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FRAGMENT-MNP: A model of micro- and nanoplastic fragmentation in the environment

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Software

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Summary

The degradation and fragmentation of plastics in the environment is an important but relatively poorly characterised process. Fragmentation leads to the formation of micro- and nanoplastics, and research has shown that particle size and shape, and thereby fragmentation, impacts a variety of processes, such as the ability of organisms to uptake plastics, and the movement of plastics around the environment (Thompson et al., 2024; Thornton Hampton et al., 2022). In this paper, we present the FRAGMENT-MNP model as an open-source mechanistic model of micro- and nanoplastic degradation and fragmentation. FRAGMENT-MNP predicts how pieces of plastic can break part (fragment), providing invaluable insights into fragmentation dynamics to help develop our understanding of plastic degradation and fragmentation, and offering predictive capabilities to enable better prediction of the fate and exposure of plastics in the environment.

Statement of need

By modifying particle sizes and shapes, fragmentation influences the potential risk caused by plastics in the environment. Therefore, to assess the risk caused by plastic pollution, understanding fragmentation is crucial. Predictive models are essential in helping this assessment, enabling us to fill gaps in observation data, better understand the results of experiments, and predict theoretical scenarios, such as in prospective risk assessments. Despite this, existing models that predict plastic transport, fate and exposure to organisms either do not consider fragmentation, include it only as a loss process (Quik et al., 2023), treat fragmentation as independent of the properties and residence time in the environment (Koelmans et al., 2017), or consider fragmentation as cascading (fragmenting mass can only be partitioned to the next biggest size class, rather than allowing the formation of nano-scale fragments) (Domercq et al., 2022; Kaandorp et al., 2021). In reality, fragmentation depends on the environmental stresses encountered in the environment, such as photolysis by sunlight, hydrolysis by water, enzymatic action and mechanical disruption causing the break-apart of particles (e.g. the action of waves or bioturbation by soil invertebrates). Fragmentation has also been shown to often occur via surface erosion into nanoscale fragments (Meides et al., 2021; Menzel et al., 2022), rather than in a cascading manner. There is a clear need for flexible and accessible model that can account for these factors, and FRAGMENT-MNP fills this gap.

Overview of the model

The model is fully documented at https://fragmentmnp.ceh.ac.uk. Here, we provide a brief overview of its main conceptualisation and functionality.

Particle concentrations c_k are represented in binned size classes k, with the model allowing for the fragmentation of particles from larger to smaller size classes, and the dissolution of particles into a dissolved size class with concentration c_{diss}. Conceptually, the dissolved fraction consists of oligomers, monomers and volatile organic compounds. The solutions are obtained by numerically solving the following set of differential equations:

$$\frac{dc_k}{dt} = -k_{\text{frag},k} c_k + \sum_i f_{i,k} k_{\text{frag},i} c_i - k_{\text{diss},k} c_k$$

$$\frac{dc_{\text{diss}}}{dt} = \sum_k k_{\text{diss},k} c_k$$

Here, $k_{\text{frag},k}$ is the fragmentation rate constant of size class k, $f_{i,k}$ is the fraction of daughter fragments produced from a fragmenting particle of size i that are of size k, and $k_{\text{diss},k}$ is the dissolution rate from size class k. The rate constants k_{frag} and k_{diss} can be a function of time and particle surface area, and thus are represented internally as 2D arrays. The shape of these dependencies can be controlled by model input parameters, which allow for constant, linear, polynomial, power law, exponential, logarithmic or logistic dependencies. This flexible parameterisation allows for rate constants to model a variety of physical phenomena, such as the modulation of fragmentation as polymer particles undergo weathering in the environment.

FRAGMENT-MNP is released as a `pip` package (`pip install fragmentmnp`) and comes with example configuration and data,to enable users to get started using the model in as little time as possible. A bare minimum model run is shown below, which uses these examples to run an arbitrary fragmentation scenario (with no dissolution):

```python
from fragmentmnp import FragmentMNP
from fragmentmnp.examples import minimal_config, minimal_data

# Create the model and pass it the example config and data
fmnp = FragmentMNP(minimal_config, minimal_data)
# Run the model
output = fmnp.run()
# Plot the results
output.plot()
```

Example model output showing the time evolution of particle size distributions undergoing fragmentation

Figure 1: Example model output showing the time evolution of particle size distributions undergoing fragmentation

Related work

The development of FRAGMENT-MNP is part of broader efforts to further our understanding of microplastics in the environment. For example, work is ongoing to integrate various data collated in the project that funded this work. These data include laboratory experiments that subjected a broad selection of polymers to various environmental stresses, including photolysis (Pfohl et al., 2025), hydrolysis and enzymatic activity. In this work, we aim to generate a database of fragmentation and dissolution rates across a range of polymers and stresses, which can be scaled to realistic stress combinations encountered by plastics in different environmental compartments. These data are providing important parameters to broader models of plastics in the environment, such as the UTOPIA unit-world model of microplastic exposure (Domercq et al., 2025). This model was recently used in a UK goverment (Department for Environment, Food and Rural Affairs; Defra) report on risk mitigation options against intentionally added microplastics (eftec & UKCEH, 2025). Also ongoing is the development of other models covering emissions, additive release, long-range transport and exposure, as part of associated projects funded by the European Chemical Industry Council Long-Range Research Iniative (Cefic-LRI; projects ECO56-60 and ECO68).

Author contributions

SH, CU and BL developed the code behind FRAGMENT-MNP. All authors contributed to the conceptualisation and functionality of the model. This included, but was not limited to, performing laboratory experiments that provided insights into fragmentation mechanisms, which ultimately informed elements such as input data requirements, time and surface area dependencies of rate constants, and output data and plotting capabilities. SH, MW, WW, AP and CS supervised the model development and broader project.

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