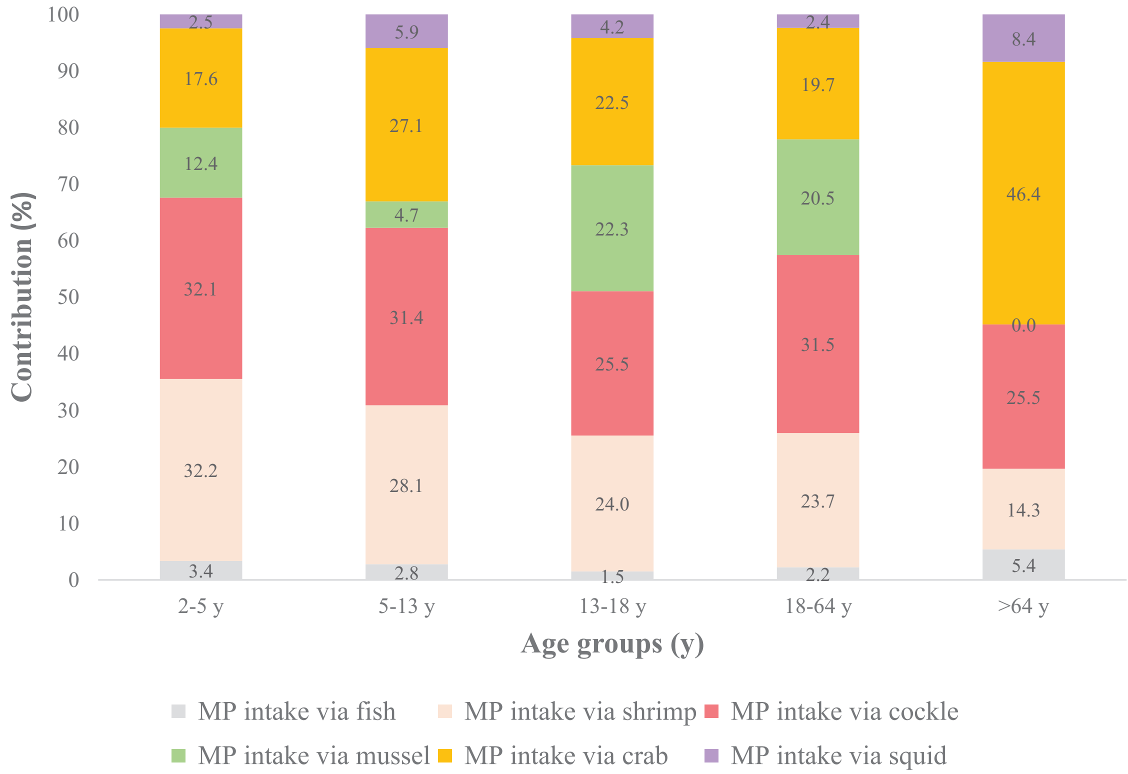


FIGURE 4 | Contribution of different seafood types (%) to total MP intake across age groups.

2022). Furthermore, the separation of the crab's internal organs, or intestines and gills, is not done, according to many food stalls or restaurants that serve crabs, at least in Semarang. This can increase the likelihood of MPs entering the human body. Previous studies have found that crabs can accumulate MPs, especially in their gills, digestive system, and hepatopancreas (Watts et al. 2014; Brennecke et al. 2015; Gopal et al. 2022).

Figure 5 shows the results of the sensitivity analysis for the Monte Carlo simulation. The parameters are ranked from high to low based on the percentage explained variance in the estimated MP intake for each age class. To rank high, a parameter must contribute significantly to total MP intake and have a relatively large variance. Cockle consumption is an important driver of the variability in MP intake, especially for children, adolescents, and adults. This is not only reflected in the dominant role of distribution, reflecting the amount consumed, but also in the distribution that reflects whether or not people consume cockles. Shrimp consumption is an important driver of the variability in MP intake in toddlers and children, while it is less important in other age groups. Mussel consumption has a significant impact on MP intake in adolescent and adult groups, although it is not the most significant variable. MP intake in the elderly group is largely influenced by two variables: the proportion of respondents who consume and do not consume crabs, and the amount of crab consumed.

Adolescents have the highest intake of MPs per person, followed by adults. However, when considering the relative body burden (MP·kg^{-1}·bw·y^{-1}), children and toddlers exhibit the highest level (Table 5). Specifically, the relative body burden for children and toddlers is 1.9 and 1.6 times higher, respectively, compared with adults. This indicates that both children and toddlers accumulate higher levels of MPs in their bodies relative to their body size, which could potentially lead to a greater risk for adverse health effects from MP exposure.

The 99th and 99.5th percentiles of the total MP intake (Table 3) show that some people may have considerable MP exposure, that is, approximately 110–430 MPs capita^{-1}·d^{-1}, with the highest values reported for adolescents, that is, 292.1 MPs capita^{-1}·d^{-1} (99th percentile) and 426.7 MPs capita^{-1}·d^{-1} (99.5th percentile). In other words: 1 out of 100 persons of the 13–18 years age class is expected to have an exposure exceeding approximately 300 MPs per day, and 1 out of 200 persons even exceeding 430 MPs per day. Very extreme cases (i.e., the maximum of 10,000 iterations) even show an exposure exceeding 2000 MPs per day. These extremes can be traced back to a high consumption of seafoods, particularly mussels and cockles, with typical consumption rates ranging between 50 and 100 g·d^{-1}. Although these high percentiles represent a real subpopulation with high consumption habits, the most extreme cases predicted by the model should be interpreted with caution. These values are the result of extrapolating the lognormal distribution beyond the upper limit of the observed consumption data in this study. Therefore, these extreme values have greater uncertainty and may not represent plausible long-term average consumption levels. A more detailed study of (the likelihood of) extreme seafood consumption patterns is required to assess the real level of the predicted extreme MP exposures from seafood.

The lowest contributor to MP intake from all types of seafood is fish, across all age groups, except for toddlers, where crab is the lowest contributor to MP intake. Although fish is the

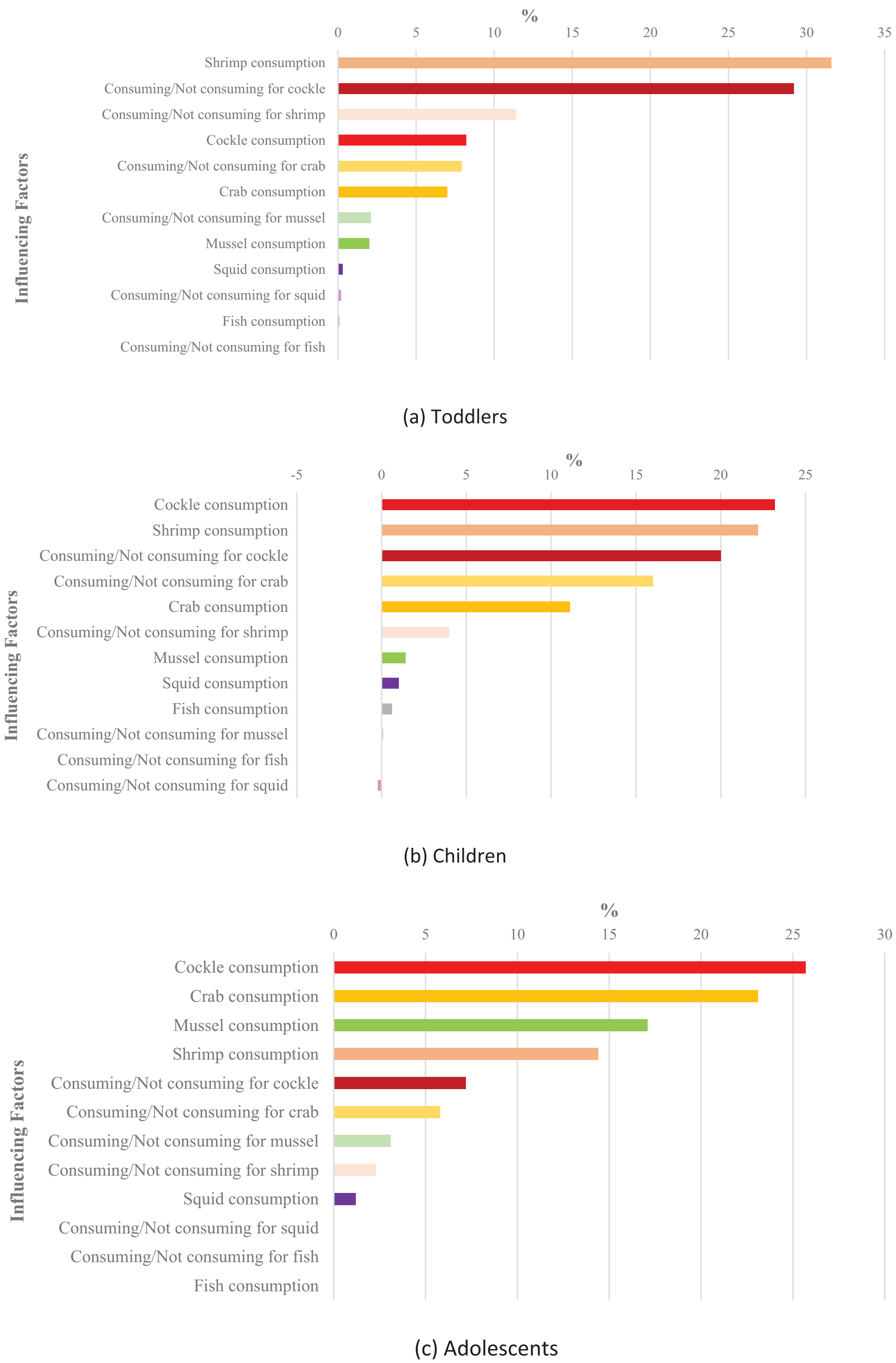
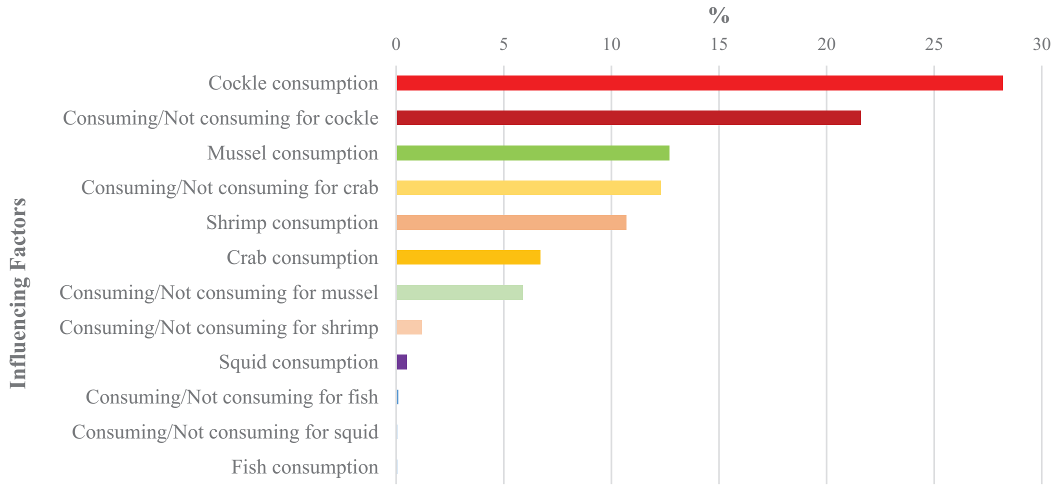
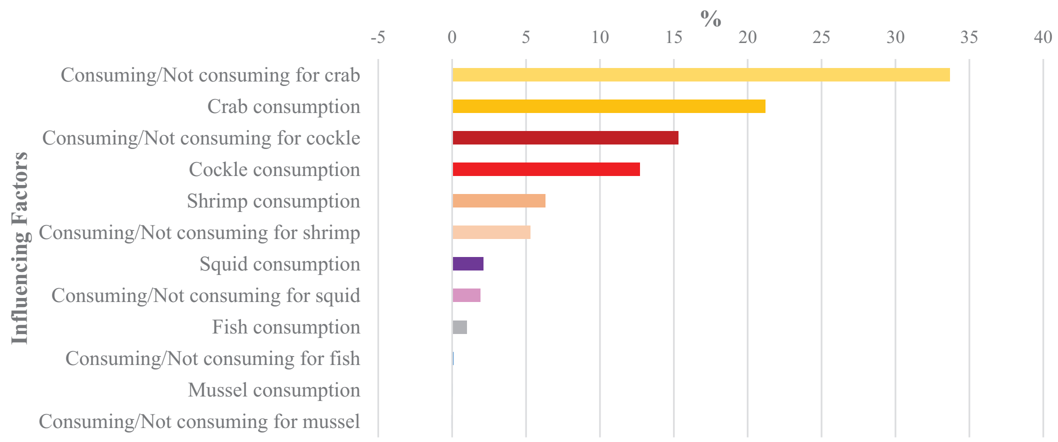


FIGURE 5 | Relative contribution of key input parameters (%) to uncertainty in estimated MP intake (%) at different age groups: (a) toddlers, (b) children, (c) adolescents, (d) adults, and (e) elderly.



(d) Adults



(e) Elderly

FIGURE 5 | (Continued)

TABLE 5 | The relative body burden of MPs based on age group.

Age group (year)	MP intake ($MP{\cdot}d^{-1}$)	Body weight ($kg{\cdot}bw$)[a]	Relative body burden ($MP{\cdot}kg^{-1}{\cdot}bw{\cdot}y^{-1}$)
2–≤5	16.6	15	404
>5–≤13	36.0	27	487
>13–≤18	47.7	48	362
>18–≤64	43.6	62	253
>64	17.7	58	111

[a](WHO 2025; Walpole et al. 2012).

most consumed seafood in Semarang, it has the lowest level of contamination compared with other types of seafood in the city, most likely because fish are usually cleaned, and the intestines—where MPs tend to accumulate—are removed. However, this can be different for nanoplastics (NPs), which are much smaller in size and likely cannot be fully removed through cleaning and separation alone. Unfortunately, NPs are difficult to detect in biological tissues using current analytical methods.

Exposure to MPs from other food sources is shown in Supporting Information Material S4. These comparisons provide an overall indication of relative exposure levels, but they are not based on fully harmonized assumptions and units. The average daily intake of MPs is higher through the consumption of seafood, according to this study, than it is through the consumption of food and beverage products like salt, honey, sugar, and beer (Smith et al. 2018; Senathirajah et al. 2021; Rubio-Armendáriz et al. 2022;

Nakat et al. 2023). That seafood is a source of relatively high MP intake compared with other food groups is supported by other studies (Van Cauwenberghe and Janssen 2014; Everaert et al. 2018; Senathirajah et al. 2021; Rubio-Armendáriz et al. 2022), but is still lower compared with the estimation by Cox et al. (2019).

The entry of MPs into humans is more significant through drinking water than through seafood (Cox et al. 2019; Danopoulos et al. 2020; Senathirajah et al. 2021; Rubio-Armendáriz et al. 2022). The significant contribution of MP intake from drinking water, especially bottled water, is due to high concentrations and greater daily consumption compared with seafood, although some studies report lower estimates due to varying MP concentrations and factors like the type of water consumed and age (Zhou et al. 2021; Bäuerlein et al. 2022).

The potential for high MP intake from paper cups may rival that from seafood, other foods, and drinking water annually. However, exposure from paper cups cannot be directly compared with food or beverages, due to a lack of data on usage patterns and varying consumption habits.

These exposure pattern findings confirm that children and adolescents are highly vulnerable due to their relatively larger body burdens and consumption of species with significant levels of contamination. These data can inform more targeted food safety policies and public education programs in Indonesia, for example, by prioritizing at-risk commodities, improving seafood cleaning practices, and incorporating MP monitoring into routine seafood control systems.

3.3 | Health Implications and Food Safety Risk Management

The ingestion of MPs through seafood has raised concerns about potential health implications, particularly because smaller particles can cross biological barriers and may enter tissues and organs. In vivo and in vitro studies show that MPs smaller than 150 µm can cause damage and dysfunction in multiple systems, including digestive, respiratory, cardiovascular, immune, reproductive, and endocrine systems (Yuan et al. 2022; Zhao et al. 2024). These studies reported biological responses such as oxidative stress, inflammation, metabolic disorders, cell death, and genetic damage, suggesting plausible mechanisms for acute, subchronic, or chronic effects.

Moreover, MPs can absorb toxic substances from the marine environment, such as persistent organic pollutants (POPs), heavy metals, and antibiotics (Sun and Wang 2023; Zhao et al. 2024). MPs can also carry endogenous chemicals such as incorporated additives, dyes, and pigments (Sun and Wang 2023). When humans consume contaminated seafood, these chemicals may accumulate in the body, potentially leading to adverse health effects. However, the overall toxicological impact on human health remains uncertain and is still an emerging area of research.

In the absence of established toxicological thresholds for microplastics, performing a formal quantitative risk characterization is not possible. This study, therefore, focuses on exposure estimation, and the findings should be interpreted qualitatively.

Seafood remains an important and healthy dietary choice because of its unique nutritional benefits. To ensure that consumption continues to be beneficial to health, awareness of potential pollutants is essential. In this study, intake estimates were derived from MP concentrations measured in fresh (raw) seafood and did not account for changes that may occur during domestic preparation or cooking. Survey data from SCQ indicated that many consumers remove viscera or gills and clean seafood before cooking, or perform a depuration on shellfish, practices that may reduce the MP intake relative to our estimates. Conversely, some cooking methods may alter rather than eliminate MPs. Eshun and Pobee (2022) reported that deep-frying has been shown to reduce MP load in fish but increase the amount of MP in used cooking oil. Thus, our intake estimates may be conservative for consumers who extensively clean seafood, while the overall direction of bias may vary depending on specific preparation and cooking habits.

For populations with a high exposure to MP-contaminated seafood, further research and regulatory action may be needed to balance risks and benefits. From a risk management perspective, the promotion of proper seafood handling practices, such as the removal of internal organs from seafood, proper removal of gills from fish and crabs, and thorough cleaning and depuration of shellfish, may help reduce MP exposure from seafood.

Overall, microplastic exposure from seafood is unavoidable, but it can be measured and possibly reduced through better production and mindful consumption. This implies that in small-scale fisheries, such as in Semarang, microplastic mitigation efforts must be focused on improving the management of plastic materials in fisheries and good handling practices. Meanwhile, consumers can still make seafood part of a healthy diet by being aware of high-risk commodities and supporting producers with high environmental standards and food safety.

4 | Conclusions

This study assessed MP intake via seafood consumption in Semarang City, Central Java, Indonesia. Our findings underline that seafood is an important MP exposure route for humans, although not the primary one. Estimated total MP intake ranged from 11.6 ± 23.3 MPs·capita^{-1}·d^{-1} in toddlers to 43.6 ± 63.1 MPs·capita^{-1}·d^{-1} in adults, with adolescents and adults exhibiting the highest absolute intake. High percentile exposure was substantial, with 95th percentile intake reaching 93 to 112 MPs·capita^{-1}·d^{-1} among adolescents and adults and rising to 132.8 MPs·capita^{-1}·d^{-1} in the elderly. Many factors, such as the type of seafood consumed, age, and personal preferences, influence the contribution of seafood to MP exposure. These factors should be considered when identifying and managing the most exposed groups.

Bivalves are a major contributor to MP intake, with contributions at the 95th percentile ranging from 48 to 57 MP·d^{-1}, suggesting that individuals with high consumption levels may face significantly greater exposure. Although this study shows no large differences in MP exposure via seafood consumption across different age groups, children and toddlers have the highest relative body burden due to lower body weight.

A small proportion of respondents are likely to have very high exposure (the 95th percentile and above), indicating the presence of high-consumption individuals who may require targeted risk-mitigation strategies. Practical measures include removing intestines and other MP-prone organs before consumption of fish and moderating the frequency of bivalve consumption, particularly for mussels and cockles, which cannot be cleaned before ingestion.

Several considerations should be taken into account when interpreting these findings. MP intakes were assumed to be derived from MP concentrations in fresh seafood, while the effects of food preparation and cooking were not addressed in this study, and the lack of current health-based toxicological reference values prevents translating intakes into quantitative health risks. Future studies should incorporate seasonal variability, investigate MP levels in processed seafood products, and link exposure estimates with emerging toxicological endpoints to provide a more complete understanding of potential health implications. Overall, these findings highlight the importance of prioritizing the monitoring of seafood species that contribute most to MP intake, while also incorporating consumer preparation and consumption habits into exposure assessments.

Author Contributions

Inneke Hantoro: conceptualization, methodology, data curation, investigation, formal analysis, visualization, writing – original draft. **Jiaqi Wang**: formal analysis, writing – review and editing. **Ansje J. Löhr**: resources, supervision, writing – review and editing. **Frank G.A.J. Van Belleghem**: supervision, writing – review and editing. **Budi Widianarko**: conceptualization, supervision, writing – review and editing, formal analysis. **Ad M.J. Ragas**: conceptualization, writing – review and editing, formal analysis, supervision.

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Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used Copilot to improve the language and readability of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Material: jfds70909-sup-0001-SuppMat.docx **Supplementary Material**: jfds70909-sup-0002-SuppMat.docx **Supplementary Material**: jfds70909-sup-0003-SuppMat.docx **Supplementary Material**: jfds70909-sup-0004-SuppMat.docx