# Form-specific prospective environmental risk assessment of graphene-based materials in European Freshwaters

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## 1. Introduction

As the application of graphene-based materials (GBMs) in diverse fields escalates, the necessity for environmental risk assessments also grows. Our previous study[1] performed a material flow analysis, identifying GBM release pathways and estimated concentrations in various environmental compartments. Although the importance of considering the different forms of GBM in environmental risk assessments is recognized, e.g. pristine graphene, graphene oxide, and reduced graphene oxide, they have so far not been accounted for.

To bridge this gap, we propose a form-specific environmental risk assessment procedure. This innovative approach combines dynamic probabilistic material flow analysis to obtain predicted environmental concentrations (PECs) with form-specific predicted no-effect concentrations (PNECs) obtained through Probabilistic Species Sensitivity Distributions (PSSD). Finally, the form-specific risk characterization ratios (RCRs) were calculated, aiming for a more accurate understanding of GBMs' environmental impact.

## 2. Material flow analysis and predicted environmental concentrations

Based on the material flow analysis for GBM, we separated the flows into the three forms pristine graphene, graphene oxide, and reduced graphene oxide and determined their final sinks in technical and environmental compartments. The majority of compartments exhibit distribution patterns of the different forms similar to that of the production compartment positioned in the flow diagram's upper left corner (Figure 1). Here, pristine graphene comprises around 59-66% of the composition, with the remaining portion evenly distributed between graphene oxide and reduced graphene oxide. Based on the environmental release flows and the size of the environmental compartments the PEC values were determined for surface waters: 0.67 ng/L (Q25-Q75 of 0.49-0.81 ng/L) for pristine graphene, 0.32 ng/L (0.25-0.39 ng/L) for graphene oxide, and 0.32 ng/L (0.25-0.39 ng/L) for reduced graphene oxide. These concentrations indicate

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comparable levels, suggesting similar extents of exposure of the different forms in surface water.

## 3. Predicted no-effect concentrations

PNECs for pristine graphene and graphene oxide were derived using the PSSD method. There was a notable scarcity of data available for estimating the PNEC of reduced graphene oxide, both in terms of the number of data points and the diversity of species and taxonomic groups considered (only five data points across five species and taxonomic groups, encompassing algae, plankton, aquatic freshwater plants, and crustaceans). The PNEC for this form was therefore derived from the most sensitive data point and an assessment factor. The PNECs for all GBM forms were found to be within the same order of magnitude. Reduced graphene oxide demonstrated the lowest toxicity, with a mean PNEC of 34 µg/L, followed by pristine graphene at 22 µg/L (13-31 µg/L), and graphene oxide at 14 µg/L (11-17 µg/L).

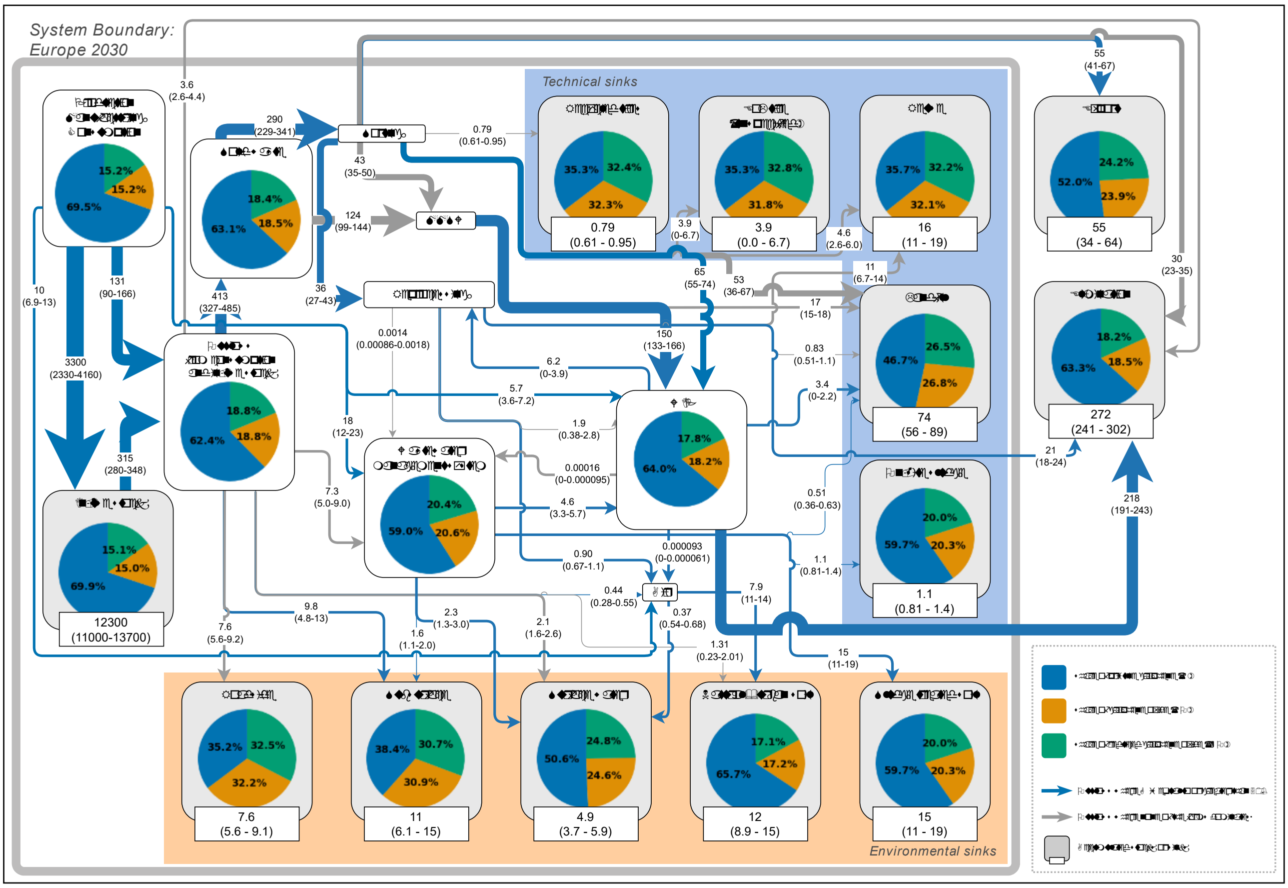


*Figure 1: Projected European 2030 GBM flow diagram (in metric tonnes). The arrow thickness reflects the mean flow, and the range between 25th percentile and 75th percentile is stated on each arrow. MMSW: Mixed municipal solid waste; WIP: Waste incineration plant; WWTP: Wastewater treatment plant.*

## 4. From specific risk assessment of GBM

The RCR for various forms of GBM were determined by dividing the PEC by the PNEC. All values were much below 1, signalling a low environmental risk for all forms of GBM.

Despite the potential for a significant increase in demand for these materials, our analysis indicates that their environmental impact remains minimal.

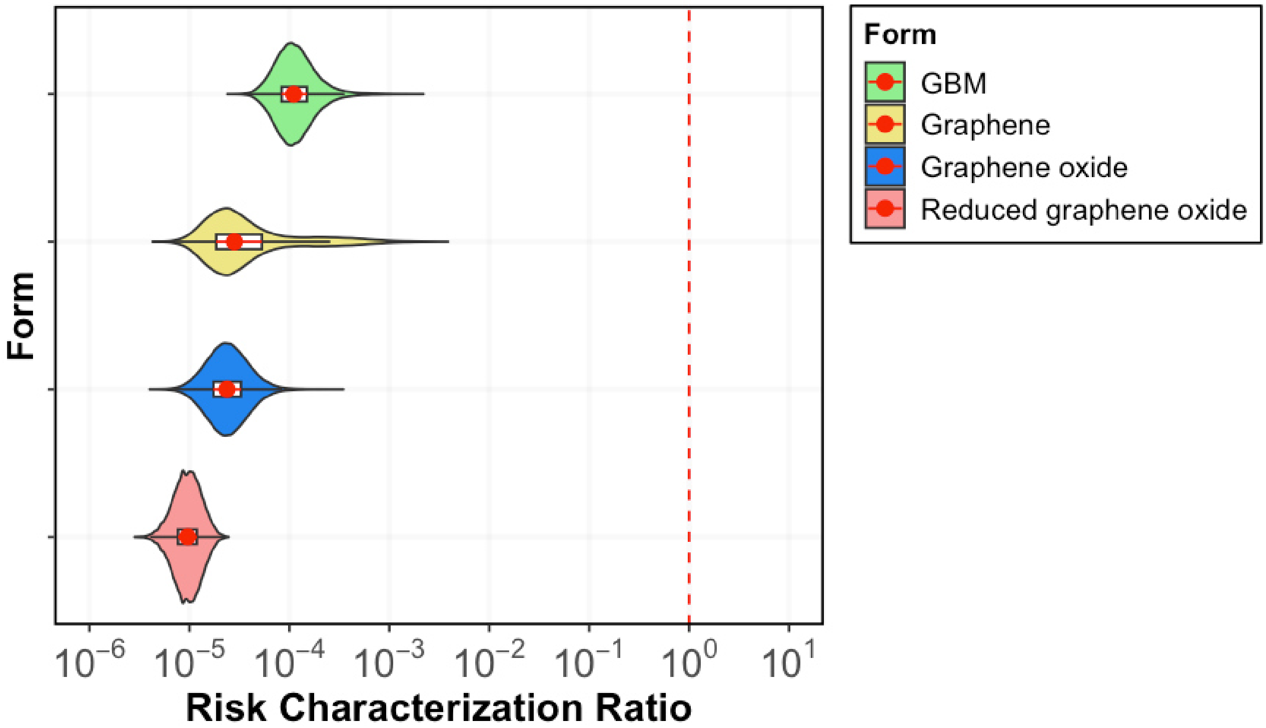


*Figure 2: Violin plot of the risk characterization ratio (RCR) of GBM and different forms of GBM. The right side of the dashed line (red) represents the area of potential environmental risks. The red vertical line indicates the RCR of 1. The red dots show the means, and the red lines show the interquartile range of the distributions.*

## 5. Conclusions

The present study effectively assessed the form-specific risk posed by GBM in European freshwaters, yielding valuable insights into the environmental repercussions of these materials. Our results not only aid in comprehending the potential risks associated with GBM but also underscore the significance of considering the distinct properties of each GBM variant in environmental risk evaluations. By elucidating the distinct environmental behaviours and impacts of pristine graphene, graphene oxide, and reduced graphene oxide, our research enhances the precision and comprehensiveness of environmental risk assessments. This comprehensive understanding of GBM's environmental dynamics can inform regulatory decisions, facilitate the development of sustainable material design, and bolster effective management strategies aimed at minimizing environmental impacts.

## 6. Acknowledgements

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## 7. References

(1) Hong, H.; Part, F.; Nowack, B. Prospective Dynamic and Probabilistic Material Flow Analysis of Graphene-Based Materials in Europe from 2004 to 2030. *Environ Sci Technol* **2022**, *56* (19), 13798–13809. https://doi.org/10.1021/ACS.EST.2C04002/SUPPL_FILE/ES2C04002_SI_001.XLSX.