



Integrated toxicokinetic/toxicodynamic assessment modeling reveals at-risk scleractinian corals under extensive microplastics impacts

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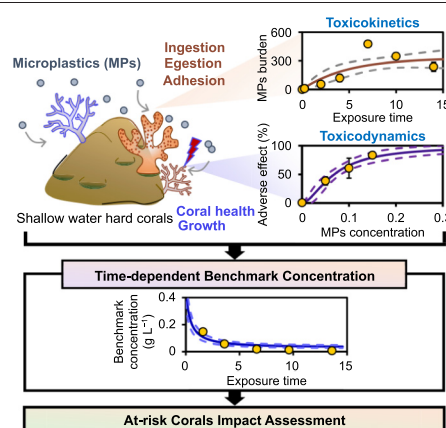
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HIGHLIGHTS

- First ecotoxicological modeling the microplastics impacts on corals was performed.
- Toxicokinetics-based coral-microplastics transport rates were estimated.
- Toxicodynamics-derived coral-microplastics response thresholds were obtained.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 19 July 2021

Received in revised form 3 October 2021

Accepted 9 October 2021

Available online 14 October 2021

Editor: Henner Hollert

Keywords:

Shallow-water scleractinian coral

Marine microplastics

Toxicokinetics

Toxicodynamics

Ecotoxicology

ABSTRACT

Marine microplastics (MPs)-induced threats to shallow-water scleractinian corals are a growing global concern that needs interdisciplinary studies. However, it remains uncertain to what extent the ecotoxicological effects of MPs can explain the potential health impacts on corals at the species-specific scale. Using recent datasets of multiple MPs-induced impacts on coral species, we developed an integrated ecotoxicological modeling approach to quantify the MPs–corals interaction dynamics. Toxicokinetic (TK)-based corals ingestion, egestion, and adhesion processes posed by MPs were comprehensively evaluated. Based on estimated uptake and egestion rates, we showed that corals were much likely to bioaccumulate marine MPs. We applied toxicodynamic (TD) models to appraise time- and concentration-dependent response patterns across MPs–corals systems. We found that marine MPs are highly toxic to corals with a median benchmark concentration causing 10% compromised coral health of 20–40 mg L⁻¹ and a mean growth inhibition rate of ~2% d⁻¹. By providing these key quantitative metrics that may inform scientists to refine existing management strategies to better understand the long-term impact of MPs on coral reef ecosystems. Our TK/TD modeling scheme can help integrating current toxicological findings to encompass a more mechanistic-, ecological-, and process-based understanding of diverse coral ecosystems that are sensitive to MPs stressor varied considerably by species and taxonomic group.

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1. Introduction

Coral reefs, one of the most biodiverse ecosystems, are experiencing rapid degradation worldwide due to intense natural and anthropogenic

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stressors (Pratchett et al., 2015). Apart from temperature stress, ocean acidification, and overfishing which are well-known stress factors causing deleterious effects to corals, high concentrations of suspended particulate matter and emerging pollutants have also received considerable attention (Anthony, 1999; Ban et al., 2014). Microplastics (MPs), defined as plastic particles ≤ 5 mm in diameter, have become an emergent threat to corals (de Oliveira Soares et al., 2020). Massive studies have evidenced the ubiquity of MPs in various marine compartments where coastal regions are of most concern due to intensive marine-based activities (Jang et al., 2020). In coral reef systems, polyethylene (PE) fibers are predominant in water, whereas polypropylene (PP) fragments are the most abundant MPs in sediment (Jeyasanta et al., 2020; Patterson et al., 2020). Mean concentrations of MPs in the Indo-Pacific region varied from 0.32–60,000 particles m^{-3} in surface water and 103.8–846.3 particles kg^{-1} in sediment, implying the potential health risk of corals and associated biota posed by MPs exposure (Patterson et al., 2020; Patti et al., 2020; Saliu et al., 2018).

Recently, a total of 30 experimental studies have identified the MPs – corals interactions (Supplementary Fig. S1), implicating the importance of species-level assessment of MPs impact on corals. Recent works have increasingly relied on laboratorial data to investigate the MPs impacts on individual species. Among which, shallow-water scleractinian corals are the main focus due to their fundamental role in functioning and stability of coral reef ecosystems, as well as increased anthropogenic pressure (Blackall et al., 2015; Stolarski et al., 2011). Corals in branching forms such as *Acropora* sp. and *Pocillopora* sp. are commonly used as model organisms in the MPs toxicity studies (Martin et al., 2019; Tang et al., 2018).

Generally, shallow water coral species mainly depend on the symbiotic relationship with zooxanthellae by which photosymbiotic byproducts are generated to allow corals to calcify at an expedited rate (Tornabene et al., 2017). On the other hand, active prey capture and passive suspension feeding account for a small percentage of daily metabolic requirements in healthy corals (Houlbrèque and Ferrier-Pagès, 2009). The heterotrophic feeding behavior leads to MPs consumption by corals from ambient environments (Axworthy and Padilla-Gamiño, 2019; Tang et al., 2021). Recent studies have revealed key patterns of MPs consumption by corals including ingestion, egestion, and retention (Hankins et al., 2018; Rotjan et al., 2019). Moreover, multiple MPs-induced effects on corals such as growth inhibition, photosynthetic performance, fertilization success, and mucus production have also been intensively investigated (Berry et al., 2019; Reichert et al., 2018, 2019). In addition, symbiont density and biomarkers related to oxidative stress had the greatest responses to MPs concentrations in wild corals (Tang et al., 2021).

A coral colony is composed by multiple individual polyps physically interconnected by a tissue layer overlying the skeleton (Luz et al., 2021). Endpoints are mostly determined on a polyp basis, unless bleaching and growth are measured at percentages of tested coral fragments. Currently, there is a lack of full mechanistic understanding of how corals expose to environmental MPs and what amount of retained MPs can induce stress response from the ecotoxicological perspectives. In view of what is currently known about MPs exposure and adverse effects on scleractinian corals, we conduct this research on limited yet valuable data to provide some updated evidence for future research. Pertaining to the physiological and biological traits of coral species, the present study develops an integrated toxicokinetic (TK)/toxicodynamic (TD) assessment framework to quantify the MPs – corals interaction dynamics. Model parameters are probabilistically estimated and provided with toxicological interpretation based on foreknowledge on MPs and coral characteristics. Most importantly, thresholds of corals health under MPs exposure would be derived in a rigorous manner.

Therefore, the purposes of this paper are threefold: (i) to quantify the rates of egestion and ingestion, as well as MPs gaining rate for corals, (ii) to examine the MPs-induced effects with derived temporal thresholds, and (iii) to inform key information which can be embedded within a wide range of management strategies for at-risk coral species.

2. Materials and methods

2.1. Study data

Data collection was completed with a strict set of inclusion criteria (Supplementary Fig. S2). Firstly, published papers were gathered from Google Scholar by using keywords of plastic, MPs, and coral. As of the end of 2020, 17 out of 20 available papers have focused on shallow-water hard corals. We thoroughly examined all publicly available research articles that were relevant to the MPs – corals interactions, paying particularly attention to data in terms of MPs concentrations over time and time-/concentration-dependent response which comprehensively present the time-course mechanisms of MPs in corals. Moreover, the data must show statistical significance between MPs-treated groups and the control based on the statistical analysis in remaining papers. Collectively, we extracted the experimental data from four papers with detailed experimental procedures: Martin et al. (2019), Reichert et al. (2019), Rotjan et al. (2019), and Syakti et al. (2019) (Fig. 1). Among these studies, PE was used as representative MP type due to their wide applications in plastic product manufacturing and common types found in MPs debris (Hale et al., 2020). Besides *Astrangia poculata* which is distributed along east coast of the United States, other four scleractinian corals species are major families of reef building in the Indo-Pacific region (OBIS, 2015).

Two studies have conducted time-course MPs ingestion experiments in an environmentally realistic scenario (Martin et al., 2019; Syakti et al., 2019). In brief, Martin et al. (2019) used three coral species tested in the presence of PE-MP beads (PE-MPs treatment) and additional food supply (mix treatment) (Fig. 1). The total exposure times were 24 h for *Pocillopora verrucosa* chambers and 28 h for *Acropora hemprichii* and *Goniastrea retiformis* chambers. Data with average PE-MP beads left in chamber of all species at each sampling time were extracted (Supplementary Table S1). On the other hand, Syakti et al., (2019) used *Acropora formosa*, a synonym of *Acropora muricata*, which were incubated in 0.15 $g L^{-1}$ of PE-MPs for a longer period of 14 days (Fig. 1). Ingested MPs in coral fragments were reported (Supplementary Table S2).

The experimental data related to corals-MPs egestion were extracted from Rotjan et al. (2019) (Fig. 1). Briefly, wild-captured *A. poculata* were firstly exposed to 0.1 g of PE-MPs together with brine shrimp eggs for 90 min. They were then transferred into MPs-free chambers to recover during 0, 30, 60, and 90 min, and 24 h post-exposure periods. Measured ingested PE-MPs remained in polyps were 27.5 ± 23.2 (mean \pm SD) 7.5 ± 8.5 , 4.1 ± 8.6 , 2.5 ± 2.4 , and 0.4 ± 0.8 particles per polyp, respectively.

The time- and concentration-dependent effects of compromised coral health including bleaching were also evaluated in Syakti et al. (2019) (Fig. 1 and Supplementary Table S3). The other toxicity test was associated with significant coral growth by using coral *A. muricata* for 24 weeks (Reichert et al., 2019) (Fig. 1). Reichert et al. (2019) assessed growth parameters including changes in surface area, volume, and calcification rate of corals posed by MPs concentration at 0.25 $mg L^{-1}$ for each six-week interval. All each six-week interval in that all parameters were normalized to surface area in advanced. Because many of the original data have noteworthy uncertainties, we only adopted mean values for further analyses (Supplementary Table S4).

2.2. Toxicokinetic models

Prior to exerting a toxic effect, toxicant transfer between environment and target sites leading to accumulation need to be evaluated (Fig. 2A). Here we developed three TK models to optimally fit the time-dependent MPs-coral relationships based on different experimental designs (Fig. 2B). Firstly, a one-compartment TK model was used to fit mass of ingested MPs in fragments of *A. muricata* to obtain uptake and egestion rate constants,







Martin et al. (2019)	Rotjan et al. (2019)	Syakti et al. (2019)	Reichert et al. (2019)
Coral species			
			
<i>Pocillopora verrucosa</i>	<i>Astrangia poculata</i>	<i>Acropora muricata</i>	<i>Acropora muricata</i>
			
<i>Goniastrea retiformis</i>			
			
<i>Acropora hemprichii</i>			
PE-MPs size (\bar{d}_p, μm)			
$\bar{d}_p = 53\text{--}500$	$\bar{d}_p = 200.2$	$\bar{d}_p < 100$	$\bar{d}_p = 175.5 \pm 73.5$
Treatment: exposure concentration (C) and time (T)			
<ul style="list-style-type: none"> PE-MPs treatment: $C = 13645 \pm 139$ particles L^{-1} Mix treatment: $C = \text{PE-MPs } (6524 \pm 56 \text{ particles } \text{L}^{-1})$ and preys (6585 ± 32 <i>Artemia salina</i> eggs and nauplii L^{-1}) $T = 0, 2, 4, 6, 12, 24,$ and 28 hours 	$C = 0.1 \text{ g } (\sim 8500$ particles) with 0.1 g brine shrimp eggs $T = 90 \text{ min}$	$C = 0.05, 0.1,$ and $0.15 \text{ g } \text{L}^{-1}$ $T = 0, 2, 4, 7, 10,$ and 14 days	$C = 0.25 \text{ mg } \text{L}^{-1}$ $T = 0, 6, 12, 18,$ and 24 weeks
Measurement			
Time-dependent MPs ingestion	Time-dependent MPs egestion	<ul style="list-style-type: none"> Time-dependent MPs ingestion Compromised coral health (bleaching) 	Growth rate: surface area, volume, and calcification rate

Fig. 1. Study data adopted from four published research articles.

$$\frac{dC_i(t)}{dt} = k_u C_w - k_e C_i(t), \tag{1}$$

where C_i is the mass of ingested MPs (mg), C_w is taken as a constant MPs concentration of $0.15 \text{ g } \text{L}^{-1}$ in aquaria, t is the exposure time (d), k_u is the uptake rate constant (L d^{-1}), and k_e is the egestion rate constant (d^{-1}). In view of the solution of Eq. (1) (Supplementary Table S5, Eq. (T1)), the bioconcentration factor (BCF) can be calculated as the ratio of k_u and k_e , with $\text{BCF} > 1$ indicating bioaccumulation of MPs occurred in corals.

Moreover, our study determined the ability to excrete MPs by *A. poculata* coral polyps after an acute exposure. Due to a dramatically decreased pattern of ingested MPs remained in polyps (Rotjan et al., 2019), an exponential decay equation was applied to describe the egestion dynamics,

$$C_B(t) = C_{B,0} \cdot \exp(-k_e t), \tag{2}$$

where C_B is the MPs abundance per bulk of polyp (particles polyp^{-1}) and $C_{B,0}$ is the inherent MPs abundance per polyp. Based on the experimental data, $C_{B,0}$ was 27.5 particles polyp^{-1} (Rotjan et al., 2019).

Given that no egestion or detachment of MPs was observed in Martin et al. (2019), we thus incorporated the Verhulst logistic equation into the TK model to describe the interactions between MPs and coral polyps driven by ingestion and adhesion. The Verhulst logistic equation was originally used in population growth modeling (Tsoularis and Wallace, 2002). Regression of remaining MPs abundance in chamber (C_w , particles L^{-1}) was first refit using a statistical model (Supplementary Table S5, Eq. (T2)).

In contrast to aiming at MPs removal from waters, our study focused on corals themselves in which biokinetics occurred. Considering that MPs ingestion in a polyp and adhesion on polyp surface have the saturation-level characteristics, a logistic-based TK model involving exponential and stationary phases can be used as,

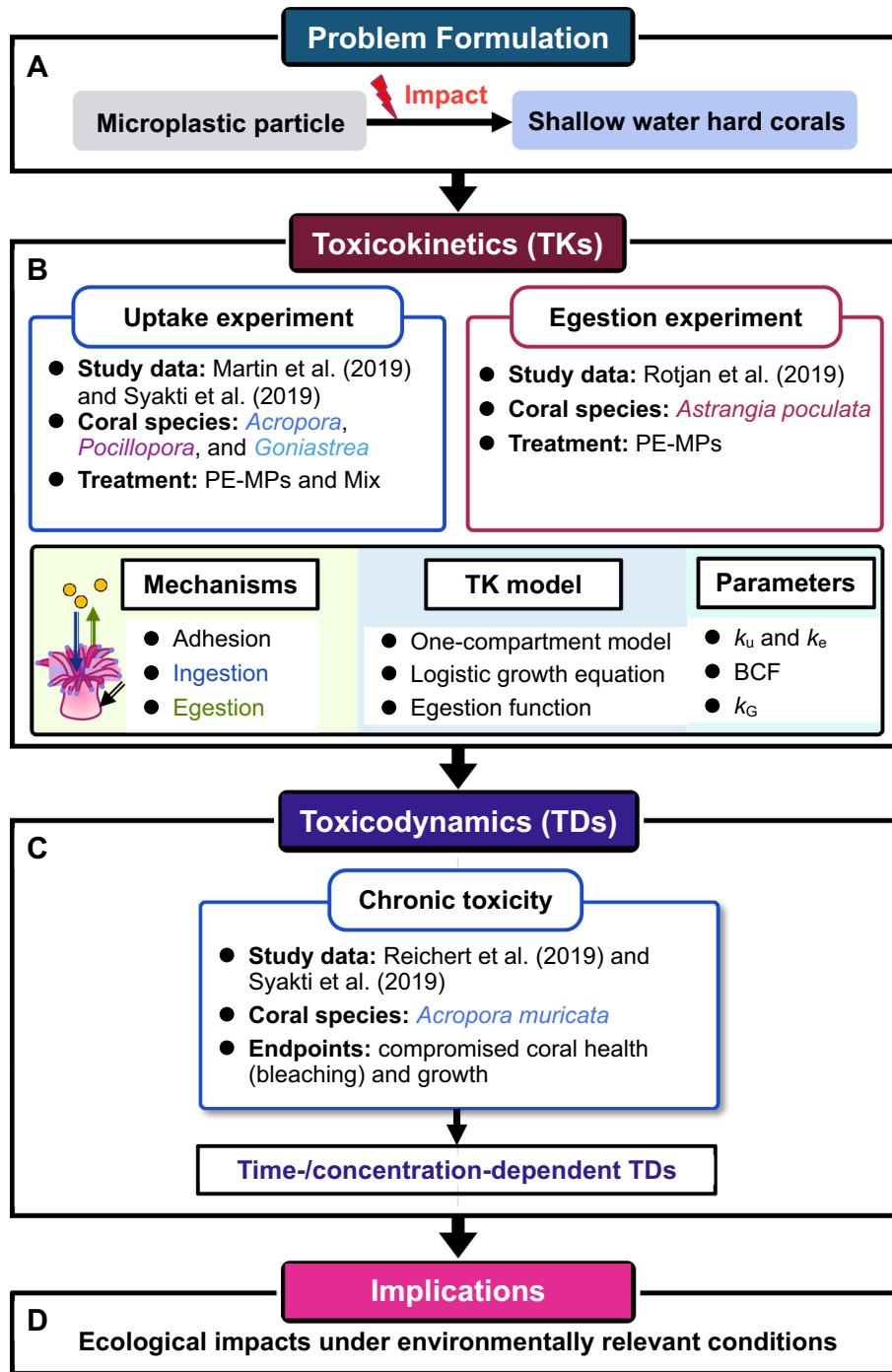


Fig. 2. Schematic showing the study framework of TK/TD assessments for corals in response to MPs exposure.

$$\frac{dC_B(t)}{dt} = k_G C_B(t) \left(1 - \frac{C_B(t)}{C_{B,\max}} \right), \quad (3)$$

where k_G is the gaining rate of MPs from culture water (h^{-1}) and $C_{B,\max}$ is the maximal MPs abundance per polyp (particles polyp $^{-1}$) served as the carrying capacity. The solution of Eq. (3) (Supplementary Table S5, Eq. (T3)) reveals that the carrying capacity plays an important role in MPs ingestion/adhesion in corals.

2.3. Toxicodynamic models

Based on the valuable and comprehensive toxicity data obtained from Syakti et al. (2019), both time- and concentration-dependent

toxicity patterns of MPs on compromised coral health, especially bleaching, can be explained by the TD analysis (Fig. 2C). While several mathematical models could be used to fit the dose-response relationships to estimate toxicological parameters, the standard Hill model provides a theoretical explanation for such sigmoidal curves. Given that compromised coral health including bleaching were expressed in percentage terms, the maximum adverse effect would be 100%. Therefore, for a certain exposure duration, we used a two-parameter Hill model to fit the concentration-effect relationships,

$$E(C_W) = \frac{100 \cdot C_W^n}{EC50^n + C_W^n}, \quad (4)$$

where E is the adverse effect (%), EC_{50} is the median effect concentration ($g L^{-1}$), and n is the Hill coefficient, indicating the slope of the fitting curve. Moreover, benchmark concentration (BMC_{10}) which denotes threshold causing 10% effect can be estimated from the established Hill models.

Preliminarily, model-derived BMC_{10} s of time-varying exposure were beyond the simple relationship expressed by the Haber's rule (Tennekes and Sánchez-Bayo, 2013). Hence, to describe BMC_{10} s with time-course features, our approach simply combined the well-established one-compartment TK and Hill models. There are two toxicity models that are derived based on the different toxicological concepts: (i) the time-integrated concentration (TIC) toxicity model and (ii) the whole-body burden (WBB) toxicity model (Liao and Lin, 2001). The TIC toxicity model is based on area under the concentration-time curve (AUC) which is commonly used to assess the extent of exposure of a toxicant (Scheff et al., 2011). The AUC is defined as the integration of $C_i(t)$ to the exposure time t and can be calculated as,

$$AUC = \int_0^t C_i(t) dt = \int_0^t \frac{k_u}{k_e} C_W (1 - \exp(-k_e t)) dt = \frac{BCF}{k_e} C_W (k_e t + \exp(-k_e t) - 1). \quad (5)$$

Since $BMC_{10}(t)$ is the threshold level of MPs exposure concentration, C_W in Eq. (5) can be replaced with $BMC_{10}(t)$. We then rewrote Eq. (5) and added a constant value ($BMC_{10}(\infty)$) in terms of compensatory mechanisms in organism and was referred to as the TIC toxicity model,

$$BMC_{10}(t) = \frac{AUC}{BCF} \left(\frac{k_e}{k_e t + e^{-k_e t} - 1} \right) + BMC_{10}(\infty), \quad (6)$$

where $BMC_{10}(\infty)$ is the BMC_{10} value at infinite time ($g L^{-1}$).

The other approach is the WBB toxicity model, by directly applying the solution of the one-compartment TK equation in Eq. (T1) (Supplementary Table S5). Likewise, regarding C_W as $BMC_{10}(t)$, the WBB toxicity model can then be expressed as,

$$BMC_{10}(t) = \frac{BMC_{10}(\infty)}{BCF(1 - e^{-k_e t})}. \quad (7)$$

Therefore, based on previously estimated TK parameters (i.e., k_e and BCF), we could determine the best-fit values of $BMC_{10}(\infty)$ from both toxicity models and AUC value from the TIC toxicity model.

Based on the interpreted time-course concentration-response relationships via TD modeling, we were further interested in knowing internal concentration of MPs in corals causing threshold effect. By incorporating the constructed TIC toxicity model into the one-compartment TK model, namely substitution of C_W in Eq. (T1) by $BMC_{10}(t)$ as Eq. (6), time-dependent whole-body burden of MPs in coral fragments inducing 10% adverse effects ($C_{E10}(t)$) can be predicted as,

$$C_{E10}(t) = AUC \left(\frac{k_e(1 - e^{-k_e t})}{k_e t + e^{-k_e t} - 1} \right) + BCF(1 - e^{-k_e t}) BMC_{10}(\infty). \quad (8)$$

On the other hand, considering chronic toxicity endpoints related to coral growth, a von Bertalanffy function, widely used to model growth for numerous species over time, was employed to appraise the impact of MPs exposure on surface area, volume, and calcification rate (Lee et al., 2020). The function typically showing a sigmoidal fashion with the lag section is expressed as a generalized logistic equation,

$$E(t) = E_{\max}(1 - \exp(-k(t - t_0))), \quad (9)$$

where $E(t)$ denotes the time-dependent growth effect comparing with control (%), E_{\max} is the maximal growth rate, k is the growth coefficient (d^{-1}), and t_0 is the lag time (d).

On the basis of this rationale (Fig. 2A, B, C), a TK/TD-based threshold approach can therefore be applied to implicate the ecological impacts on the coral reef ecosystems under the environmentally relevant conditions (Fig. 2D).

2.4. Data analysis and statistics

The software used in this work to perform the TK/TD model fittings is TableCurve 2D (Version 5.01, AISN Software, Mapleton, OR, USA). Percentiles of 2.5th and 97.5th were generated as the 95% confidence intervals (CIs) for curve fittings. All estimates were presented as mean values with their standard errors (SE). A Monte Carlo simulation for generating statistical distributions of toxicological parameters was performed by Crystal Ball software (Version 11.1.2.4, Oracle, Inc., USA).

3. Results

3.1. Toxicokinetics of MPs uptake and egestion in coral fragments

The one-compartment TK model well described 14-day MPs ingestion in *A. muricata* coral fragments ($r^2 = 0.70$, p -value < 0.001) and the estimated biokinetic parameters of k_u (0.45 ± 0.16 (mean \pm SE) $L d^{-1}$) and k_e ($0.20 \pm 0.10 d^{-1}$) could be obtained (Fig. 3A; Supplementary Table S6). In light of much higher level of k_u than k_e , BCF was calculated as 2.78 ± 1.83 , indicating that MPs were much likely to be bioaccumulated in corals via chronic exposure (Supplementary Table S6). However, the curve-fitting of MPs egestion in *A. poculata* polyps had a small r^2 ($r^2 = 0.50$, p -value < 0.05) due to large standard deviations of fitted data and the dramatically decline of exponential curve within an hour (Fig. 3B,C). The estimated k_e for corals in clean water was $28.80 \pm 12.67 d^{-1}$.

3.2. Patterns of MPs ingestion and adhesion in coral polyps

The regression results indicated that remaining MPs in chamber for mix treatment reached a steady-state within a half day, toward 241 particles L^{-1} , whereas a relatively moderate decline of remaining MPs was

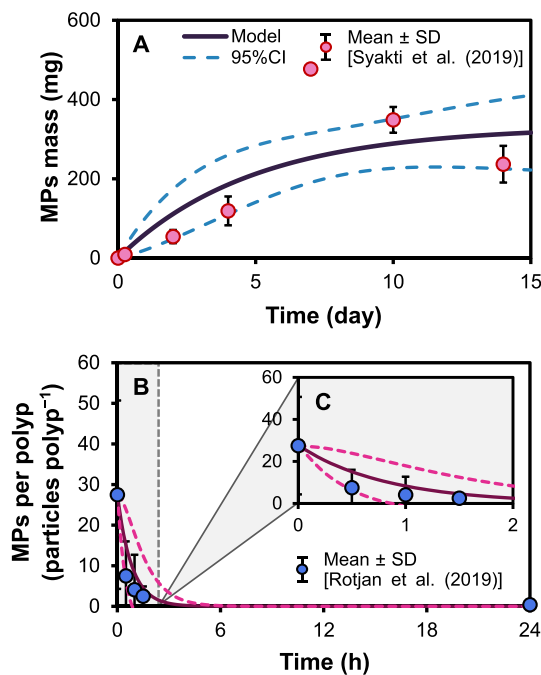


Fig. 3. (A) Fitting one-compartment TK model to the mass of MPs ingested by *A. muricata* corals during a 14-day exposure experiment. (B, C) Fitted exponential decay function describing MPs egestion from *A. poculata* polyps.

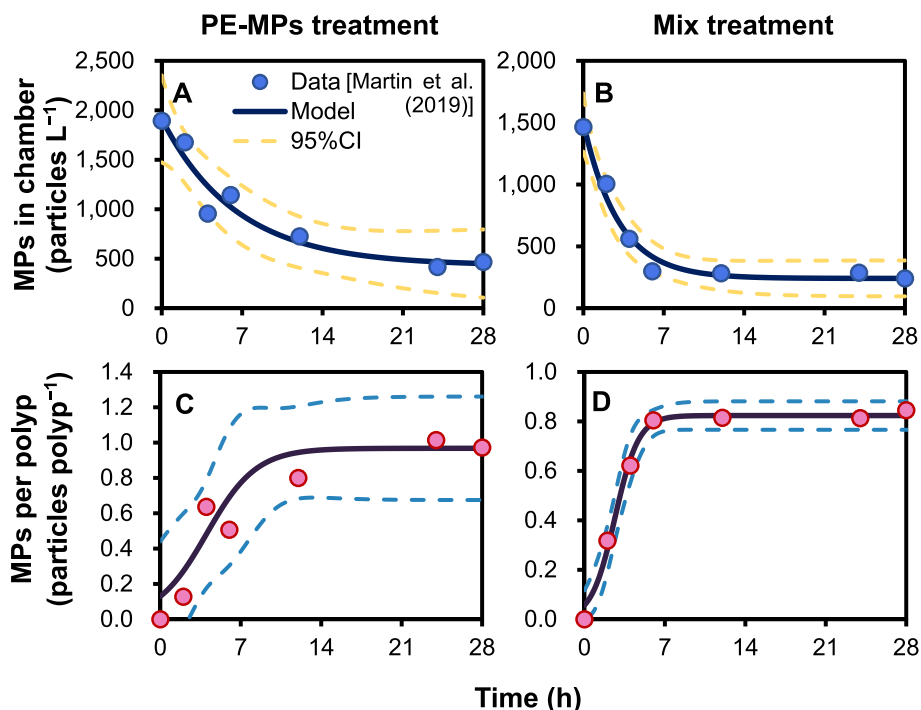


Fig. 4. Reconstructed time-course curves of MPs concentrations in (A, B) chamber and (C, D) coral species treated with PE-MPs only or PE-MPs and *Artemia* (mix).

observed in PE-MPs treatment, approaching 431 particles L⁻¹ at the 28th hour (Fig. 4A,B; Supplementary Table S7). The time-concentration patterns of PE-MPs and mix treatments were best fitted by the Verhulst logistic-based TK model in describing MPs uptake and adhesion in polyps ($r^2 = 0.87$ and 0.99 , respectively) (Fig. 4C,D). Parameter estimates of k_G and $C_{B,max}$ for PE-MPs treatment were 0.46 ± 0.25 h⁻¹ and 0.97 ± 0.11 particles polyp⁻¹, respectively (Fig. 4C; Supplementary Table S8). On the other hand, the role of food supply in mix treatment was found to double increase k_G of 0.98 ± 0.15 h⁻¹ (Fig. 4D; Supplementary Table S8). Another plausible reason could be explained by the half $C_{B,0}$ value of 0.06 particles polyp⁻¹ in mix treatment compared to that of 0.13 particles polyp⁻¹ in PE-MPs treatment (Fig. 4D; Supplementary Table S8).

3.3. Toxicodynamic analysis for compromised coral health

The fitted exposure time-specific concentration-effect curves were statistically significant on day-7, 10, and 14 exposures ($r^2 > 0.92$, p -value < 0.001) (Fig. 5). The maximum EC_{50} s of compromised coral health and bleaching were 0.43 and 0.32 g L⁻¹, respectively, occurred in day-4 exposure (Supplementary Table S9). Except the result for day-4 exposure, EC_{50} decreased with increasing exposure duration, indicating that a low level of MPs concentration would cause coral bleaching and necrosis under a long-term exposure (Supplementary Table S9).

The derived $BMC_{10}(t)$ had the similar pattern which were better described by the TIC toxicity model ($r^2 \approx -0.9$), compared to the WBB toxicity model ($r^2 \approx -0.7$) (Fig. 6A–D). Though the lowest BMC_{10} estimates were 0.01 g L⁻¹, $BMC_{10}(\infty)$ of compromised coral health and bleaching referred to as the horizontal asymptote were 0.02 and 0.04 g L⁻¹, respectively (Fig. 6A–D; Supplementary Tables S9–10). The AUC s in the TIC toxicity model for compromised coral health and bleaching were 0.12 g d (Fig. 6A,C; Supplementary Table S10). Moreover, based on the established TIC toxicity model, the time-dependent MPs body burdens per coral fragment causing 10% adverse effects were predicted (Fig. 6E). The result showed an increasing temporal pattern, indicating that whole body burden of MPs in corals was far from equilibrium within a 14-day exposure.

3.4. Time-dependent toxicodynamic analysis on coral growth

The inhibition of varied growth rates in *A. muricata* impacted by MPs exposure observed each 6 weeks generally increase toward maximum adverse effects on surface area, volume, and calcification rate (Fig. 7). The best-fit of exposure time-response TD modeling demonstrated that the estimated mean t_{05} s were 7–10 d, indicating a relatively short lag time for coral growth in response to MPs (Fig. 7; Supplementary Table S11). The fitted coefficients ks of growth inhibition rate were nearly the same, with a mean value of $\sim 2\%$ d⁻¹ (Supplementary Table S11).

4. Discussion

4.1. Toxicologically relevant MPs accumulation in corals

This study investigated the time-dependent toxicological pattern of MPs in coral species from four families. The TK/TD modeling gave insightful interpretations of toxicity test data over more descriptive methods. To our best knowledge, only a handful of studies have calculated bioconcentration factors at steady-state (i.e., BCF) for corals based on the uptake and depuration kinetics of metals in corals (Hédouin et al., 2016; Metian et al., 2015). Evident bioaccumulation of PE-MPs in corals was firstly quantified in this study in that BCF for *A. muricata* indicated a serious ingestion and retention of MPs in polyps, implying a consequential impact on coral health.

Previous works rarely investigated time-course MPs concentration in corals in that average ingestion rates were usually provided. Our uptake rate estimate (k_u) for *A. muricata* in 0.15 g L⁻¹ of MPs treatment was 0.45 L d⁻¹, resulting in 0.07 g MPs uptake per day. A feeding trial showed that *Dipsastrea pallida* in size of 21–84 cm² consumed 14–660 $\mu\text{g cm}^{-2} \text{d}^{-1}$, equivalent to 4.54×10^{-3} –0.02 g MPs per day (Hall et al., 2015). We speculated that the 12-h incubated period for *D. pallida* was too short for corals to reach a steady-state condition with higher uptake rate as *A. muricata* incubated for a period of 14 days (Hall et al., 2015; Syakti et al., 2019). In addition, due to finite capacity per polyp, *A. muricata* posed by smaller MPs ($< 100 \mu\text{m}$)

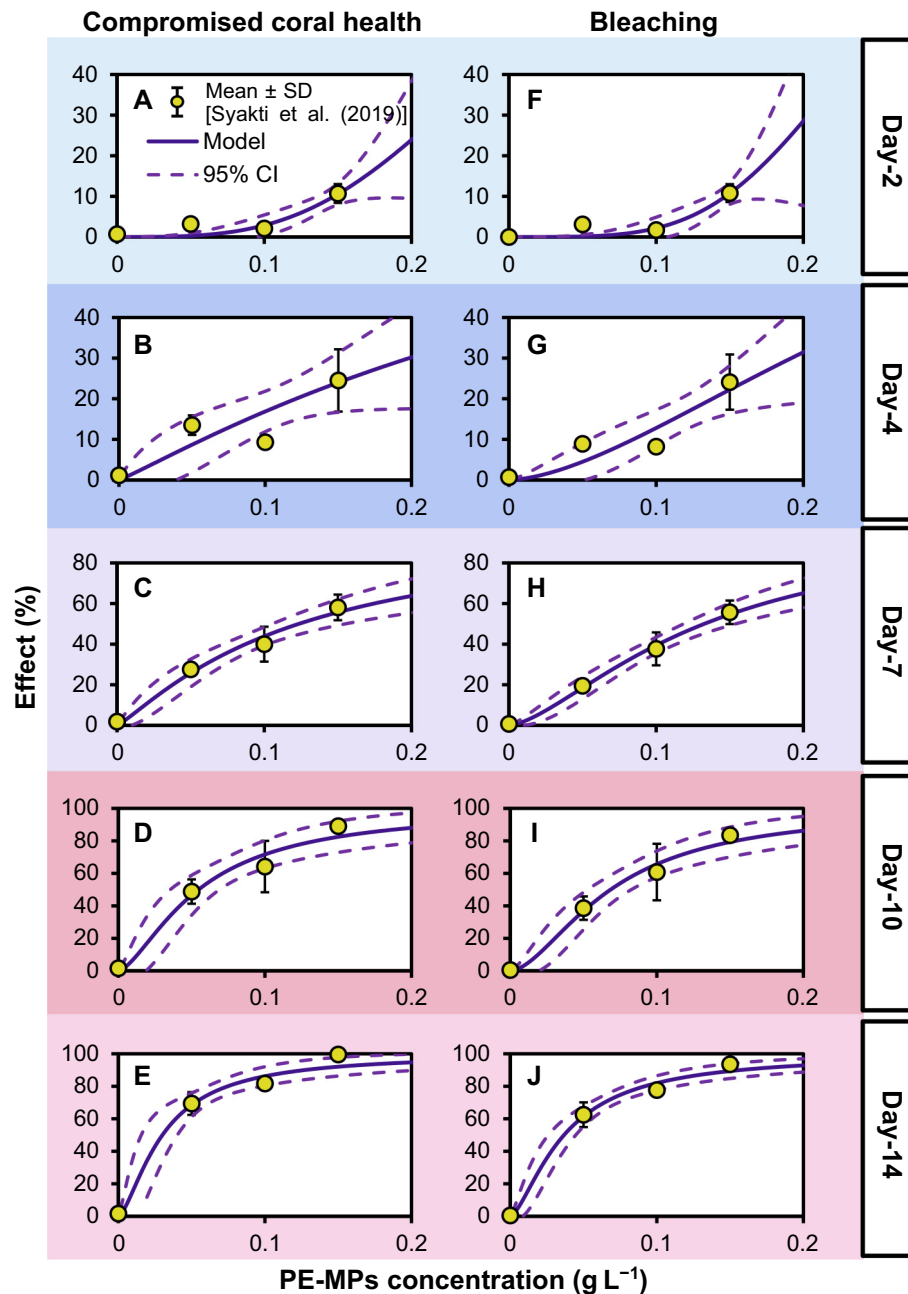


Fig. 5. Relationships between health effects of *A. muricata* and MPs concentrations over different exposure durations fitted by the two-parameter Hill model.

could ingest and retain more MPs, whereas few *D. pallida* polyps were able to ingest more than one plastic particle ($>100\ \mu\text{m}$) during the incubation. Different species traits such as polyp number per coral fragment and polyp size might also influence the ingestion rates of MPs (Hierl et al., 2021).

Factors that influence MPs ingestion rate can be intra- or interspecies. Polyp volume showed no limitation on MPs consumption for *A. poculata*, whereas polyp size significantly affected ingestion rate among coral species (Reichert et al., 2018; Rotjan et al., 2019). A field study reported that the average MPs amounts in small-polyp coral *P. damicornis* and large-polyp coral *Galaxea fascicularis* were 3.68 ± 3.94 (mean \pm SD) and 5.89 ± 5.15 particles cm^{-2} , respectively (Tang et al., 2021). Generally, scleractinian corals have small polyps in average diameter of 1–3 mm which are also the most common sizes of environmental MPs in water across the coral reef ecosystem (Jensen et al., 2019; Jeyasanta et al., 2020; NOAA, 2021; Patterson et al., 2020). MPs

ingestion in small polyp corals is highly likely to be affected due to limited feeding capacity subject to retained MPs and digestibility of natural food sources, whereas corals with larger polyp diameters can potentially better control uptake and egestion (Hankins et al., 2018; Hierl et al., 2021).

Schematic of MPs incorporation in coral tissues was performed in Hierl et al. (2021). Briefly, MPs might adhere to the outer epidermis area of the coral tentacle or attach to the coenosarc. Mucus production as a defense mechanism in corals is likely to be triggered to prevent adhesion of MPs on coral surfaces (Martin et al., 2019). When MPs are caught by a tentacle, feeding process starts and MPs are incorporated inside the gastric cavity inducing tissue necrosis. Because of the healing process of the tissue damage by clonal tissue overgrowth and partial encrustation, MPs are fully embedded in the coral skeleton.

Skeletal morphology being an inter-species factor of adhesion rate suggested that massive corals have higher adhesion rate than branching

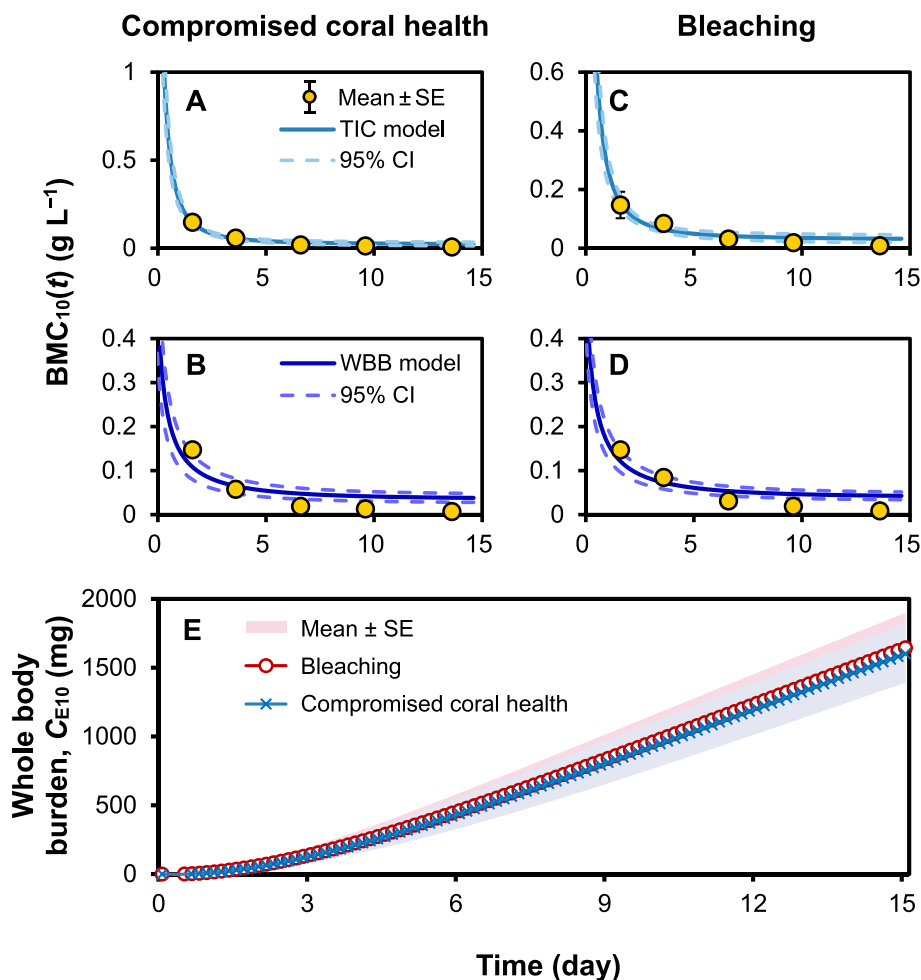


Fig. 6. Optimal fits of the TIC and WBB toxicity models for time-dependent benchmark concentration ($BMC_{10}(t)$) causing (A, B) compromised coral health and (C, D) bleaching. (E) Predicted time-varying whole body burden of MPs in corals at the site of action causing 10% impacts.

corals, indicating that adhesion efficiency of corals as a whole depended on MPs concentration in water (Martin et al., 2019). Given lower adhesion rate for corals posed by half MPs concentration in the mix treatment, however, the estimated MPs gaining rate (k_G) from TK modeling was two-fold higher as compared with that in the PE-MPs treatment. Higher k_G could be ascribed to greater MPs ingestion in the presence of brine shrimps. The result was consistent with the findings in Savinelli et al. (2020) that food sources significantly increased MPs ingestion by 26% on average, indicating a lack of avoidance mechanism enabling the polyps to discern between food items and MPs when occurring simultaneously. Indiscriminate feeding behavior was observed in corals and other planktivores who may mistake plankton-sized MPs as preys (Montano et al., 2020). The elevated feeding activity is likely to be a behavioral compensatory response of the corals to enhance capture efficiency due to nutrient deficit caused by MPs ingestion (Chapron et al., 2020).

Moreover, species-specific ingestion and egestion rates depend largely on MPs shape and size, whereas corals prefer to ingest MPs having similar size to their feeds (Corona et al., 2020; Hall et al., 2015; Reichert et al., 2018). The MPs shapes such as fibers and beads are plausibly key factors for particle retention and subsequent nutritional loss (Rotjan et al., 2019). Retention time of MPs in the coral digestive cavity was ~90 min (Reichert et al., 2018; Savinelli et al., 2020). The retained MPs not only can induce stress responses, but also incur energetic costs via the MPs egestion process, leading to the high potential health impacts (Hankins et al., 2018). In general, several studies have found that most ingested MPs were quickly egested (Allen et al., 2017;

Hankins et al., 2018; Rotjan et al., 2019). Our egestion rate estimates (k_e s) for corals during MPs treatment and in clean water were 0.2 and 29 d⁻¹, respectively.

Due to the complex mechanism of MPs ingestion and adhesion, three different TK models were used to mechanistically elucidate the variation of exposure assessment. Our robust model fitting reliably determined the toxicological parameters for MPs – corals system. However, the experimental data using spherical MPs adopted in this present study may restrict the application scope of modeling parameters for realistic exposure in marine water. In situ studies are therefore needed in support of better understanding the bioavailability and bioaccumulation of MPs for coral species. A full understanding of MPs dynamics in corals requires a further investigation under the environmentally realistic exposure conditions to improve the present TK modeling and regulatory decision making.

4.2. Stress responses in corals posed by microplastic exposure

Multiple MPs-induced impacts on corals have been studied, though only bleaching and tissue health, as well as coral growth were included in our TD analysis. To date, only three studies have tested different MPs exposure concentrations in toxicity assays on corals (Berry et al., 2019; Grillo et al., 2021; Syakti et al., 2019). However, none of acute toxicity endpoints such as enzymatic activity, embryo development, and larval settlement were statistically different from the experimental controls (Berry et al., 2019; Grillo et al., 2021). On the other hand, compromised coral health was significantly observed during a 14-day exposure

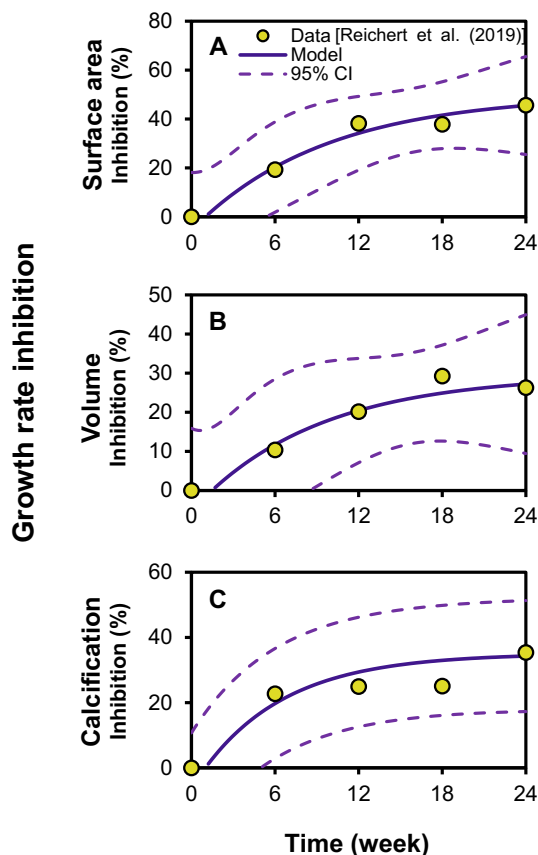


Fig. 7. Growth inhibition changes in (A) surface area, (B) volume, (C) and calcification rate of *A. muricata* coral during a 24-week MPs exposure fitted by the Von Bertalanffy equation.

period, which was worth interpreting the toxicological findings (Syakti et al., 2019). We provided time-dependent EC_{50} and BMC_{10} that were the essential metrics in further risk assessment for managing MPs exposure-induced health impacts.

MPs become a new environmental stressor potentially responsible for compromising coral health. Generally, loss of zooxanthellae and photosynthetic pigment per zooxanthella from the coral host trigger bleaching mechanism which is the most commonly reported response variable (Ban et al., 2014). A 70–90% or greater reduction in zooxanthella density would cause completely bleached corals (Douglas, 2003). Despite insignificant change of zooxanthella density in corals associated with 24-h exposure of MPs, mass expulsion of zooxanthellae was found in aquariums with 93% coral bleaching at the end of 14-day exposure (Syakti et al., 2019; Tang et al., 2018). Based on our estimation, long-term exposure of MPs at ambient concentrations (i.e., $BMC_{10}(\infty)$) ranging from 0.02–0.04 $g L^{-1}$ could induce the benchmark effect of compromised coral health. Our $BMC_{10}(\infty)$ level of MPs is supported by the previous results (Reichert et al., 2018, 2019). They indicated that no changes of symbiont densities in four coral species and minor compromised coral health were observed during a 6-week exposure at concentration of 0.25 $mg L^{-1}$, whereas the low and moderate impacts of bleaching or necrosis were found during a 4-week exposure at a high concentration of 0.1 $g L^{-1}$ (Reichert et al., 2018, 2019).

We integrated the TIC toxicity model and the one-compartment TK model to predict time-dependent MPs body burden at benchmark effect. More concentrated symbionts were released into water which can be explained by increasing MPs burden in coral polyps, implying that MPs intake led to a stress response in the internal mechanism of the coral–algal symbiosis. (Syakti et al., 2019). The mechanism might be related to the membrane structures where ingested MPs and the symbionts were found in the same cell layer (Okubo et al., 2018).

Occupation by MPs in polyps could suppress the uptake of symbionts into host cells thus disturb symbiosis (Okubo et al., 2018, 2020). Moreover, bleached corals are more easily to uptake MPs which then spread throughout the body and are less expelled (Okubo et al., 2020). Though coral health impact might not be merely induced by ingested and retained MPs, a study demonstrated that adhered MPs on coral surface could partly block out light and thus hinder the symbiotic relationship between zooxanthellae and corals (Tang et al., 2018). Therefore, a general framework for evaluating coral species vulnerability to MPs stressor that is based on physiological trait would enable a thorough assessment across many more species and taxonomic groups.

Apart from bleaching, coral growth rates have been widely used as health indicators in the environmental assessments of coral subject to physiological stress (Chapron et al., 2018; Gold and Palumbi, 2018). Our results indicated that growth inhibition rates (k_s) were $\sim 2\% d^{-1}$. A reduction of 8–11% change of tissue surface area for corals was found over a 12-week exposure (Hankins et al., 2021). Though other two scleractinian coral species tested in Reichert et al. (2019) showed no significant change of growth in surface area, volume, and calcification rate. Neither was the calcification effect responsible for most of skeletal growth and carbonate production observed in other species exposed to high concentrations of MPs during the short- or long-term exposure (Hankins et al., 2018; Lanctôt et al., 2020). We deduced from above information that growth response to MPs exposure was species-specific, and *A. muricata* having high growth rate reached the toxic threshold in a more sensitive manner (Anderson et al., 2017). In addition, growth reduction in surface area reached 50% of maximum effect which might need the long-term observations for years.

Rare MPs effect concentrations were available for reef-dwelling organisms. Costa et al. (2020) showed that average EC_{50} s for immobility of ephyrae jellyfish were 1.36 and 0.53 $mg L^{-1}$ post 24 and 48 h of PE-MPs exposure, respectively, providing some justification of our results of rapidly decreased time-dependent EC_{50} s. The EC_{50} and BMC_{10} values for larval growth reduction were 16.2–16.6 and 2.7–3.8 $mg L^{-1}$, respectively, in the sea urchin embryos–MPs test (Oliviero et al., 2019). In copepod toxicity studies, EC_{50} values for larvae survival post 48 h and feeding rate post 24 h were 4.32 and $\sim 60 mg L^{-1}$, respectively (Beiras et al., 2019; Yu et al., 2020). Even though corals are relatively insensitive to acute MPs exposure among marine organisms, those species' vulnerability to MPs impact may directly affect food source of coral polyps. Collateral damage including impacts on food-web structure and trophic transfer of MPs might indirectly threaten biodiversity and balance of coral reef ecosystems.

4.3. Limitations and implications

Although our approach is subject to several variabilities and assumptions in our modeling, mathematical models are one tool among many for making better use of the available data and to provide model-informed insights into MPs impacts on corals. We included ingestion, egestion, and adhesion in the TK analysis, whereas two fundamental biological traits, coral health and growth, are also assessed by TD modeling. However, we can only present a plausible range of model parameters together with alarming thresholds for a particular adverse effect, without a large dataset for refinement and validation of the TK/TD models. The well-established biocriteria should be based on sound scientific principles to closely represent the natural biota, and be quantifiable to identify marginally disturbed sites (Jamieson et al., 1998). Future research is encouraged to conduct chronic toxicity assays in a range of MPs concentrations and to carry out the long-term experimental data to facilitate a mechanism-based comparison of effects from different environmental conditions and endpoints.

Scleractinian corals grow on boulder rock at shallow region are subject to environmental MPs in water column and sediments. The central Indo-Pacific and the Great Barrier Reef of Australia are renowned for the global center of coral diversity (Veron et al., 2015). To date, dozens of

field studies have investigated MPs abundance and characteristics in coral reef systems, yet few of them measured concentrations of MPs in coral polyps (Tang et al., 2021). The present ecotoxicological models is capable of predicting internal burden of MPs in corals. It is timely, in view of our concern about worldwide coral crisis, to provide key quantitative information to the integrated toxicity risk assessment in which exposure and effect assessments were mechanistically performed by the TK/TD modeling.

If we compared BMC_{10} of coral bleaching to the database of MPs abundance in global ocean compiled by Chen et al. (2021), those environmental data sampled along tropical and subtropical coastal regions had much lower levels of MPs concentration ranging from 10^{-6} – 10 mg L⁻¹. The preliminary comparison implicates that current status of MPs pollution seems a tolerable level for corals. Yet, realistic exposure conditions such as exposure pathways of corals to MPs remain unclear. Moreover, compositions of MPs types are diverse in marine environments due to different physical properties of polymers like density and degradation mechanism (Guo and Wang, 2019; Lithner et al., 2011; Sun et al., 2018). Therefore, corals exposed to different polymer types of MPs are likely to show different levels of adverse effects (Xiao et al., 2021). Given the limited data available from laboratory and field studies, we thus realize that it is difficult to truly assess the ecological risk of corals in response to environmental MPs.

Interestingly, we found that MPs induced similar negative effects on corals as suspended sediment which is one of the well-known stressors (Humanes et al., 2017). The tolerance thresholds for coral species to suspended sediment exposure vary between 10 and 1000 mg L⁻¹ of total suspended sediment (Browne et al., 2015). The range encompasses our threshold estimates of 20–40 mg L⁻¹ for MPs. However, the physical and biological factors involved in bleaching, growth reduction, and other impacts on coral communities are more complicated. The multiple interacting stressors having an additive effect would cause deleterious consequences for corals at both organismal and ecosystem levels (Ban et al., 2014).

MPs as a microbial vector can increase prevalence of coral disease and even mortality (Rotjan et al., 2019). Recently, MPs in combination with thermal stress were also investigated (Axworthy and Padilla-Gamiño, 2019; Mendrik et al., 2021). Since MPs could increase the bio-accessibility of sorbed contaminants and polymer additives, corals may suffer higher bioaccumulation of chemicals during MPs ingestion (Khalid et al., 2021). It is recognized that the adverse effects of MPs on aquatic organisms could be synergistically exacerbated in a dose- or size-dependent manner when organic or inorganic pollutants and MPs coexist (Liu et al., 2021). Because corals are simultaneously exposed to the complex mixture of MPs and adhered substances in the natural environment, a multi-stressor concern is useful to project how corals response to environmentally realistic MPs and to capture the heterogeneity of species' vulnerability, which is crucial for designing conservation strategies. The present threshold estimate can serve as a lenient limit of acceptable exposure concentration of MPs for corals. Considerable efforts are needed to address composite risks of MPs on corals whose habitats are suffering various anthropogenic stressors. A focus on characterizing environmental MPs and associated stressors in coral ecosystems is recommended to reflect realistic exposure condition of MPs for corals. More comprehensive toxicological testing is also required to enhance the knowledge of complex response mechanism and TK/TD behavior. Furthermore, it is important to understand larger-scale change across species in a local ecosystem.

5. Conclusions

Although some species-specific MPs–corals interaction patterns have been investigated, here we provide what is to our knowledge the first TK/TD-based ecotoxicological view to explain corals response to MPs appraised with valuable published quantitative data. Corals may have differing tolerances to MPs exposure, and our approach provides

useful guidelines for choosing species-specific toxic thresholds in a risk-based manner. Estimated TK parameters indicate high bioconcentration of MPs during exposure. Time- and concentration-dependent health effects of corals posed by MPs were performed in a combination of various TD models. Rate constants and thresholds of MPs can serve as preliminary benchmarks which are useful in designating and managing a coral reef protected area against further pollution and degradation. Meanwhile, our modeling scheme highlights the need of more research to overcome data gaps and to better understand the critical role of MPs in the ecological network among corals, environments, and other stressors. Overall, our work constitutes key quantitative metrics that may help scientists to refine existing conservation/management strategies for the long-term impact of MPs on coral reef ecosystems.

CRediT authorship contribution statement

Chi-Yun Chen: Methodology, Software, Formal analysis, Writing – original draft. **Tien-Hsuan Lu:** Methodology, Writing – review & editing. **Chung-Min Liao:** Conceptualization, Writing – review & editing, Supervision.

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.

Acknowledgements

This work was supported by the Ministry of Science and Technology of Republic of China under Grant MOST 109-2221-E-002-088-MY2.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2021.150964>.

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