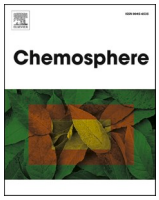
Chemosphere 373 (2025) 144117

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere



Micro-and nanoplastics in soil: New insights, knowledge gaps and challenges

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HIGHLIGHTS

- Interdisciplinary, international conference on (micro-nano)plastics in soil.
- Outcomes from three workshops with around 150 participants.
- Vision on insights, knowledge gaps and challenges.

GRAPHICAL ABSTRACT

ARTICLE INFO

Handling editor: Derek Muir

This article is part of a special issue entitled: Plastics in Soil published in Chemosphere.

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[1] Dick Vethaak sadly passed away in 2024.

https://doi.org/10.1016/j.chemosphere.2025.144117
Received 28 October 2024; Received in revised form 7 January 2025; Accepted 12 January 2025
Available online 25 January 2025

1. Introduction

A major current environmental challenge in soil and water management is plastic pollution. Plastic may enter the environment as waste (e.g. litter) and via intentional use of plastic products (e.g. geo- or agricultural films). In the environment plastics may degrade to form (secondary) micro- and nanoplastics (MNPs) resulting in exposure to these MNPs by organisms. As awareness grows about the need to prevent MNP pollution, recent studies have shown that environmental risks of MNPs can no longer be excluded, especially in soils (Redondo-Hasselerharm et al., 2024; Koelmans et al., 2023; Tunali et al., 2023). While knowledge about the full extent of the MNP pollution problem in soil is still developing, it is clear that MNPs are now widespread in soil and can enter the soil via various routes and sources (Quik et al., 2024). However, it remains a significant challenge to analyse MNPs reliably and cost-effectively in the soil environment as an heterogenous matrix by definition, and which in turn hinders efforts to assess the true scale of the problem. Together, these challenges complicate finding solutions to MNP pollution. A crucial step in finding effective solutions is bringing together scientific experts from different disciplines along with decision makers in the sector and policymakers, to facilitate knowledge exchange, engage in in-depth discussions, and identify future research and policy directions for effective solutions.

With this notion in mind, three interactive sessions were organised during the 'International Conference (2024): (Micro-nano)plastics in Soil' held in Utrecht, the Netherlands, on the 13–14th of March 2024. The conference brought together scientists from different disciplines, policymakers, and environmental consultants. This short perspective reports on the main insights gained from three interactive workshop sessions, the interdisciplinary discussions of this conference and special issue sparked in the wider community beyond the attendees of the sessions. The outcomes of these three sessions are synthesised and underpinned with leading references which we believe may help the 'plastics' community, from scientists to policymakers, to work together towards reducing the environmental impacts of plastics. The interactive workshop sessions addressed three topics: 1) Analytical challenges of micro- (MP; 1 μm–5000 μm) and nanoplastics (NP; <1 μm), 2) 'One-Health' approaches to problem identification, and 3) Risk assessment to inform policy. The following sections provide insights into these interactive sessions.

2. (Micro-nano)plastics in soil: the main analytical challenges in sampling, extraction, and analysis & characterisation

The analysis of micro-and nanoplastics in soils is still experiencing severe challenges with regards to the suitability and inter-comparability of field and laboratory analytical methods. Challenging is the extraction of MNPs from different types of soil but also the further characterization of MNPs in soil extracts is difficult as long as plastics are complex composed materials which are also differently aged and weathered under various environmental circumstances. These range from the availability of sufficiently accurate characterisation methods, to a lack of standardisation and often insufficient quality controls of existing protocols for microplastic sampling from soils to the diverse methods deployed for microplastic particle extraction from soil matrices, which together severely limit the inter-comparability of quantitative and qualitative characterisations of microplastics in environmental samples.

The representativity of field samples of soils is for instance limited by the relatively small amount of sample (mass or volume) that is obtained and used for further extraction. Commonly used amounts of soils are usually less than 100 g of dry weight sample. The main reason for the relatively small sample masses or volumes being used is the need to remove the widely abundant organic matter from the sample through a range of complex digestion steps. The duration of this preparatory step scales with the mass of soil material required for digestion. Such limitations of course bear the risk of sample bias and low representativity of the actual field conditions. Approaches such as sub-sampling across larger areas and sample aggregation, as well as aligning sampling strategies along a transect using prior background information may provide viable approaches to ensuring representativity of obtained results (Cowger et al., 2024). Even the recording of basic meta-information, i.e., how much sample has been extracted and by what means (grab sampling, coring, etc.), and reporting of accurate sampling depths and locations would improve the potential for intercomparisons and meta-analyses (Redondo-Hasselerharm et al., 2024). The crucial steps are summarized in Fig. 1.

Besides the analytical challenges involved with reliable soil sampling, the diversity and order of different steps required to extract plastic particles from soils creates additional potential for methodological biases. These are caused by the choice of chemical agents used for density separation (mainly salts like e.g. $ZnCl_2$, NaCl, NaI) to the different designs of separation units, the number and type of filtration steps and filter sizes used as well as the exact types of digestion methods and agents. Comparisons of frequently used digestion agents and methods as well as different parent microplastic material types have revealed significant differences not only in the final microplastic recovery rates but also with regard to induced particle degradation. The non-standardisation of analytical methods and the lack of common reporting guidelines for sample treatment do not only limit the ability to compare MNP particle numbers across different studies but likely also affect reported lower limits of analyzed particle sizes. While MNPs in soil are at times reported for particle sizes down to very few micrometres (Moeck et al., 2023), the degree of particle degradation and possible fragmentation induced by the sample treatment is usually unknown.

The sum of required tasks of sample preparation before actual laboratory analyses causes a substantial challenge to the numbers of samples that can realistically be analyzed in soil studies. Together with the time required by the chosen analytical method for particle detection and polymer identification this severely limits achievable sample throughputs. The throughput is even further reduced if in addition to polymer information, particle surface properties or the content of chemical additives and co-pollutants are analyzed. Given these challenges that limit sample numbers of individual studies, it seems even more important to develop protocols and analytical approaches or mathematical techniques for aligning outcomes of different studies that allow the reliable intercomparison across different studies (Koelmans et al., 2020). Due to the complex nature of analyzed soils as well as the diversity of microplastic sources in soils that of course affect material properties, it seems unlikely that a single standardized sampling, extraction and analysis protocol will be able to give justice to the complexity of the analytical challenge. Rather, agreed minimum reporting standards and reliable intercomparisons studies are required that support the comparability and transfer of information between studies.

3. A "One Health" approach to the problem of micro- and nanoplastics in terrestrial food chains

The ubiquitous presence of MNPs in our environment enlarges the chances for uptake by animals and humans (Krause et al., 2024). Once in the environment, MNPs can be taken up by plants, animals and humans via the air, soil, water and food; as illustrated in the One Health approach (Fig. 2).

MNPs, in particular nanoplastics (NPs <1 μm), can pass important barriers in the body (Vethaak and Legler, 2021). For example, a recent study in mice demonstrated that when administered an MNP mixture consisting of particles of 9.5 μm, 1.1 μm and 0.3 μm (0.3 mg/size/dose), the NPs of 0.3 μm passed the blood-brain barrier within 2 h after gavage (Kopatz et al., 2023). Plastic polymers have also been detected in human blood at an average level of 1.6 μg/mL after pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) in a pilot study with 22 healthy volunteers (Leslie et al., 2022). Recently, the study was repeated with 68 blood samples, after optimization of the Py-GC-MS conditions, which

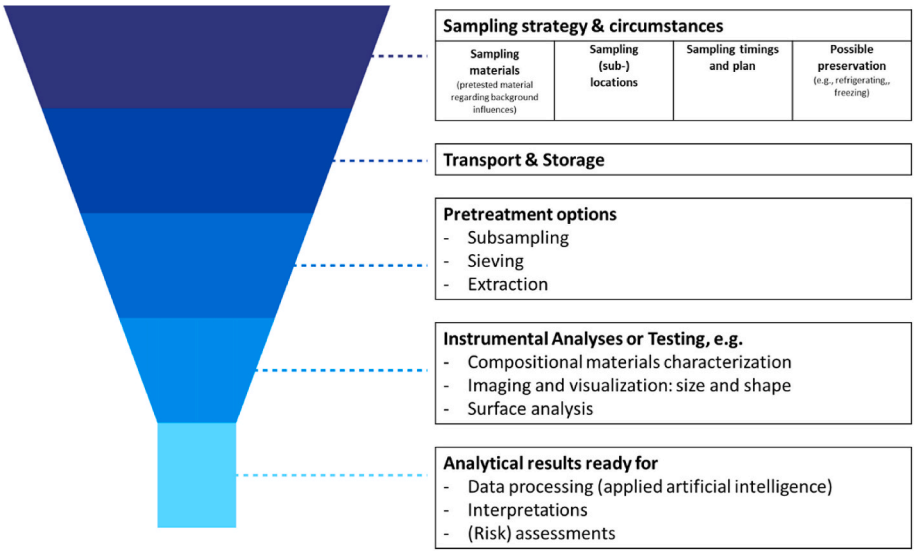

Fig. 1. (Micro-nano)plastics in soil: the main analytical processes.

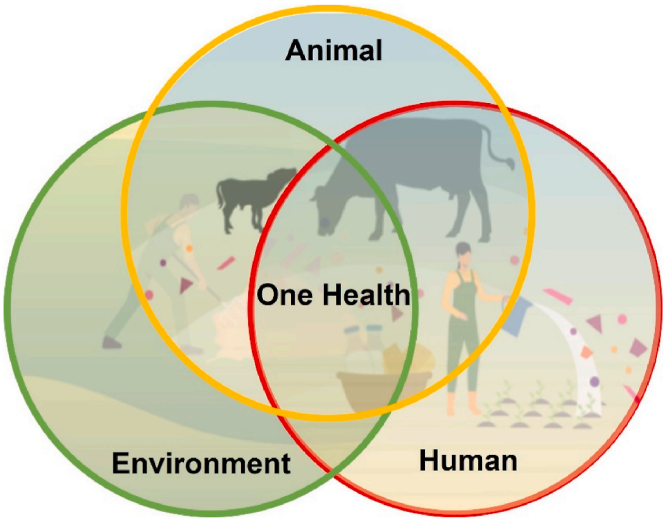

Fig. 2. Studying MNP exposure and effects requires a One Heath approach. MNPs originating from plastic usage by humans accumulate in the environment and may be transferred via the terrestrial food chain to animals, as well as to humans via animal-derived consumption products.

demonstrated an average level of polymers of 268 ng/mL, with polyethylene as the dominating polymer, followed by polyvinylchloride, polyethylene terephthalate and polymethyl methacrylate (Brits et al., 2024). The presence of plastic polymers in blood suggests that plastics are also circulating in our body and are able to reach and enter our organs.

Studies are ongoing to determine the main exposure routes of MNPs on humans, and have shown than plastics can be transferred to humans via the terrestrial food chain. This indicates that the role of farm animals as a potential link between the environment and human health via animal-derived food products should not be overlooked (Aardema et al., 2024). One of the first indications for plastic transfer in the food chain came from a study in Mexico that measured the amount of plastic in soil, earthworm casts, chicken faeces and chicken gizzards (Huerta Lwanga et al., 2017). The detection of microplastics (<5 mm) and macroplastics (5–150 mm) in this study demonstrated that humans can be exposed via consumption of animal derived products like chicken gizzards. In lettuce hydroponically exposed for 3 weeks, europium labelled polystyrene nanoplastics (PS-NPs) of 100 nm were measurable in the roots at all concentrations tested (15, 150 and 1500 μg/L) but in the shoots only at the highest exposure level. This demonstrates that plants dose-dependently take up NPs from their environment (Zantis et al., 2024). In the same study snails fed for 19 days with the formerly NP exposed lettuce excreted NPs via faeces, indicating the uptake of NPs from the plant into the snails. This is another indication that MNPs can indeed travel from the environment via soil and plants towards the animals and may eventually reach humans via animal-derived products.

Once MNPs are orally taken up by animals it has been demonstrated that they are able to accumulate in several organs and also reach the genital organs of rodents (da Silva Brito et al., 2022). Via the genital organs, plastics may affect the next generation, which stresses the importance of developing test models that are able to demonstrate the potential impact of early life MNP exposures on oocytes and embryos. With the innovative bovine *in vitro* fertilization (IVF) model, based on slaughterhouse ovaries, it is possible to test the impact of NPs during periconception in a model that resembles humans, due to the large reproductive similarities between bovine and human (Menezo and Herubel, 2002). With the bovine IVF model, it was demonstrated that oocytes take up small NPs of 50 nm to which they were exposed during maturation (Yang et al., 2023). After intravenous injection of stage 18–19 d chicken embryos with high doses, EU labelled NPs of 150 nm were shown to specifically accumulate in heart, liver and kidneys (Wang et al., 2024). The above studies demonstrate the need to investigate how plastics may be distributed via the food chain, and to assess the exposure levels to which animals and humans are exposed from early life onwards to better understand how MNPs may impact us and future generations.

4. Elicitation of experts and stakeholders to facilitate the implementation of risk assessment in policymaking

MNPs are ubiquitous in the environment including soils (Briassoulis, 2023; Rutgers et al., 2022; Zhou et al., 2021) and exposure of environmental organisms is expected to continue to increase given future scenarios for plastics consumption (OECD, 2022). MNPs are found to adversely affect aquatic (de Ruijter et al., 2020) and terrestrial organisms (Huo et al., 2022) and may impact on overall ecosystem health (Zhang et al., 2020; de Souza Machado et al., 2019). Yet the extent to which microplastics pose risks remains uncertain (Koelmans et al., 2023; Redondo-Hasselerharm et al., 2024). In part this uncertainty relates to the ability of existing risks assessment approaches to deal with the complex nature of MNP pollution (e.g. complex mixture of particles with

different sizes and properties and different types of effects, i.e. particle, chemical and/or microbiological effects). Much environmental policy depends on risk assessments to inform regulatory actions such as restricting emissions, specific land use and/or require soil remediation. Thus, a regulatory risk assessment approach for MNPs will increase the ability of policy makers to make science-based policies for tackling MNP pollution.

One of the key requirements for such a risk assessment method is support within the scientific community, so that policymakers can rely on it with confidence. A tool that is sometimes used for this purpose is expert elicitation. For instance, in support of a policy recommendation to the European Commission, a formalized expert elicitation was conducted regarding the harmfulness and risks of MNPs to the environment and human health (see the SAPEA report *Plastics in Nature and Society*, SAPEA, 2019). At that time, it was not yet possible to assess the risks quantitatively, so expert judgment was relied upon. Quantitative assessments only became possible in 2020 (Koelmans et al., 2020), and the first implementation in a regulatory context took place in 2022 (Mehinto et al., 2022). Mehinto and co-workers also conducted an expert elicitation, where both confidence in the assessment method and the management thresholds derived from the method were quantitatively scored (Mehinto et al., 2022)

In brief, Koelmans et al. (2020) describes a method to align metrics from exposure and effect studies on microplastics in order to conduct an environmental risk assessment. This includes.

- Correcting for differences in size ranges based on limitations of the measurement technique used in exposure studies.
- Solving the incomparability of effect and exposure data caused by differences in physical characteristics of the MNP types used in effect tests and those measured in exposure studies.
- Correcting for bioavailability of microplastic based on size limits for ingestion of specific organisms.
- Filling in the gaps where data is lacking size ranges are estimated using a power law model.

Applying this approach solves key challenges for conducting environmental risk assessment of MNP based on assumptions on the ecologically relevant metric to be applied.

However, the question remains if the approach by Koelmans et al. (2020) is fit for informing soil quality limits and when one would need to use risk limits for policies on plastics in soils. To this end, during the 'International Conference (2024): (Micro-nano)plastics in Soil' workshop perspectives of the use and limitations of the approach by Koelmans et al. (2020) (as applied by Redondo-Hasselerharm et al., 2024, to the soil system) were discussed. Further, input from participants was collected on potential risk management measurements to further identify how the outcomes of a risk assessment are to be used by policy makers. Input for the expert elicitation was collected using Mentimeter^{tm} (www.mentimeter.com). To facilitate the discussion, first a presentation and Q&A session was held to explain the basics of the approach of Koelmans et al. (2020). The session focused specially on MPs, because Redondo-Hasselerharm et al. (2024) limited their study to MPs.

Depending on the question, between 26 and 29 experts and stakeholders participated in the sessions' survey. A list of all questions and responses is provided in Table S1 and Table S2 of **Supplementary information**. The participants were a mix of people working in government (9 of the 28 people who shared this information), science (9), consultancy (5), industry (4) and 'other' (1). Most respondents had some understanding of the essence of the Koelmans et al. (2020) approach for risk assessment of microplastics ('Yes': 12; 'Maybe': 14, 'No': 3) which we deemed sufficient to consider the answers of the follow up questions related to the usefulness and further implementation of this approach.

When asked about the participants main reservations or doubts about the Koelmans et al. (2020) approach, two main reservations or doubts became clear (Table S1). First was about whether the approach itself is complete enough for a risk assessment of MPs. Specific reservations included that the approach does not cover aspects like chemical additives or MP type. It should be noted the Koelmans et al. (2020) was specifically developed to include physical effects of microplastics and therefore never intended to include all potential aspects of MPs pollution. To address the effects of exposure to MP on plastic-associated chemical exposure, several tools and frameworks have already been made available (Koelmans et al., 2016, 2022; Wang et al., 2019). Nonetheless, the participants' responses indicate the demand for additional risk assessment that also considers aspects like polymer type and additives. A second doubt was about the practical applicability of the approach to inform policy. Most participants were rather positive as to whether the approach is fit for policy ('Yes': 6; 'Maybe': 14; 'No': 2). However, according to the participants priorities for further work should lie with developing a validated measurement method and clear test guidelines and guidance for ecotoxicity testing. Further, a clear majority ('Yes': 20, 'Maybe': 0; 'No': 7) stated that further risk assessment is needed for taking further action on mitigating MP pollution. According to the participants, this would be to increase acceptance of policy measures and inform decisions on soil remediation.

In the last part of the questionnaire the participants were asked what policy measures are needed when a risk assessment would show that MP environmental concentrations are 1) below the risk limit, 2) close to the tipping point of risk (within the margin of error), or 3) exceeding risk limits. A large portion of the respondents chose 'taking measures to limit emissions independent of the outcome of a risk assessment' (Fig. 3). According to the participants, only when environmental concentrations are close to or exceed risk limits an additional focus should go towards reducing exposure. Other options such as monitoring or identifying temporal trends where only considered when environmental concentrations are close to or below the risk limit.

Overall, the workshop showed that the participants were rather positive towards the approach described by Koelmans et al. (2020), and as applied by Redondo-Hasselerharm et al. (2024) to soil although there are also some doubts about the practical applicability for policy and whether the approach alone meet the full demand to inform policy. Nonetheless, the workshop highlighted the demand for a risk assessment to inform policy decisions on MNPs. However, it should be noted that the participants were a mix of people from different sectors (i.e. government, industry, science, and consultancy) and that their responses were grouped as one whereas the knowledge and perspectives on what is needed for policy likely differs between these groups. Further, about half of the respondents indicated to have no or limited understanding of the Koelmans et al. (2020) risk assessment concept for particle effects. Therefore, the results of this workshop should be interpreted with care.

5. Conclusions

By the interactive workshop sessions and interdisciplinary discussions, new insights, knowledge gaps and challenges were further identified on MNPs in soil. Gathering diverse perspectives, resulted into relevant conclusions on the three performed workshop sessions: Session 1) Analytical challenges of MNPs: The lively workshop discussions highlighted the need for more standardisation in analytical approaches for analysis of microplastics in soil. However, achieving these seems to be a long way down the line, despite some encouraging recent advances in approaches for validations and intercomparisons. Importantly, advances are required in the standardisation of analytical approaches. The workshop highlighted that a similar efforts are required to develop common reporting standards and pathways towards comparability for sampling, MNP extraction and characterisation methods.

Session 2) 'One-Health' approaches to problem identification: The workshop on risk assessment highlighted a clear demand for MNP risk assessments among the various participants groups. However, the specific demands for the application of such risk assessments differ. The

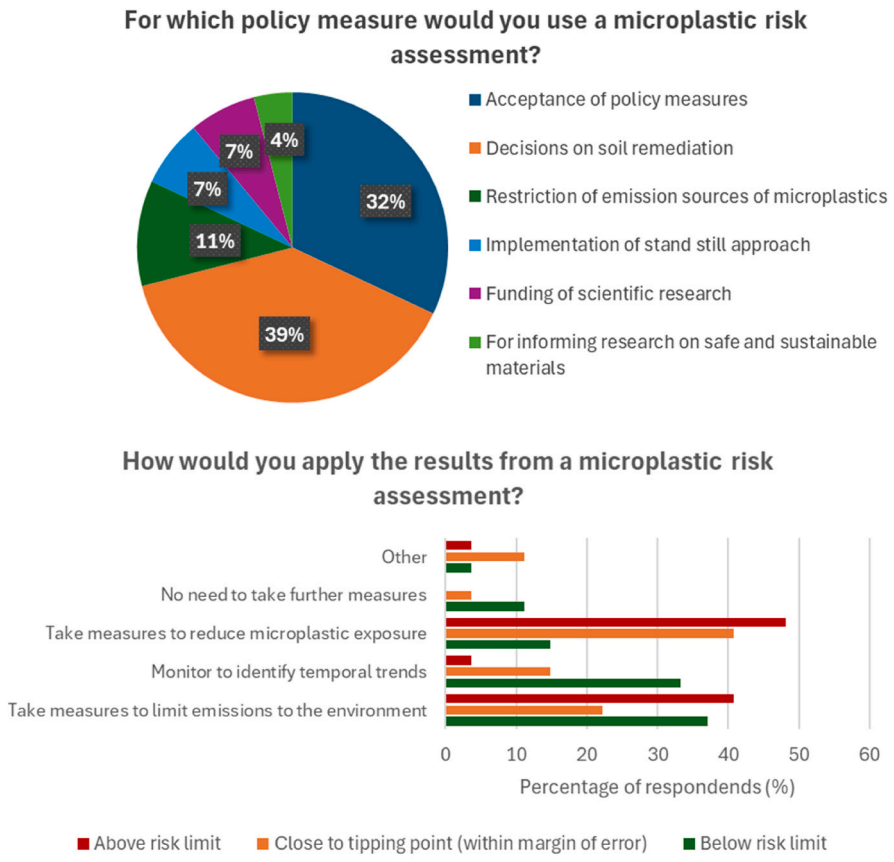

Fig. 3. Responses of participants of the workshop on risk assessment of microplastics in soils to the questions "For which policy measure would you use a microplastic risk assessment?" (N = 28) (top) and "How would you apply the results from a microplastic risk assessment?" (N = 26–27, depending on the scenario) (bottom). Participants were asked to answer the latter questions for scenarios considered, i.e., when exposure concentrations are above risk limits (red bars), close to the tipping point (within margin of error) (orange bars) and below risk limits (green bars).

needs of policymakers at different levels of government (from international and national, and from central to regional government) may require further investigation to ensure that risk assessment approaches developed in science align with those needs, which may lead to more effective solutions for the microplastic pollution problem.

Session 3) Risk assessment to inform policy. Each session concluded that further research is essential. Following this workshop, the National Institute for Public Health and the Environment (RIVM) will organise additional more focussed workshops with scientists and Dutch policy makers. Through this series of workshops, more insights from the scientific community will be gained on how environmental risks of MPs should be determined, identifying how Koelmans et al. (2020) can be applied in MPs risk assessment and how it fits the needs of policy makers. Ultimately, the contribution to better science-based policies for regulating MP pollution in the environment are intended.

CRediT authorship contribution statement

Petra Krystek: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Albert A. Koelmans:** Writing – review & editing, Writing – original draft, Investigation. **Joris Quik:** Writing – review & editing, Writing – original draft, Investigation. **Elmer Swart:** Writing – review & editing, Writing – original draft, Investigation. **Stefan Krause:** Writing – review & editing, Writing – original draft, Investigation. **Juliette Legler:** Writing – review & editing, Writing – original draft, Investigation. **Hilde Aardema:** Writing – review & editing, Writing – original draft, Investigation. **Dick Vethaak:** Writing – original draft, Investigation.

Declaration of competing interest

The authors declare they have no conflicts of interest related to this work to disclose.

Acknowledgement

The 'International Conference (2024): (Micro-nano)plastics in Soil' was organised by Deltares and the Dutch Ministry of Infrastructure and Water management (I&W). Special thanks to Lisette Peters (I&W) for all support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2025.144117.

Data availability

The data is included

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