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The Toxicity of Microplastics Explorer (ToMEx) 2.0

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Abstract

In 2021 the Toxicity of Microplastics Explorer (ToMEx, https://microplastics.sccwrp.org) was released as an open source, open access database and web application for microplastics toxicity. Since then, it has been utilized by the microplastic research community for the exploration, visualization, and analysis of toxicity data for both hazard characterization and risk assessment. The peer-reviewed literature has continued to grow exponentially, making ToMEx out-of-date. To ensure the continued utility of ToMEx, an international crowd-sourcing approach was utilized to update ToMEx by extracting data from additional studies published since the original release. Through this process, both the aquatic and human health ToMEx databases roughly doubled in size, and modest increases in data diversity (e.g., number of species represented, types of test particles) were observed in the aquatic organisms database. However, most trends (e.g., greater toxicities observed with smaller particle sizes, lack of dose–response data etc.) observed in the first iteration of ToMEx remained constant. A previously developed framework for deriving ecological health-based microplastic thresholds using species sensitivity distributions was reapplied to determine how thresholds and their associated uncertainty intervals would change following the database update. Twelve new studies passed minimum screening criteria and were deemed fit for the purpose of threshold derivation. The addition of new data allowed for the separation of freshwater and marine compartments which had previously been combined due to a lack of applicable toxicity data for freshwater species. When molecular and cellular level endpoints were included, freshwater thresholds were comparable or increased from values calculated using previous data (-5 to 2.5-fold

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change) whereas marine thresholds dramatically decreased (-5000 to -29-fold change). However, when endpoints were restricted to organism and above, marine and freshwater thresholds were comparable to those calculated previously (-20 to 14-fold change). Confidence intervals for both marine and freshwater thresholds remained wide. The doubling of the database increases the value of ToMEx for researchers, particularly those focused on characterizing hazards associated with microplastics. Its utility remains limited for environmental managers as 89% of studies in ToMEx 2.0 failed to meet minimum screening criteria for threshold derivation, highlighting the need to generate fit-for-purpose toxicity data for threshold development. However, ToMEx continues to be a useful research tool, and future iterations could become even more powerful through novel artificial intelligence applications to streamline data curation and even predict toxicological outcomes.

Keywords Microplastic, Toxicity, Aquatic organisms, Human health, Database

Introduction

Within the past twenty years, microplastics research has rapidly expanded as scientists have documented the presence of microplastics in almost every matrix, habitat, and organism they have investigated [33], emphasizing the ubiquity of this global contaminant and the inevitability of exposure. Naturally, this has been followed by a deluge of studies focused on the toxicological effects of microplastics, with hundreds of peer-reviewed studies now published each year [8]. These studies have been predominately focused on aquatic organisms, documenting the effects of microplastic exposure on metabolic function, immunity, growth, development, and reproduction [3]. The number of studies investigating adverse effects of microplastics in mammals were initially much fewer than those focused on aquatic organisms, but as public concern has risen over the potential impacts of microplastic exposure on human health, there has been a recent surge of microplastic toxicity studies using mammalian test organisms [38]. Microplastics are a diverse contaminant suite, comprising a wide range of particle sizes (defined to include particles between 1 nm and 5 mm) [4, 10] characteristics (e.g., morphologies, polymer types, surface functionalizations), and oftentimes sorbed or added chemicals [31]. This diversity is reflected in the microplastic toxicity literature, as studies have employed a wide range of experimental designs, endpoints, test particles, and species [34, 37].

While the amount and diversity of microplastic toxicity data has provided opportunities to investigate unique questions and new lines of research, it has also presented challenges with regard to data extraction and synthesis, making it difficult to identify high-quality, fit-for-purpose studies, distill information, and draw meaningful, clear scientific conclusions required to inform management actions. However, the field is emerging from its initial exploration phase as researchers and environmental managers call for improved data quality through more robust particle characterization, thoughtful experimental design, and the development of quality assurance and control requirements for microplastic toxicity testing [11, 19, 28, 34]. Even editorial boards of scientific journals have begun to issue statements describing minimum requirements for studies to be considered for publication [21, 32]. In addition, the development of screening criteria for toxicity data has significantly advanced threshold development and preliminary risk assessment exercises for both aquatic organisms and humans by aiding in the identification of relevant data sets of sufficient quality [9, 12].

As microplastics toxicity research adapts to increased scientific rigor and the generation of data for specific applications (e.g., hypothesis testing, hazard identification, mechanistic understanding, and risk assessment), there is a need to coalesce, organize, and query existing and emerging data sets consistently and efficiently. The Toxicity of Microplastics Explorer (ToMEx) is designed to address this need by allowing researchers to find and analyze microplastic toxicity data in a workable format using an intuitive web application. ToMEx was originally created for a scientific expert working group as part of the California Microplastics Health Effects Workshop to facilitate data exploration and the derivation of health-based thresholds for aquatic organisms and drinking water [6, 25, 35]. However, the utility of ToMEx for the research community was quickly recognized, and the first iteration of ToMEx was publicly released in 2021 [34]. Since its release, ToMEx has proven to be a useful tool for characterizing the research landscape [2, 36] and exploring new applications for the synthesis and analysis of microplastic toxicity data [14]. For example, the ToMEx database was recently used to expand upon a Bayesian species sensitivity distribution model previously developed for spherical microplastics to include fibers and fragments, providing critical insight into the role of particle morphology on toxicological outcomes in aquatic organisms [14].

The first iteration of ToMEx is becoming increasingly outdated as the most recent study in the database was published in 2021. In addition, the environmental thresholds derived from the ToMEx 1.0 data [25] came with high uncertainty, and it was expected that uncertainty

would decrease with the addition of new data. The primary goal of this project was to update the ToMEx database with more recent data to create ToMEx 2.0. To do this, members of the global microplastic research community were recruited via professional networks to help extract and evaluate the quality of toxicity data from the primary literature. A reapplication of the California framework for deriving health-based thresholds for aquatic organisms, originally described by Mehinto et al. [25], was performed to determine if thresholds could be improved (e.g., separation between tiers, narrowing of confidence intervals) using the increased volume of data in ToMEx 2.0. Finally, the use of an artificial intelligence (AI) Large Language Model (LLM) was evaluated in a small pilot study for its potential to aid in future data mining exercises to keep ToMEx up to date and thereby ensure its continued utility. Here, we introduce ToMEx 2.0 as a resource to the research community for the continued facilitation of hazard characterization for microplastics.

Methods

Literature search

An original literature search was conducted through Web of Science for papers published between 1 January 2021 to 11 January 2023 using the following search string: (effect OR impact OR endpoint OR toxicity) AND (microplastic(s) OR microbead OR polyethylene (PE) OR polystyrene (PS) OR polyamide (PA) OR polypropylene (PP) OR polyvinyl chloride (PVC)). A total of 5,060 studies were identified. The titles and abstracts of each study were screened to determine eligibility for inclusion into the ToMEx database. Specifically, studies were required to focus on at least one of the following criteria as previously described in Thornton Hampton et al. [35]: 1) the toxicological effects of microplastics, 2) the toxicological effects of microplastic leachates (i.e., chemicals migrating from plastics), and/or 3) the toxicological effects of microplastics in the presence of other chemical contaminants (i.e., chemical co-exposure or chemical transfer studies). Studies focused solely on the effects of plastics greater than 5 mm, field observations, or toxicokinetics were excluded. After screening, 354 and 139 studies were found eligible for the aquatic organisms and human health databases, respectively. A complete list of studies identified for screening and selected for data extraction may be found in the Supplemental Materials.

Virtual workgroup series

A crowd-sourcing approach was used to mine and validate toxicity data from eligible studies. Researchers were recruited via social media and professional networks to participate in a virtual workgroup. Participants were first trained on how to extract and structure data from selected studies (see Supplementary Information for guidance documents and data templates). Data regarding test organisms, experimental parameters, biological effects, test particle characteristics, and experimental verification were extracted in accordance with the previously established data categories found in ToMEx 1.0 [35]. The participants were then instructed to select at least two studies according to their expertise and complete the data mining exercise from the previously screened list (see Supplementary Information for the complete list of studies).

To validate data mining and study quality assessments, participants were randomly partnered with another workgroup participant and instructed to check the accuracy, completeness, and data structure of each template and to come to an agreement with their partner before submitting final data templates to the database. In exchange for submitting completed, validated data templates, workgroup participants were granted early access to ToMEx 2.0 and invited to be coauthors on this manuscript. Over 60 participants from 14 different nations participated in the complete virtual workshop series.

Reapplication of threshold derivation framework

Following the ToMEx database update, the California threshold derivation framework for aquatic organisms [25] was reapplied as previously described to determine if thresholds might improve (i.e., become more precise) with the inclusion of new, possibly higher quality toxicity data. Detailed methods for threshold calculations are described in Mehinto et al. [25], though the approach is summarized here for clarity. Only one minor modification was made for the determination of bioaccessibility (see Supplemental Information for more details). Briefly, toxicity data meeting a pre-determined set of minimum quality criteria were extracted from the ToMEx 2.0 database. Four sets of critical thresholds, ranging from low to high regulatory concern, were calculated using a species sensitivity distribution (SSD) approach. Each set included four threshold values separated by predefined parameters for hazard concentration, data collapsing, and point estimate selection. Thresholds 1 and 2 included molecular to population level endpoints whereas thresholds 3 and 4 included only organismal and population level endpoints. Two sets of thresholds correspond to the effect mechanism of food dilution, for which the data were aligned according to particle volume, restricting bioavailability according to mouth opening size (i.e., particle length). The other two sets of thresholds correspond to the effect mechanism of tissue translocation, for which the data were aligned according to particle surface area, restricting bioavailability to translocatable particle length (i.e.,

83 µm). Thresholds were rescaled to a default distribution of 1 to 5,000 µm. Alignments were performed using methods developed by Koelmans et al. [18]. For this exercise, all aspects of the framework and analytical process remained the same as described by Mehinto et al. [25] except separate SSDs were created for freshwater and marine species and data were aligned according to habitat [20], Table S2). The contribution of data points at the lower concentration range of the SSDs were investigated in more detail to identify highly influential data points driving shifts in the derived thresholds.

Artificial intelligence pilot study

To explore less labor-intensive ways to keep ToMEx up to date, we tested the Generative Pre-trained Transformer (GPT) 3.5 Turbo Application Program Interface from Open AI to pilot automated data mining [26]. To do this, a subset of 10 manuscripts from ToMEx 1.0 were selected so that data mining results generated by GPT 3.5 could be compared to the data previously generated from manual data mining. The model did not allow the upload of an entire manuscript at once, so the text was split into the largest sized chunks possible (i.e., 13,600 characters). The temperature, a parameter which controls the creativity or randomness of text generated, was set to zero for low creativity. The maximum token limit was set to 50 (~200 characters) to ensure brief responses. The frequency and presence penalties were set to zero to ensure verbatim responses were given. Each prompt was formatted as follows:"Excerpt from a peer-reviewed manuscript on microplastic toxicity: \n", manuscript text, data mining prompt. A total of 25 prompts were tested for each manuscript (Table S1). Responses provided by GPT 3.5 were directly compared to the data published in ToMEx. An answer was deemed accurate if the model's output could be quickly interpreted as equivalent to the manually annotated response.

Results & discussion

Database size & diversity

The aquatic organisms database grew 2.2-fold from 5,871 to 12,798 data points, representing toxicity data from almost 300 studies (Table 1). Increases in the overall amount of data also resulted in greater data diversity for some data types, suggesting that some commonly cited gaps in knowledge are starting to be addressed. For example, the number of unique polymer types increased from 13 in ToMEx 1.0 to 21 in ToMEx 2.0 (Fig. 1). Increases in relative data diversity were also observed for particle morphology. The aquatic organisms database also gained additional fragment (n = 1,911 data points) and fiber (n = 368 data points) toxicity data. In addition to the expansion of polymer types, toxicity data for 23 new freshwater species and 32 new marine species were added (Table 1). This is due in part to the addition of sediment-based toxicity data in ToMEx 2.0 (n = 20 species, n = 929 data points), which were not well-represented in ToMEx 1.0 (n = 16 species, n = 464 data points). Increases in species diversity are promising for better understanding the potential consequences of microplastic exposure across a range of taxa and may also help in understanding the relationship between microplastic sensitivity and specific behavioral or physiological traits [1, 24]. Toxicity data for more species may also enhance studies or analyses aimed at predicting community-level outcomes following microplastic exposure, as these exercises must rely on hazard data from a wide range of taxa.

Table 1 Summary comparison of the first iteration of the Toxicity of Microplastics Explorer Database (ToMEx 1.0) and the updated database (ToMEx 2.0) for aquatic organisms

Aquatic Organisms Database		
	ToMEx 1.0	**ToMEx 2.0**
Total Number of Studies	162	286
Particle only	155	274
Chemical co-exposure	12	34
Chemical transfer	8	19
Leachate	10	13
Total Number of Data Points	5,871	12,798
Acute data	3,462	7,698
Chronic data	2,409	5,100
In vivo data	5,829	12,462
In vitro data	42	336
≥ 3 test concentrations	3,086	5,744
Total Number of Species Represented	109	164
Freshwater species	40	63
Marine species	69	101

In comparison to the aquatic organisms database, the human health database grew significantly despite adding only 23 studies. The studies added were data-rich, expanding the database from 3,904 to 7,499 data points (1.9-fold change) (Table 2). More than 60% of the data in this database were extracted from in vitro studies. This wealth of in vitro toxicity data is helpful for scientists investigating the toxicological mechanisms of microplastics, but it has limited applicability for managers as methods to use in vitro toxicity data to predict effects in vivo are unclear for microplastics. However, this also highlights an opportunity for researchers to explore the application of new approach methodologies to microplastics [22]. The human health database did not gain significant number of new polymer types, but there were increases in toxicity data for polymers other than polystyrene (e.g., polyethylene, polypropylene, and

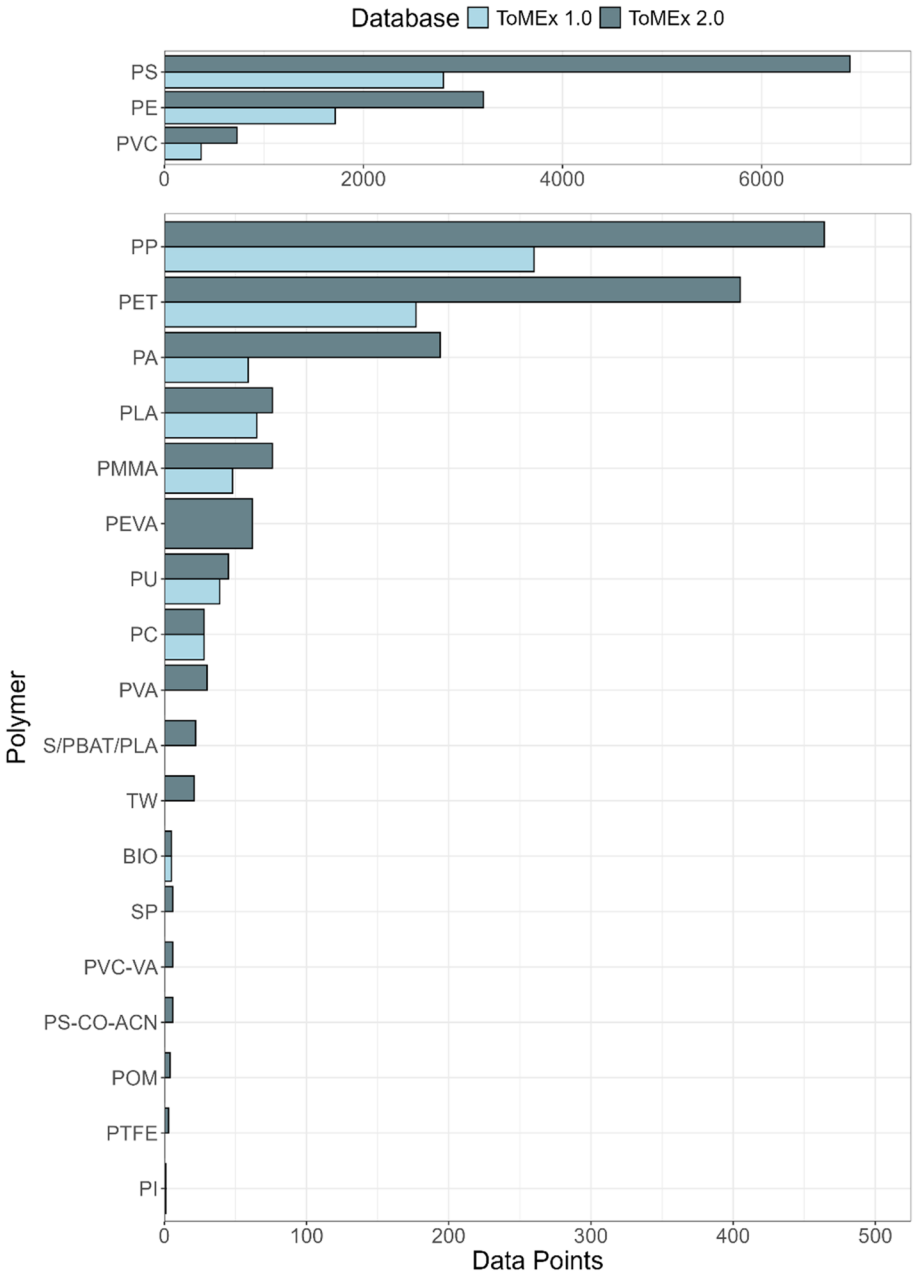

Fig. 1 Polymer types of particles represented in the ToMEx 1.0 and ToMEx 2.0 aquatic organisms database. Abbreviations: PS, Polystyrene; PE, Polyethylene; PVC, Polyvinylchloride; PP, Polypropylene; PET, Polyethylene Terephthalate; MIX, mixture of polymer types; HDPE, High Density Polyethylene; PA, Polyamide; LDPE, Low Density Polyethylene; PLA, Polylactic Acid; PEVA, Polyethylene Vinyl Acetate; PMMA, Polymethylmethacrylate; PU, Polyurethane; PVA, Polyvinyl Acetate; PC, Polycarbonate; S/PBAT/PLA, Starch/Polybutylene Adipate Terephthalate/Polylactic Acid; TW, Tire Wear; SP, Sodium Polyacrylate; PVC-VA, Polyvinylchloride/vinylacetate co-polymer; PS-CO-ACN, Poly(Styrene-co-acrylonitrile); MDPE, Medium Density Polyethylene; BIO, Biopolymer; POM, Polyoxymethylene; PTFE, Polytetrafluoroethylene; PI, Polyisoprene

polyvinylchloride) (Figure S1). For particle morphology, ToMEx 1.0 was dominated by studies using spherical particles. Here, the human health database gained additional fragment toxicity data ($n = 754$ data points), though fiber toxicity data remained absent (Figure S1).

The field has long been criticized for its continued use of particle types rarely found in real-world environmental samples [7, 34]. Some of the new polymer types added to the database are obscure (e.g., polyoxymethylene, polyvinylchloride/vinyl acetate co-polymer), but others, such

Table 2 Summary comparison of the first iteration of the Toxicity of Microplastics Explorer Database (ToMEx 1.0) and the updated database (ToMEx 2.0) for human health

Human Health Database		
	ToMEx 1.0	**ToMEx 2.0**
Total Number of Publications	55	78
Particle only	54	71
Chemical co-exposure	7	7
Chemical transfer	0	0
Leachate	0	0
Total Number of Data Points	3,904	7,499
In vivo data	2,512	4,579
In vitro data	1,392	2,920
≥ 3 Test Concentrations	2,052	4,189
Total Number of Species Represented	6	7

as tire wear particles, represent critical additions to the database given their common occurrence in environmental samples and known toxicity [23]. More toxicity data for a diverse range of polymers and morphologies will help researchers better understand the relative toxicity of different particles as well as the importance of material type and morphology compared to other particle characteristics such as particle size in causing toxicity.

Despite the addition of new polymers and particle morphologies to both databases and new species to the aquatic organisms database, dominant study types remained largely unchanged from ToMEx 1.0 for both databases. Though some chemical co-exposure, chemical transfer, and leachate studies were added to the aquatic organisms database, particle-only effect type studies still dominate both databases (Tables 1 and 2), and despite the influx of new polymer types, both databases continue to be dominated by toxicity data for polystyrene spheres ranging in size from 1-100 µm (Figures S1 and S2). A lack of change was also observed with regard to the types of biological endpoints studied as fitness (e.g., mortality, reproduction, growth, etc.) and metabolism-related endpoints continued to dominate the aquatic organisms and human health databases, respectively (Figures S3 and S4). Though a modest change may be expected given that ToMEx 1.0 was created less than three years ago [35], the data indicates a relatively homogenous research landscape when it comes to study design, selected test particles, and the types of biological endpoints evaluated. In the near term, these data add value to the ToMEx database, and consistency amongst experimental designs allows studies to be more easily compared. However, researchers should carefully consider the novelty and potential data applications of future studies to avoid needless repetition and ensure that the field continues to progress towards a deeper understanding of microplastic impacts.

Data quality

The aquatic organisms and human health databases were compared against minimum acceptability criteria as determined previously [9, 12, 25]. Studies passed most of the minimum reporting requirements (Figs. 2 and S5). However, roughly a quarter of the human health studies and half of the aquatic organisms studies in ToMEx 2.0 used an insufficient number of test concentrations (i.e., < 3) to describe dose–response relationships. While studies with few test concentrations may be appropriate to answer specific questions regarding types of exposures (e.g., testing different particle types at similar concentrations or determination of effect mechanisms), they are limited in their ability to describe dose–response relationships, the lack of which has been highlighted as a critical data need for risk assessment [34]. The inability for most studies to meet minimum quality criteria is most clearly reflected in the aquatic organisms database, as the proportion of studies passing minimum acceptability criteria in ToMEx 1.0 (i.e., 13% of the total number of studies) was almost identical to the number of passing studies in ToMEx 2.0 (i.e., 12% of the total number of studies). This result reemphasizes previous calls to generate dose–response data for microplastics to improve risk thresholds and decrease the large amount of uncertainty currently reflected in derived values.

Reapplication of threshold derivation framework

Here, an additional 12 studies from the ToMEx 2.0 database update passed previously minimum selection criteria and were used to recalculate thresholds [25]. With the addition of these new data, separate sets of thresholds could be calculated for marine and freshwater organisms, which had previously been combined due to a lack of data. Changes in threshold values were greater when cellular and molecular level data were included (i.e., thresholds 1 and 2) in comparison to threshold values calculated from only organism and population-level data (i.e., thresholds 3 and 4). Marine threshold 1 and 2 values for food dilution and tissue translocation were lower than those reported previously (−5000 to −29-fold change), and confidence intervals for food dilution (−123 to −100-fold change) and translocation narrowed (−16-fold change) (Tables 3 and S3). In comparison, marine threshold 3 and 4 values for food dilution and tissue translocation were only slightly decreased to those previously calculated (−20 to −1), and confidence intervals remained the same or narrowed (−43 to -onefold change).

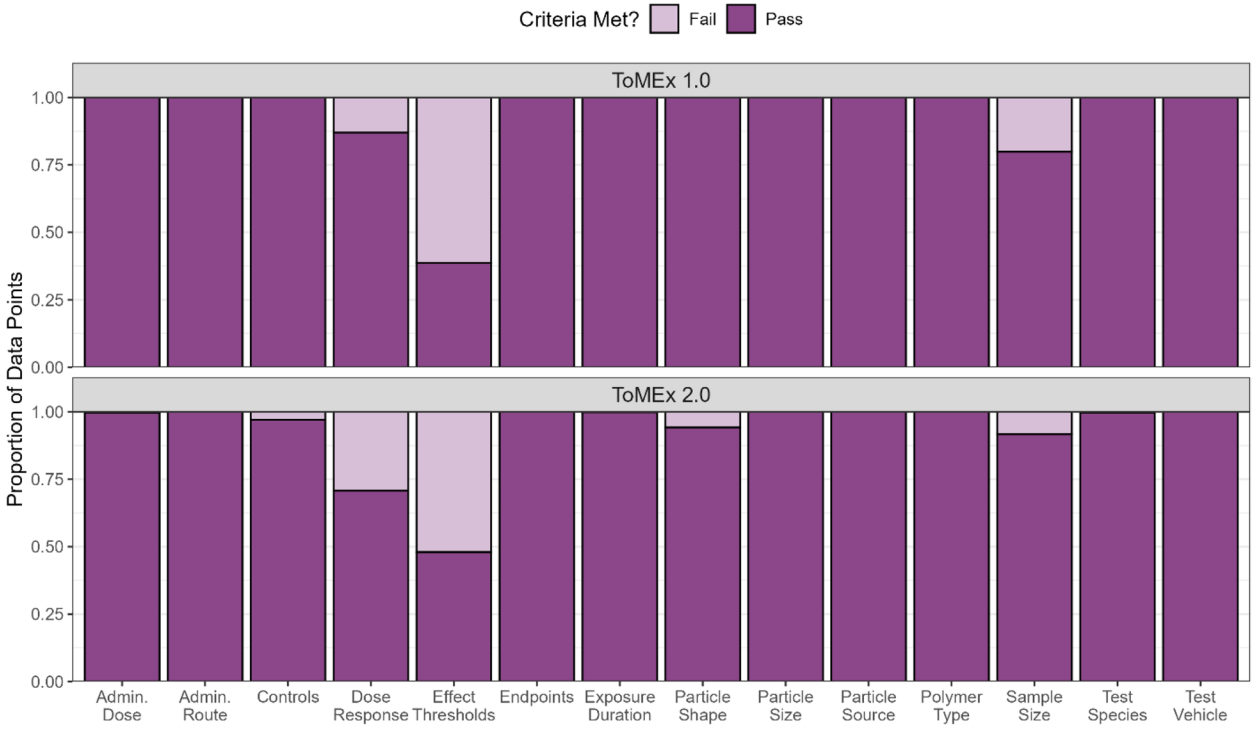

Fig. 2 Number of data points passing minimum reporting criteria in the human health database

Table 3 Microplastics toxicity thresholds for marine aquatic organisms for food dilution, relevant for particle sizes between 1 and 5000 µm using data from ToMEx 2.0 in comparison to thresholds generated using the previous iteration of the database

Threshold	particles/L (95% CI)		mg/L (95% CI)	
	ToMEx 1.0	ToMEx 2.0	ToMEx 1.0	ToMEx 2.0
#1 Investigative Monitoring	0.2 [a]	5×10^{-5} [a]	0.04 [a]	8×10^{-6} [a]
#2 Discharge Monitoring	2 (0.2–123)	3×10^{-3} (5×10^{-5}–1)	0.4 (0.04–20)	4×10^{-4} (8×10^{-6}–0.2)
#3 Management Planning	3 (0.3–261)	0.3 (0.03–7)	0.6 (0.05–43)	0.05 (5×10^{-3}–1)
#4 Source Control	23 (2–1,150)	1 (0.2–44)	4 (0.3–188)	0.2 (0.04–7)

[a] Threshold 1 is the lower 95% confidence interval of the hazardous concentration for five percent of the species (HC5) calculated for Threshold 2, therefore confidence intervals cannot be reported for this threshold

Freshwater threshold 1 and 2 values were similar for both food dilution (−4 to threefold change) and tissue translocation (−5 to twofold change) and confidence intervals narrowed and widened depending on the threshold (−4 to fourfold change) (Tables 4 and S4). Threshold values 3 and 4 for both effect mechanisms were increased (4 to 14-fold change) and confidence intervals widened (0 to ninefold change) when expressed as particle counts. When expressed in mass, there was minimal change in threshold values (−1 to twofold change) and confidence intervals (1.3 to twofold change).

The underlying data, particularly those at the lowest points on the SSDs, were investigated to identify potential drivers for the changes observed. Both sets of marine thresholds were found to be driven by toxicity data for the Mediterranean mussel (*Mytilus galloprovincialis*) and white sea urchin (*Pseudechinus huttoni*) from studies published by Capolupo et al. [5] and Richardson et al. [30], respectively. Both studies observed statistically significant changes in biological markers of general and oxidative stress (e.g., superoxide dismutase activity, catalase activity, etc.) following microplastic exposure. Endpoints at higher levels of biological organization were also evaluated (e.g., developmental markers, mortality, etc.), but no alterations were observed above the cellular level. If the results of these two studies are evaluated in isolation, this suggests that organisms may experience mild to moderate impacts at the cellular level and below,

Table 4 Microplastics toxicity thresholds for freshwater aquatic organisms for food dilution, relevant for particle sizes between 1 and 5000 µm using data from ToMEx 2.0 in comparison to thresholds generated using the previous iteration of the database

Threshold	particles/L (95% CI)		mg/L (95% CI)	
	ToMEx 1.0	ToMEx 2.0	ToMEx 1.0	ToMEx 2.0
#1 Investigative Monitoring	0.2[a]	0.4 [a]	0.04 [a]	0.01[a]
#2 Discharge Monitoring	2 (0.2–123)	5 (0.4–147)	0.4 (0.04- 20)	0.2 (0.01–5)
#3 Management Planning	3 (0.3–261)	42 (28–2,420)	0.6 (0.05- 43)	1 (1–85)
#4 Source Control	23 (2- 1,150)	144 (63–6,990)	4 (0.3- 188)	5 (2–244)

[a] Threshold 1 is the lower 95% confidence interval of the hazardous concentration for five percent of the species (HC5) calculated for Threshold 2, therefore confidence intervals cannot be reported for this threshold

but overall fitness may not be impacted, as effects do not manifest above the cellular level. This is not to say that these studies are not useful or of poor quality but rather carefully consider the appropriateness of these data for threshold development (e.g., exposure duration, number of test concentrations). Screening tools such as the minimum acceptability criteria employed here and in previous exercises provide a useful mechanism for identifying data possibly fit for the purpose of threshold derivation, but the dramatic impact of these two studies on the final threshold values reemphasizes the critical need for expert evaluation of the underlying data (see Supplementary Information for raw data, summary tables, and species sensitivity distribution figures pertaining to threshold analyses).

Artificial intelligence

On average, GPT 3.5 appeared to perform with ~ 50% accuracy across the prompts, with some prompts having zero accurate responses (e.g., estimated body length of the organism) and other prompts having 100% accuracy (e.g., detergent used in the exposure) (Fig. 3). Response accuracy to the prompts was strongly predicted by the complexity of the question and whether or not the answer was reported explicitly in manuscripts. For example, high performance was observed for prompts to identify the name of the test species (75%) and whether the study had a negative control (100%). For each of these, it is likely that the exact word listed in the prompt could be found in the manuscript. Alternatively, animal body length (0% accuracy) is not often explicitly reported in manuscripts and would thus usually need to be extracted from another source. Therefore, it makes sense that GPT would struggle more to answer questions that require specific knowledge that may not be part of the AI's corpus. Another issue observed was that sample sizes, replicates, and sample frequency were often convoluted concepts by GPT, leading to confusion and lower accuracies in those questions.

Overall, GPT showed promise for data mining exercises, but there are major challenges that must be resolved before implementation. For instance, when GPT provides an answer to a prompt, it also provides a narrative describing its reasoning for the answer. While this may be helpful in troubleshooting, it becomes an issue for automating data extraction on a large scale. The results of this pilot may be used to design future studies in which prompts are revised to improve accuracy and provide answers in the desired format (e.g., completed data template). Since the pilot study was conducted in 2023, newer GPT models have been released (GPT 4.0 is available at the time of writing) and some of the data extraction issues described herein may already be addressed (i.e., prompt size limits, response lengths) [27]. In fact, a recent study leveraged ChatGPT and Gemini to perform QA/QC screening tasks for studies focused on human exposure to microplastics in drinking water with accuracy rates greater than 90% in many instances [29]. AI is already transforming toxicology as a field to predict toxicities, analyze data, elucidate effect mechanisms, and perform quantitative risk assessments including uncertainty outputs [17]. For example, ToMEx may provide a foundational training data set for AI tools already used to elucidate adverse outcome pathways [15, 16], and the application of predictive toxicity models may help reduce the need for animal testing while supporting applications such as probabilistic risk assessment [13]. As such, future iterations of ToMEx will aim to integrate and apply emerging AI technologies well beyond data mining applications.

Conclusions

The ToMEx database was successfully updated by leveraging the collective power of the global microplastics research community to mine data from studies published after the release of ToMEx 1.0, effectively doubling the size of both the aquatic organisms and human health databases. ToMEx 2.0 can be freely accessed from https://microplastics.sccwrp.org. Despite some evidence that the ToMEx

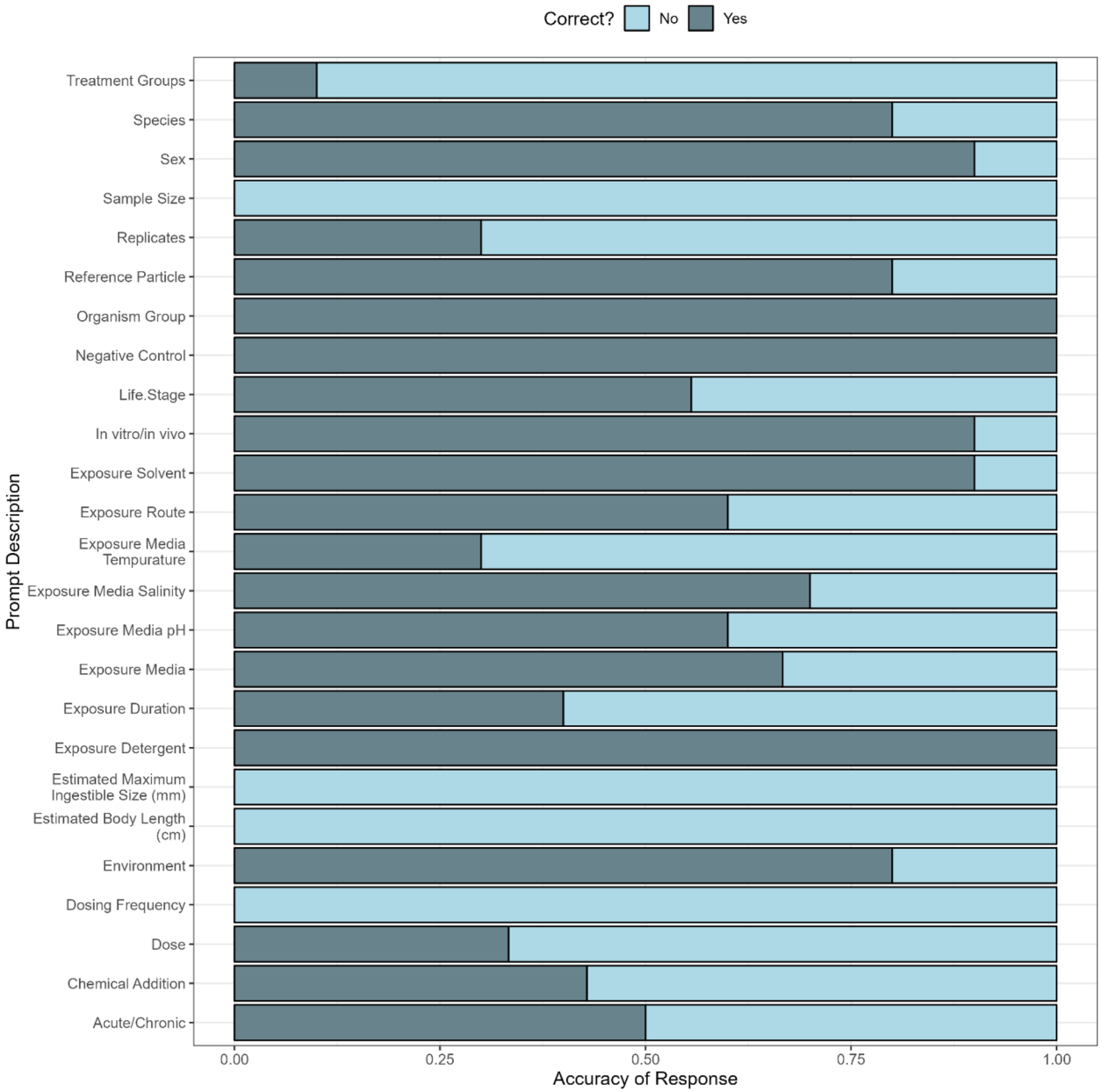

Fig. 3 Accuracy of responses provided by Generative Pre-trained Transformer (GPT) 3.5 turbo application program interface from Open AI ($n = 10$ studies)

2.0 dataset may be slightly more diverse (i.e., new polymer types and species in the aquatic organisms database and additional data for historically understudied polymer types and morphologies in the human health database), the vast majority of new data displayed trends similar to those observed for ToMEx 1.0. Though only a relatively short time has passed since ToMEx was first released, these findings highlight the fact that microplastic toxicity research is still evolving and that there is much foundational work to be done before critical research gaps can be addressed, particularly for the development of health-based thresholds. Although new data replicating previous findings is helpful, a wider variety of data is needed to accurately answer pressing questions about microplastic toxicity and risk. Of course, there is also a need for a continuing effort to add these data to the ToMEx database. Though AI was only explored for data mining as a small pilot study here, future iterations of ToMEx will seek to explore additional uses previously used to characterize hazards for other environmental contaminants.

Abbreviations

AI	Artificial Intelligence
GPT	Generative Pre-trained Transformer
ToMEx	Toxicity of Microplastics Explorer

Supplementary Information

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Supplementary Material 1.
Supplementary Material 2.
Supplementary Material 3.
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Supplementary Material 16.

Authors' contributions

Conceptualization, Supervision, Writing: LMTH, ACM. Data Curation: LMTH, DB, BCA, SC, WC, DD, EKH, SJH, MMM, ELM, LM, EES, SS, ALAV, MV. Analysis and Visualization: LMTH, ELM. Reviewing and Editing: DB, BCA, SC, WC, DD, EKH, SJH, MMM, ELM, LM, EES, SS, KTA, ALAV, QPVA, DA, JLB, AB, KB, LB, VB, AB, JB, VC, TC, GC, PC, PMCD, LSL, SMG, LH, AH, YI, NK,CMK, AKK, PK, IBK, AK, CL,SBK, FDLL, LWL, HL, JM, UMS, SM, JPN, ZP, TP, DAP, EV, AFRMR, GR, SR, MHS, JS, MScho, MSchw, KJS, TMS, RS, MS, ANT, CMW, MV, AY, RZ. Note: All authors were required to extract and validate data from at least two peer reviewed studies to be included as a coauthor on this manuscript.

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Data availability

The web applications may be accessed at https://microplastics.sccwrp.org. The database is open access and may be downloaded via web applications. Source code for the Aquatic Organisms and Human Health apps may be found at (https://github.com/SCCWRP/ToMEx_AquaticOrganisms) and (https://github.com/SCCWRP/ToMEx_HumanHealth) respectively.

Declarations

Competing interests

The authors LMTH, DBW, BCA, SC, WC, DD, EKH, MMM, ELM, LM, EES, SS, KTA, QPVA, ALAV, DA, JLB, AB, KB, LB, VB, AB, JB, VC, TC, GC, PC, PMCDS, LDSL, SMG, LH, AH, YI, NK, CMK, AKK, PK, IBK, AK, CL, SBK, FDLL, LWL, HL, JM, UMS, SM, ZP, TP, DAP, EK, AFRMR, GR, SR, MHS, JS, MScho, MSchw, KS, TMS, RS, MS, ANT, MV, CMW, AY, RZF, and ACM declare having no known competing financial interests or professional relationships that could have appeared to influence the work reported in this paper. The following authors declare financial interests/professional relationships which may be considered as potential competing interests:

- SJH currently works for an environmental consulting firm that provides technical support related to microplastics to private and public stakeholders. The present work was funded internally as R&D and conducted independently. The opinions herein do not necessarily reflect those of any affiliated organizations.
- JPN currently works for a trade association that provides technical support related to microplastics to private stakeholders. The present work was conducted independently and on personal time. The opinions herein do not necessarily reflect those of any affiliated organizations.

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