



Delft University of Technology

Document Version

Final published version

Licence

CC BY-NC-ND

Citation (APA)

Uguagliati, F., Waqas, A., Chassagne, C., Waldschläger, K., Zattin, M., & Ghinassi, M. (2026). Microplastic fibres as active agents in mud deposition. *Scientific Reports*, 16(1), Article 22354. <https://doi.org/10.1038/s41598-026-52867-z>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

In case the licence states "Dutch Copyright Act (Article 25fa)", this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.



OPEN Microplastic fibres as active agents in mud deposition

Francesca Uguagliati^{1✉}, Ali Waqas^{2,3}, Claire Chassagne², Kryss Waldschläger⁴, Massimiliano Zattin¹ & Massimiliano Ghinassi¹

Clay-rich sediments are essential to the structure and function of freshwater and transitional ecosystems, affecting turbidity, stabilising channels, and providing important benthic habitats. Microplastics are widely distributed in these environments and have traditionally been seen as passive pollutant carriers, despite their well-known ability to interact with clay minerals. In this study, we explore whether microplastics can actively contribute to mud accumulation by altering the aggregation and settling behaviour of clay particles. Using natural river sediments, we compare flocculation and settling dynamics before and after adding microplastic fibres of different polymer types. Our findings indicate that microplastics facilitate the formation of larger clay flocs compared to those in microplastic-free mud, leading to increased floc settling velocities. Collectively, these processes significantly enhance mud deposition, suggesting that, beyond their recognised role as pollutant carriers, microplastics may exert a broader and previously underestimated influence on natural sedimentary dynamics and associated biomorphodynamic processes.

Clay-rich sediments are essential components of freshwater, transitional, and mixed environments, where they regulate turbidity, stabilise substrates, and support key ecological functions^{1,2}. Imbalances in sediment availability, whether excessive or limited, can significantly alter ecosystem structure and the services these systems provide^{2–7}. Due to their cohesive properties, fine-grained suspended sediments are predominantly transported as flocs rather than individual particles^{8,9}. These aggregates, composed of inorganic particles, organic matter (including living organisms and detritus), and interstitial water, form through physicochemical interactions related to particle surface charges^{10–12}. Their properties depend on sediment concentration, organic content, salinity, and turbulence, with flocculation enhancing settling velocity and sedimentation rates^{9,10,12–16}. Flocs also play a key role in contaminant transport, as many substances are associated with suspended particles and their mobility is influenced by aggregation processes¹⁷.

This is particularly relevant for emerging pollutants such as microplastics (MPs), whose interactions with flocs can influence their distribution and fate in aquatic systems. MPs, defined as plastic particles ranging from 1 μm to 5 mm, occur in a variety of shapes, including beads, fragments, films, and fibres, the latter being the most frequently observed in environmental samples^{18–21}. They are widespread in freshwater and transitional environments, raising increasing ecological and toxicological concerns. Once released, MPs can act as vectors for pollutants and pathogens and interact with clay particles, becoming incorporated into flocs and aggregates^{22–25}. Although MPs are often considered passive contaminants, primarily accumulating within fine sediments and forming localised hotspots, this perspective may be incomplete, as MPs may also influence broader environmental processes, such as biogeochemical cycling and sediment transport^{26,27}.

The behaviour of MPs and cohesive fine sediments is therefore closely interconnected^{28–32}. When MPs aggregate with suspended sediments and become incorporated into flocs, their transport is governed by aggregate dynamics, potentially enhancing removal from the water column and promoting sedimentation^{33,34}. Floc formation depends not only on microplastic properties^{35–38} but also on environmental factors such as salinity, organic matter content, biofilm development, and hydrodynamic conditions^{39–41}. This suggests that MPs may not simply behave as passive contaminants, but could also influence sediment aggregation and deposition processes.

Building on this premise, this study investigates the interactions between MP fibres of four different polymers and muddy sediments under controlled experimental conditions simulating natural environments. This approach overcomes common limitations of in situ studies, including the difficulty of sampling flocs while preserving their structure^{42,43}. Sediments used in the experiments were collected from an inactive reach of a natural river (Arno

¹Department of Geosciences, University of Padova, Padova 35131, Italy. ²Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Section of Environmental Fluid Mechanics, Delft University of Technology, Delft 2628, The Netherlands. ³NMDC Group, Abu Dhabi 3649, UAE. ⁴Hydrology and Environmental Hydraulics Group, Wageningen University and Research, Wageningen 6708, The Netherlands. ✉email: francesca.uguagliati@phd.unipd.it

River, Central Italy), selected based on (i) prior evidence of MPs trapping under both bedload and settling conditions⁴⁴, (ii) the dominance of settling processes favouring interactions between clay particles and MPs, and (iii) the availability of sediment concentration data enabling robust experimental control⁴⁵.

Microplastic influence on floc size, shape, and settling dynamics

To investigate the influence of MP fibres on floc properties and settling behaviour, a series of experiments was conducted to measure the size, shape, and settling velocity of flocs formed by natural river mud (median grain size 38 μm ; total organic content 6.8%; Supplementary Material 3, Fig. S1), both in the presence and absence of MP fibres. Four types of MP fibres were used, each composed of a different polymer: polypropylene (PP), polyamide 6.6 (PA), polyester (PES), and aramid (AR). Detailed descriptions of these fibres are provided in the Materials and Methods section. The settling behaviour of isolated, non-aggregated fibres was also compared to that of fibres incorporated into flocs.

Microplastic effects on floc size and shape

Video analysis highlighted distinct differences in the particle size, defined as the equivalent spherical diameter (Fig. 1a), of plastic-free mud flocs compared to those formed in the presence of MP fibres. The plastic-free mud suspension generates the smallest flocs, with sizes generally ranging from approximately 20 μm to just under 200 μm , although a few outliers extend up to 600 μm . In contrast, a noticeable increase in aggregate size is observed for suspensions containing MP fibres. Among the four mixtures containing MP fibres, the mud combined with PP and AR fibres exhibits the largest aggregates, with mean sizes of $467.2 \pm 156.5 \mu\text{m}$ and $276.6 \pm 177.7 \mu\text{m}$, respectively. These mixtures also display extreme outliers, with floc sizes reaching 1158.7 μm for mud with PP fibres and 927.4 μm for mud with AR fibres. Differently, flocs formed in mud containing PA and PES fibres tend to be smaller, with mean sizes of $202.2 \pm 110.9 \mu\text{m}$ and $177.6 \pm 107.9 \mu\text{m}$, respectively, and outliers reaching up to 602.1 μm for PA and 488.8 μm for PES. The mean size of plastic-free flocs is $81.0 \pm 50.4 \mu\text{m}$. In contrast, the average mean size of aggregates formed in the four mixtures containing MP fibres is 280.9 μm , indicating that MP fibres lead to nearly four times larger aggregates than plastic-free mud flocs. Overall, the incorporation of MP fibres markedly increases floc size relative to plastic-free mud flocs, as confirmed by exceedance probability distributions (Supplementary Material 3, Fig. S6a) and a one-sided KS test ($kstest2$, $p < 0.01$, $\alpha = 0.05$).

The incorporation of MP fibres also impacts the shape of flocs (Fig. 1b), forming more irregular morphologies than the generally spherical flocs observed in the plastic-free mud suspension. The aspect ratio of plastic-free flocs typically ranges between 0.3 and 1. In contrast, aggregates containing MP fibres exhibit a dual trend, with flocs maintaining a spherical shape (aspect ratios between 0.0168 and 1), while others are more elongated (aspect ratios between 0.001 and 0.01). This distinction is particularly evident in mixtures containing PA, PES, and AR fibres. In contrast, in aggregates with PP fibres, most aspect ratios fall between 0.1 and 1, indicating a predominance of spherical shapes.

The increase in floc size in sediment mixtures containing MP fibres can be attributed to several factors. Due to their low affinity for water, MPs tend to aggregate with other particles, including organic matter, suspended solids, contaminants, and other MPs³⁵. Physicochemical interactions at the MP interface primarily govern this behaviour. The hydrophobic surfaces of MPs facilitate adhesion to natural organic matter and biofilms by repelling water molecules. Concurrently, van der Waals forces promote attraction between MPs and mineral particles, enhancing particle-particle interactions. Electrostatic forces, influenced by parameters such as pH and ionic strength, further control aggregation processes and contribute to the formation of larger aggregates⁴⁶. Moreover, extracellular polymeric substances and dissolved organic matter can drive flocculation through polymer bridging mechanisms, leading to the incorporation of MPs into larger flocs⁴⁷. The curliness of PP fibres may also account for the relatively larger flocs they formed in comparison with those of PA, PES, and AR fibres. A curled morphology increases surface area and hydrodynamic resistance, enhancing the entanglement of fibres and promoting sediment interlocking⁴⁸. That results in the formation of additional contact points for sediment adhesion, leading to the development of more voluminous aggregates. Additionally, an increased drag experienced by curled fibres also prolongs their suspension, providing more opportunities for particle interaction and adhesion⁴⁹. Similarly, the low density of PP fibres, the only buoyant polymer examined in this study, extends their suspension time, increases the likelihood of particle adhesion and growth, ultimately forming the largest flocs¹². Flocs containing PP fibres are not only larger but also more spherical than those formed with PA, PES, or AR fibres, which tend to be more elongated. This difference stems from the curled structure of PP fibres, which encourages self-entanglement and the formation of compact, rounded bundles that effectively trap sediment particles and retain a dense morphology. Moreover, the low density of PP fibres increases suspension time, allowing flocs more time to mature and naturally compact into a more spherical shape. In contrast, the elongated aggregates formed by PA, PES, and AR fibres may result from lower maturity, as younger flocs tend to be more open and irregular⁵⁰. The elongated, irregular shapes may also arise through mechanisms similar to those observed in flocs associated with cyanobacteria, which influence floc morphology by forming string-like structures that act as anchoring points and promote elongation⁵¹. Similarly, the presence of organic fibres in the plastic-free mud suspension could explain the occasional appearance of elongated flocs, as these fibres may mimic the structural role of MP fibres or cyanobacteria.

Microplastic effects on floc settling

The mean settling velocity of flocs (Fig. 2) composed solely of mud ($2.5 \pm 1.6 \text{ mm/s}$) is comparable to the mean settling velocities of the pure fibres: $3.0 \pm 1.9 \text{ mm/s}$ for PA, $1.9 \pm 1.5 \text{ mm/s}$ for PES, and $2.6 \pm 1.4 \text{ mm/s}$ for AR. Regarding the flocs generated in the mud-MP fibre mixture, even the slowest-settling flocs generally exhibited higher settling velocities than those composed exclusively of mud. Flocs with PA fibres had the lowest mean settling velocity at $3.7 \pm 2.1 \text{ mm/s}$, with a maximum of 10.3 mm/s. Flocs with PES fibres displayed intermediate

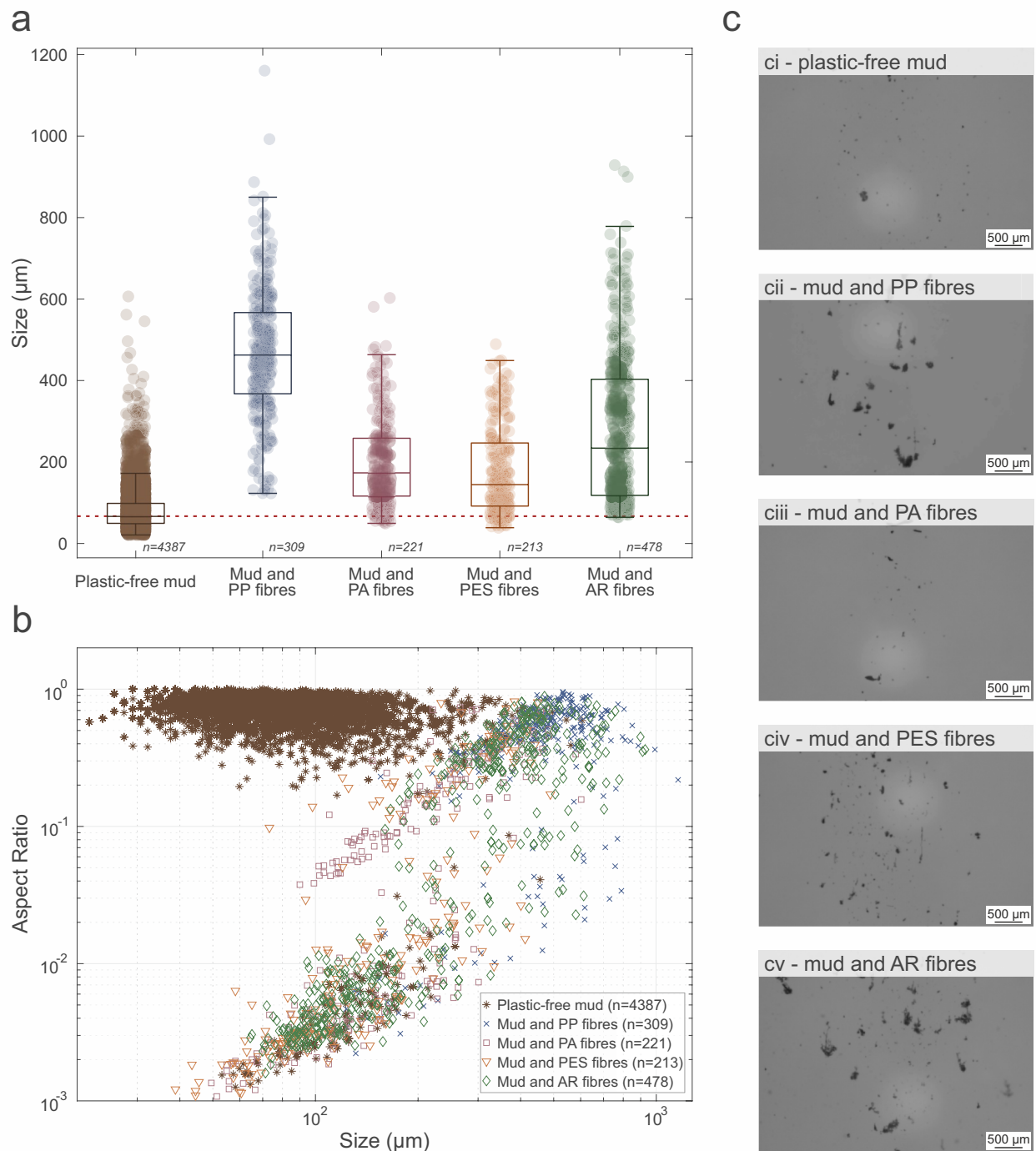


Fig. 1. Floc size and shape. **(a)** Boxplot illustrating the floc size distribution of the plastic-free mud suspension alongside the five mixtures containing MP fibres. The red dashed line indicates the median size of the plastic-free mud flocs, providing a point of comparison with the values obtained from the other four mixtures. The values of n (indicating the number of data analysed for each group) are shown in panel a and also apply to the data presented in panel b. **(b)** Aspect ratio versus size illustrates the relationship between floc size and shape. **(c)** Video frames of flocs formed from the plastic-free mud suspension (ci) and the five mixtures containing MP fibres (cii–cv) captured using high-resolution camera equipment.

settling behaviour, with a mean velocity of 4.8 ± 2.2 mm/s and a peak of 18.5 mm/s, while those containing AR fibres had a mean velocity of 5.3 ± 2.6 mm/s and a slightly lower maximum of 15.9 mm/s. Among all tested mixtures, flocs containing PP fibres exhibited the highest settling velocities, with a mean of 10.4 ± 5.6 mm/s and a peak of 22.0 mm/s. On average, the presence of MP fibres results in exhibiting a settling velocity slightly more

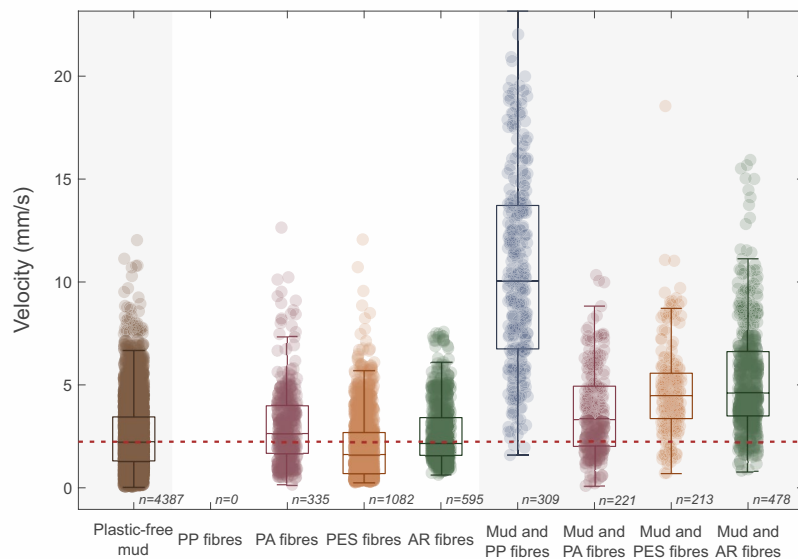


Fig. 2. Floc settling velocity. Distribution of settling velocities for flocs formed in the plastic-free mud suspension and in the four mixtures containing MP fibres. The chart also includes the settling rates of pure fibres for comparison. The settling velocity of pure PP fibres was not measured due to their buoyancy in water. The red dashed line represents the median settling velocity of the plastic-free mud flocs, offering a comparison with the velocities obtained from the other four mixtures and the pure, non-aggregated fibres. The values of n indicate the number of data analysed for each group.

than twice that of plastic-free flocs. Results also show that the behaviour of flocs with non-buoyant fibres can be distinguished from that of flocs with buoyant fibres. The incorporation into flocs of non-buoyant fibres, such as PA, PES, and AR, results in a slight increase in settling velocity compared to their clean, unaggregated state. On the other hand, buoyant PP fibres, which remain afloat when clean, exhibit a median settling velocity that is more than twice that of the flocs formed in the other three MP-sediment mixtures. Overall, the incorporation of MP fibres significantly enhances the settling velocity of flocs compared to those formed from the plastic-free mud suspension, a trend further supported by exceedance probability distributions (Supplementary Material 3, Fig. S6b) and statistically confirmed by a one-sided KS test (kstest2, $p < 0.01$, $\alpha = 0.05$).

Floc settling velocity is primarily influenced by floc size and shape, with larger flocs generally exhibiting higher settling velocities due to increased mass⁵². Although porosity, which typically increases with floc size, can counteract this effect, size and mass remain the dominant determinants of settling behaviour⁵³. Moreover, as flocs grow, they establish more linkages with other particles, including sediment, organic matter, MPs, or natural fibres, further increasing their mass and increasing their settling dynamics¹⁰. In addition to the increase in size and settling velocity due to fibre incorporation, floc shape played a crucial role. More spherical flocs, such as those generated in the PP fibre mixture, experience reduced flow resistance and settle more efficiently than elongated or irregularly shaped ones⁵². Therefore, the enhanced settling rate of flocs formed in the PP fibre mixture can be attributed not only to their increased size but also to their more spherical shape. Results show, therefore, that incorporation of MP fibre into the flocs significantly altered their morphometric characteristics and hydrological behaviour. Specifically, MP fibre in mud suspensions promotes the formation of larger aggregates that settle at higher velocities than those formed in the plastic-free suspensions. Worth highlighting is the behaviour of the flocs formed in the PP-mud mixture. Due to their buoyancy, these fibres remained suspended for a longer period, which allowed the formation of more mature flocs. This, together with the curly morphology of the fibres that facilitated greater sediment attachment, significantly enhanced their settling velocity.

Implications for freshwater and transitional environments

Our results demonstrate that the presence of MP fibres markedly enhances floc size, leading to a corresponding increase in settling velocity. Aggregates formed in mud-MP mixtures are, on average, four times larger and settle nearly twice as fast as those in plastic-free conditions. A preliminary estimate based on median values from floc analysis indicates a fourfold increase in floc size, from a median equivalent spherical diameter of 66 μm in flocs formed in the plastic-free suspension to an average of 253 μm in flocs incorporating microfibres (calculated from the median size of flocs formed in the four MP-fibre mixtures). A similar approximation using floc settling rates suggests a doubling, from a median value of 2.2 mm/s for plastic-free flocs to an average of 5.86 mm/s for those containing MP fibres. Such changes, reflected in the increased floc size and settling velocity, suggest a considerable acceleration of sediment deposition rates under equivalent hydrodynamic conditions, indicating that the incorporation of microfibres can substantially enhance sediment deposition potential in freshwater and transitional environments. This enhanced sedimentation may have significant ecological effects on ecosystems

where MPs interact with fine-grained sediments, such as rivers and, more broadly, freshwater and transitional environments.

In riverine environments, accelerated sediment deposition can lead to excessive siltation, resulting in significant environmental and infrastructural challenges. Excessive sedimentation shallows waterways, reducing channel capacity, altering flow dynamics, and increasing the risk of flooding⁵⁴. At the same time, it impedes navigation and increases maintenance costs due to frequent dredging⁵⁵. In natural river systems, abandoned channels often become sediment sinks, disrupting hydrological connectivity and destabilising and weakening riverbanks⁵⁶. Beyond river ecosystems, all freshwater and transitional environments could be affected by increased sedimentation caused by flocculation driven by MP fibres. In water reservoirs, silt accumulation leads to faster infilling, reducing storage capacity, affecting water supply, hydroelectric generation, and flood control efficiency, while increasing maintenance costs and potentially speeding up eutrophication by burying organic matter⁴. In wetlands, lagoons, and estuaries, where fine cohesive sediments are abundant and salinity levels are higher, flocculation is naturally enhanced⁵⁷, and the presence of MP fibres could further amplify the formation and deposition of larger flocs, accelerating sediment accumulation. Regarding rivers, excessive sedimentation can shallow tidal channels, disrupting marsh hydrology by constraining tidal water flow⁵⁸. Similarly, excessive sediment build-up in estuaries can alter water flow and circulation patterns⁵⁹.

Regarding MPs' final fate, their ability to interact with fine cohesive sediments and other suspended particulate matter, as well as their enhanced sedimentation when incorporated into sediment aggregates, contributes to the temporary or even permanent storage of these particles. This process reduces their flux to the sea, potentially altering their ecological impact by creating localised hotspots of MP accumulation⁶⁰. Given the widespread presence of MPs in freshwater and transitional environments, along with the ecological and hydrological importance of these areas, our findings indicate that high concentrations of MPs may cause non-linear changes in the sedimentation of mud, suggesting the existence of a tipping point beyond which system dynamics are significantly altered.

Limitations and future research

This study provides important insights into how MP fibres influence floc formation and sedimentation, but several limitations related to the materials and methods should be considered. In particular, the characteristics of the MP fibres used in this study may influence flocculation dynamics and sediment behaviour, while the properties of the sediments and water provide the baseline context for these processes. These aspects frame the context in which the following limitations and considerations should be considered.

Although our experiments used relatively high MP concentrations, effects on floc formation and settling are expected to be smaller at environmentally relevant levels. Nonetheless, even low fibre amounts could influence aggregation, particularly in sensitive or low-energy aquatic systems, highlighting the need for further investigation across a range of concentrations. This potential threshold underscores the vulnerability of these ecosystems to MP accumulation, with consequences for morphological stability and ecological health. These findings also suggest a possible feedback loop between accelerated sedimentation and MPs' fate. In systems experiencing high sedimentation rates, MPs become buried in the floodplain, riverbed, or estuarine sediments, temporarily removing them from the water column³³. However, these sediments can act as dynamic rather than static sinks: high-flow events or disturbance may remobilise buried MPs, facilitating downstream transport or re-exposure²⁷. Additionally, sediment-MP interactions can modify the bioavailability of MPs to benthic fauna, especially deposit feeders, thereby linking physical processes to ecological effects⁶¹. Further research is needed to better constrain the concentration levels at which such effects emerge, including experiments across a wider range of MP and suspended sediment concentrations. Moreover, although fibres are the most common MP shapes found in the environment^{24,62,63}, it is essential to explore how other MP types, varying in size, shape, density, polymer composition, and degradation state, impact sedimentary processes. In this context, it should be noted that, although the fibre length used in this study lies toward the upper end of environmentally observed sizes^{19,24,64,65}, it remains within realistic environmental ranges and allows clear observation of fibre-particle interactions, while acknowledging that smaller, more common fibres could produce different effects. As Wu et al. observed⁶⁰, the incorporation of MPs into flocs seems to be influenced by their surface roughness, shape irregularities, and dimensions, highlighting the need for a more comprehensive understanding of how these characteristics interact with flocculation dynamics.

In addition, as experiments were conducted at a single pH, variations in pH may influence particle surface charge and, consequently, flocculation processes and MP-sediment interactions⁶⁶. Future studies should therefore consider the combined effects of pH and MPs to better capture environmental variability. Moreover, the chemical composition and surface charge of the mud were not assessed in this study and could influence flocculation dynamics^{66,67}. Future work should consider these factors alongside MP fibres to better understand their combined effects on sediment aggregation and settling. In addition, floc persistence and mechanical stability represent an important, yet unquantified, control on floc behaviour. Floc persistence and resistance to disaggregation were not directly quantified in this study; however, the observed increase in size and irregularity of aggregates in the presence of MP fibres is likely to influence both settling behaviour and susceptibility to mechanical breakage under flow conditions^{68,69}. The balance between enhanced deposition and increased breakage is expected to depend on local hydrodynamic conditions, highlighting the need for future studies to assess floc stability under variable flow regimes.

Together, these findings indicate that rising MP concentrations may have a wider and previously underestimated impact on aquatic systems, with cascading effects across multiple levels of ecosystem structure and function. By acting as an emergent driver of changes in sedimentary and biogeochemical dynamics, MP loading could weaken environmental resilience and sustainability, highlighting the need for an integrated, system-wide approach to monitoring, risk assessment, and management.

Materials and methods

Sediments

The sediments employed in this study were collected from the Arno River (Tuscany, Central Italy). The sampling site was located approximately 30 km upstream of Florence (S. Giovanni Valdarno), at a distance preventing marine influence. Mud was picked up from an abandoned reach of the main channel, permanently hosting water with a maximum depth of 50 cm at the river's low-flow stage. Sediments were collected 7 days after the peak of a major flood event (5 March 2024) and refrigerated at 4 °C. Before starting the experiments, the sediment samples were thoroughly stirred to achieve homogeneity. Subsequently, 43 g of wet sediments were dried overnight in an oven at 100 °C. This small volume of wet sediment was weighed before and after being in the oven to determine the sample's water content (57.7%) and to calculate the appropriate sediment concentration required for the experiments.

Particle size distribution (PSD) analysis of sediments was conducted using Malvern Mastersizer 2000, which employs static light scattering (SLS) to analyse grain size distribution. During the analysis, the suspension was recirculated between the mixing jar and the Malvern Mastersizer 2000 using a peristaltic pump, ensuring continuous flow through the instrument.

The total Organic Carbon (TOC) content of sediments was determined using the NEN 6484 Dutch standard technique for loss on ignition⁷⁰. The organic matter content of the dry sample was determined by the weight loss of the sample following heating for 5 h at 600 °C.

Microplastics

500 µm long fibres of four different polymers were used for the experiments. Fibres were purchased as shortcut fibres from STW Technical Fibres (DE). The selected polymers were: (i) Polypropylene (PP), (ii) Polyamide 6.6 (PA), (iii) Polyester (PES), and (iv) Aramid (AR). These polymers have densities ranging from 0.9 to 1.44 g cm⁻³ and represent some of the most commonly encountered plastics in environmental plastic waste. Moreover, their densities span a range of plastic materials, including values below and above water density. Together with their length, microfiber features, selected to reflect the average sizes of microfibers commonly reported in environmental studies²⁴, in detail, are:

- PP: density 0.9–0.92 g cm⁻³, diameter 21 µm.
- PA: density 1.14 g cm⁻³, diameter 19 µm.
- PES: density 1.38 g cm⁻³, diameter 16.9–19.7 µm.
- AR: density 1.44 g cm⁻³, diameter 10–20 µm.

PSD analysis was also conducted for the pure fibres using Malvern Mastersizer 2000 (Supplementary Material 1). For these analyses, the d_{10} and d_{90} values correspond to the diameter and length data provided by the supplier (Supplementary Material 3, Fig. S2).

Experiments

A total of five experiments were conducted. For each experiment, a suspension of tap water (specifications in Supplementary Material 3, Table S1) and sediments was prepared at a concentration of 1 g/L, corresponding to one gram of sediment per litre of water. This concentration was selected since it reflects the average sediment discharge in the Arno River during flood events⁴⁵. Four experiments were conducted by adding MP fibres to the suspensions, creating four mixtures, each one with a different polymer. The fifth experiment, which served as a control test, was conducted without adding fibres. To obtain the studied mixtures, a fibre-sediment ratio of 1:25, 0.04 g of microfibers was added for each gram of sediment⁶⁰. An approximation, derived from the dimensional and density characteristics of the microfibers, enabled the calculation of the average mass of an individual fibre. This, in turn, facilitated the estimation of the particle concentration in the mixtures, yielding an average value of approximately 260,000 particles per litre (MP/L). This MP concentration exceeds most values currently reported in the literature⁷¹. Nevertheless, it should be noted that concentration data reported in previous years were often obtained using poorly tested and non-standardised protocols, which may have caused significant underestimation of actual MP content⁷². Recently, advances in sampling and analytical methods have allowed the detection of substantially higher MP concentrations compared to those reported in earlier research stages. For example, Monnanni et al.⁶⁵ analysed the waters of the Arno River, a moderately polluted Italian river characterised by a relatively small catchment area, limited population density, and effective waste management policies, and found MP concentrations substantially exceeding those typically documented. This was chiefly due to the improved sensitivity and resolution of their sampling and analytical techniques. If similar methods were employed in more polluted rivers, comparable concentrations to those in our study would likely be identified.

Rotating wheel

A rotating wheel (Fig. 3) was used to induce flocculation at low shear. The rotating wheel (inner diameter of 34 cm and a depth of 7 cm) is designed to perform full circular rotations along its axis, ensuring continuous motion that keeps sediment suspended and potentially increases the likelihood of floc formation. The rotating wheel was filled to the top with 8 L of the prepared mixtures for all experiments. The mixtures were subjected to a shear rate of 10 s⁻¹ in the rotating wheel for 2 h, after which the apparatus was stopped to allow the flocs to settle completely. The flocs were subsequently collected from the settled sediments using a 50 mL capacity pipette with a 3 mm diameter. The flocs were carefully deposited at the top of a settling column used in the FLOCCAM setup (described below), with the pipette aperture in direct contact with the water surface of the column. This ensured that the flocs settled naturally, solely under the influence of gravity. Floc sizes and corresponding settling velocities were then measured using a settling column equipped with a high-resolution camera.

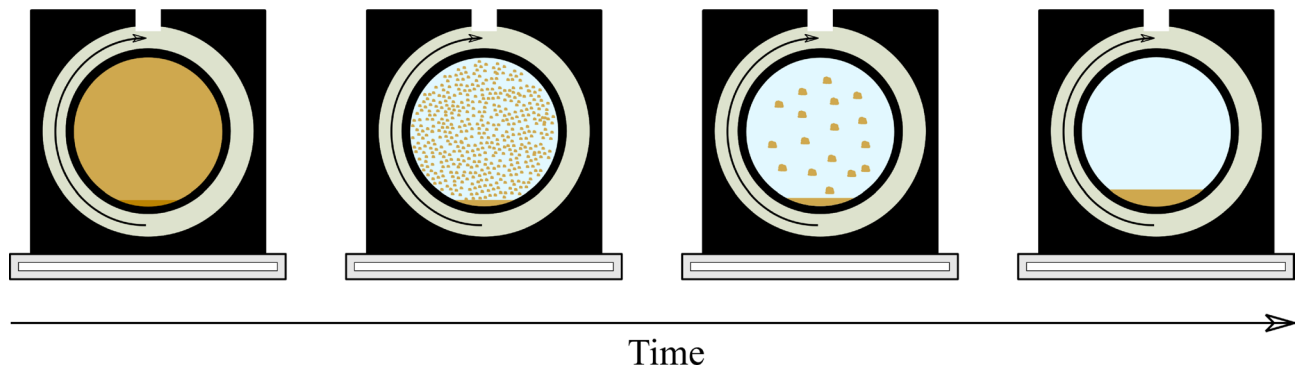


Fig. 3. The rotating wheel apparatus. Schematic representation of the rotating wheel apparatus and the flocculation experiment steps. Figure reproduced from Ali et al.⁷³, licensed under CC BY 4.0.

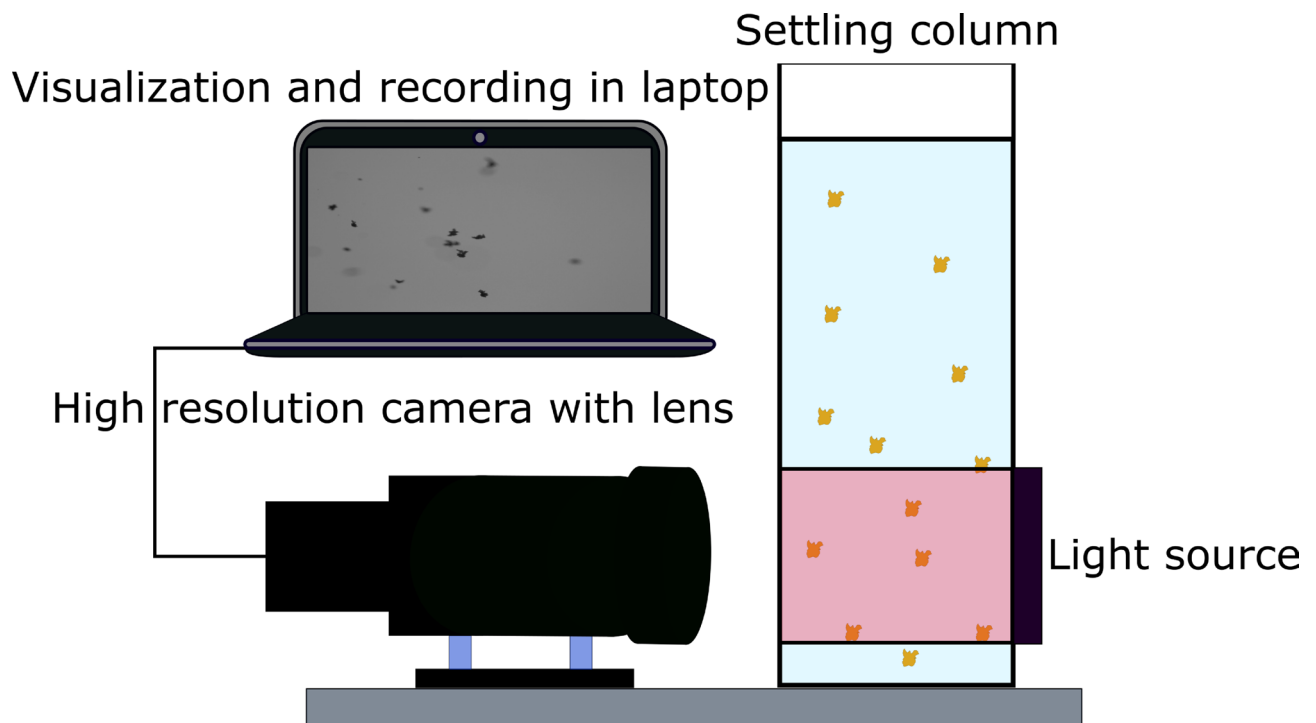


Fig. 4. FLOCCAM setup. Schematic representation of the FLOCCAM setup. Figure reproduced from Ali et al.⁷⁶, licensed under CC BY 4.0.

Conventionally, the most common procedure used to generate flocs in laboratory experiments is the jar test. As reported in Ali et al.⁷³, the innovative instrument used in this work differs significantly from the jar test in its hydrodynamics. While jar tests rely on turbulent mixing to keep particles suspended, the wheel creates a low-shear environment where flocs form through gentle entrainment and settling. This condition favours the rapid formation of larger flocs, likely due to enhanced interaction between clay and organic matter at low shear. Compared to jars, flocs produced in the wheel are consistently larger, supporting the idea that the wheel setup more closely mimics natural sedimentation processes.

FLOCCAM

The FLOCCAM setup (Fig. 4) utilises video microscopy to estimate PSDs greater than 20 μm and settling velocities of floc samples^{66,67,74}. Flocs' PSD, shape, and settling velocities are determined from video recordings of settling flocs in a settling column, with data processed using the Safas software package⁷⁵. The equipment includes several key components. A cylindrical settling column (10 cm x 10 cm x 30 cm) with glass front and rear panels and plastic sides. A 5MP CMOS camera with a resolution of 2592 x 2048 pixels and a pixel size of 4.8 μm to capture the video footage. The camera, identified as iDS UI-3180CP-M-GL Rev.2.1 (AB02546), is equipped with a Global Shutter. A telecentric lens, the S5VPJ2898, manufactured by Sill Optics GmbH & Co. KG, is used in combination with the camera. This lens has a tuneable working distance and provides an

approximate pixel size of 8.6 μm . A Flat Lights TH2 Series Red LED light panel (63 $\times$ 60 cm), known for its high directivity, ensures adequate illumination during the experiments. The light source is controlled by a DC 24 V Input Controller for LED Lights (model PB-2430-1) by CCS Inc. Data recording and analysis are conducted on a Dell Inspiron-15-7590 laptop. Additionally, a conical plastic feed well directs the flow of flocs, with a 2 mm by 10 mm rectangular opening at its end. Flocs' parameters are measured and recorded approximately 30 cm below the injection point.

The FLOCCAM equipment was used to measure flocs' parameters from all five mixtures. Additionally, the plastic-free mud sediments were also measured with this instrument without undergoing flocculation. Thus, it was possible to observe the effect of flocculation on the clean mud mixture.

Safas

Safas (Sedimentation and Floc Analysis Software) is a Python-based module designed to process and analyse images and videos of flocs⁷⁵. The software package enables users to efficiently measure and store data such as size, morphology, and settling velocity in an accessible format. The software is also an open-source Python tool that allows users to access and extend its image filters. These filters have been developed and tested to accurately segment and quantify floc images, offering a range of functions that ensure precise and reliable results.

The parameters derived from the floc videos and utilised for the analysis were the equivalent spherical diameter and aspect ratio, obtained through measurements of the major and minor axes of the flocs, and the flocs' settling rate, derived as a function of the equivalent spherical diameter (Supplementary Material 2).

Given the extensive dataset, a data filtering step was applied after a preliminary analysis for the four experiments involving microfibers in the mixture. Only flocs with a major axis greater than 500 μm were included to ensure the selection of aggregates containing MP fibres. This threshold was defined based on preliminary observations showing that smaller flocs did not incorporate fibres. Applying this filter does not bias the results, as fibre-containing floc consistently exceeded this size across all replicates. Results obtained from unfiltered data are presented in the Supporting Information (Fig. S3, S4, and S5).

Data availability

All data files are available in.xlsx format as Supplementary Material 1 and 2.

Received: 12 November 2025; Accepted: 8 May 2026

Published online: 17 May 2026

References

- Burban, P. Y., Lick, W. & Lick, J. The flocculation of fine-grained sediments in estuarine waters. *J. Geophys. Res. Oceans* **94**, 8323–8330 (1989).
- Owens, P. N., Petticrew, E. L. & van der Perk, M. Sediment response to catchment disturbances. *J. Soils Sediments* **10**, 591–596 (2010).
- Henley, W. F., Patterson, M. A., Neves, R. J. & Lemly, A. D. Effects of sedimentation and turbidity on lotic food webs: A concise review for natural resource managers. *Rev. Fish. Sci.* **8**, 125–139 (2000).
- Lo, E. L. et al. Sediment infill of tropical floodplain lakes: rates, controls, and implications for ecosystem services. *Front. Earth Sci.* **10**, (2022).
- Donohue, I. & Garcia Molinos, J. Impacts of increased sediment loads on the ecology of lakes. *Biol. Rev.* **84**, 517–531 (2009).
- Schleiss, A. J., Franca, M. J., Juez, C. & De Cesare, G. Reservoir sedimentation. *J. Hydraul. Res.* **54**, 595–614 (2016).
- Batalla, R. J. Sediment deficit in rivers caused by dams and instream gravel mining. A review with examples from NE Spain. *Rev. C & G* **17**(3–4), 79–91 (2003).
- Droppo, I. G., Nackaerts, K., Walling, D. E. & Williams, N. Can flocs and water stable soil aggregates be differentiated within fluvial systems?. *Catena* **60**, 1–18 (2005).
- Droppo, I. G. & Ongley, E. D. Flocculation of suspended sediment in rivers of southeastern Canada. *Water Res.* **28**, 1799–1809 (1994).
- Droppo, I. G. Rethinking what constitutes suspended sediment. *Hydrol. Process.* **15**, 1551–1564 (2001).
- Chassagne, C. & Safar, Z. Modelling flocculation: Towards an integration in large-scale sediment transport models. *Mar. Geol.* **430**, 106361 (2020).
- Deng, Z., Huang, D., He, Q. & Chassagne, C. Review of the action of organic matter on mineral sediment flocculation. *Front. Earth Sci.* **10**, (2022).
- Chen, S. & Eisma, D. Fractal geometry of *in situ* flocs in the estuarine and coastal environments. *Neth. J. Sea Res.* **33**, 173–182 (1995).
- Nicholas, A. P. & Walling, D. E. The significance of particle aggregation in the overbank deposition of suspended sediment on river floodplains. *J. Hydrol.* **186**, 275–293 (1996).
- Droppo, I. G., Leppard, G. G., Flannigan, D. T. & Liss, S. N. The freshwater floc: A functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. The Interactions between Sediments and Water: *Proceedings of the 7th International Symposium*. 43–53 (1996).
- Lamb, M. P. et al. Mud in rivers transported as flocculated and suspended bed material. *Nat. Geosci.* **13**, 566–570 (2020).
- Heidari, M. Role of natural flocculation in eliminating toxic metals. *Arch. Environ. Contam. Toxicol.* **76**, 366–374 (2019).
- Browne, M. A. et al. Accumulation of Microplastic on Shorelines Worldwide: Sources and Sinks. *Environ. Sci. Technol.* **45**, 9175–9179 (2011).
- Barrows, A. P. W., Cathey, S. E. & Petersen, C. W. Marine environment microfiber contamination: Global patterns and the diversity of microparticle origins. *Environ. Pollut.* **237**, 275–284 (2018).
- Ali, A. A. M. et al. A review on the presence of microplastics in environmental matrices within Southeast Asia: elucidating risk information through an analysis of microplastic characteristics such as size, shape, and type. *WEC&N* **3**, 12 (2024).
- Yu, J. T., Diamond, M. L. & Helm, P. A. A fit-for-purpose categorization scheme for microplastic morphologies. *Integr. Environ. Assess. Manag.* **19**, 422–435 (2023).
- Kinigopoulou, V., Pashalidis, I., Kalderis, D. & Anastopoulos, I. Microplastics as carriers of inorganic and organic contaminants in the environment: A review of recent progress. *J. Mol. Liq.* **350**, 118580 (2022).
- Rafa, N. et al. Microplastics as carriers of toxic pollutants: Source, transport, and toxicological effects. *Environ. Pollut.* **343**, 123190 (2024).

24. Cole, M. et al. Isolation of microplastics in biota-rich seawater samples and marine organisms. *Sci. Rep.* **4**, 4528 (2014).
25. Akanyange, S. N. et al. A holistic assessment of microplastic ubiquitousness: Pathway for source identification in the environment. *Sustain. Prod. Consum.* **33**, 113–145 (2022).
26. Yan, B. et al. Microplastic Pollution in Marine Environment: Occurrence, Fate, and Effects (With a Specific Focus on Biogeochemical Carbon and Nitrogen Cycles). *Microplastic Pollution* 105–126 (2021).
27. Li, K. et al. Microplastic pollution as an environmental risk exacerbating the greenhouse effect and climate change: a review. *Carbon Res.* **3**, 9 (2024).
28. Laursen, S. N. et al. Settling of buoyant microplastic in estuaries: The importance of flocculation. *STOTEN* **886**, 163976 (2023).
29. Nizzetto, L., Bussi, G., Futter, M. N., Butterfield, D. & Whitehead, P. G. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. *Environ. Sci. Process. Impacts.* **18**, 1050–1059 (2016).
30. Ho, Q. N., Fettweis, M., Spencer, K. L. & Lee, B. J. Flocculation with heterogeneous composition in water environments: A review. *Water Res.* **213**, 118147 (2022).
31. Möhlenkamp, P., Purser, A. & Thomsen, L. Plastic microbeads from cosmetic products: An experimental study of their hydrodynamic behaviour, vertical transport and resuspension in phytoplankton and sediment aggregates. *Elementa Sci. Anthropocene* **6**, 61 (2018).
32. Andersen, T. J., Rominikan, S., Olsen, I. S., Skinnebach, K. H. & Fruergaard, M. Flocculation of PVC microplastic and fine-grained cohesive sediment at environmentally realistic concentrations. *Biol. Bull.* **240**, 42–51 (2021).
33. Leiser, R., Schumann, M., Dadi, T. & Wendt-Potthoff, K. Burial of microplastics in freshwater sediments facilitated by iron-organic flocs. *Sci. Rep.* **11**, 24072 (2021).
34. Petrova, O. E. & Sauer, K. Sticky situations: Key components that control bacterial surface attachment. *J. Bacteriol.* **194**, 2413–2425 (2012).
35. Alimi, O. S., Budarz, F., Hernandez, J., Tufenkji, N. & L. M. & Microplastics and Nanoplastics in Aquatic Environments: Aggregation, Deposition, and Enhanced Contaminant Transport. *Environ. Sci. Technol.* **52**, 1704–1724 (2018).
36. Li, S. et al. Aggregation kinetics of microplastics in aquatic environment: Complex roles of electrolytes, pH, and natural organic matter. *Environ. Pollut.* **237**, 126–132 (2018).
37. Yang, X., An, C., Feng, Q., Boufadel, M. & Ji, W. Aggregation of microplastics and clay particles in the nearshore environment: Characteristics, influencing factors, and implications. *Water Res.* **224**, 119077 (2022).
38. He, W., Chen, X., Xu, C., Zhou, C. & Wang, C. Internal interaction between chemically-pretreated polypropylene microplastics and floc growth during flocculation: Critical effect on floc properties and flocculation mechanisms. *Sep. Purif. Technol.* **306**, 122710 (2023).
39. Kooi, M., van Nes, E. H., Scheffer, M. & Koelmans, A. A. Ups and downs in the ocean: Effects of biofouling on vertical transport of microplastics. *Environ. Sci. Technol.* **51**, 7963–7971 (2017).
40. Kaiser, D., Kowalski, N. & Waniek, J. J. Effects of biofouling on the sinking behavior of microplastics. *Environ. Res. Lett.* **12**, 124003 (2017).
41. Van Melkebeke, M., Janssen, C. & De Meester, S. Characteristics and sinking behavior of typical microplastics including the potential effect of biofouling: Implications for remediation. *Environ. Sci. Technol.* **54**, 8668–8680 (2020).
42. Dyer, K. R. et al. A comparison of *in situ* techniques for estuarine floc settling velocity measurements. *J. Sea Res.* **36**, 15–29 (1996).
43. Fettweis, M. Uncertainty of excess density and settling velocity of mud flocs derived from *in situ* measurements. *Estuar. Coast. Shelf Sci.* **78**, 426–436 (2008).
44. Ghinassi, M., Michielotto, A., Uguagliati, F. & Zattin, M. Mechanisms of microplastics trapping in river sediments: Insights from the Arno River (Tuscany, Italy). *STOTEN* **866**, 161273 (2023).
45. Francalanci, S., Paris, E., Solari, L., Minatti, L. & Federici, G. V. Monitoring sediment transport during floods in Tuscany. *Eng. Geol. Soc. Territory* **3**, 335–337 (2015).
46. Prajapati, A., Narayan Vaidya, A. & Kumar, A. R. Microplastic properties and their interaction with hydrophobic organic contaminants: A review. *Environ. Sci. Pollut. Res.* **29**, 49490–49512 (2022).
47. Safar, Z. Suspended Particulate Matter Formation and Accumulation in The Delta: From Monitoring to Modelling. *PhD thesis*. (Delft University of Technology, 2022).
48. Falorca, I. M. C. F. G. & Pinto, M. I. M. Effect of short, randomly distributed polypropylene microfibres on shear strength behaviour of soils. *Geosynth. Int.* **18**, 2–11 (2011).
49. Maggi, F. Flocculation dynamics of cohesive sediment. *PhD thesis*. (Delft University of Technology, 2005).
50. Liss, S. N., Liao, B. Q., Droppo, I. G., Allen, D. G. & Leppard, G. G. Effect of solids retention time on floc structure. *Water Sci. Technol.* **46**, 431–438 (2002).
51. Spencer, K. L. et al. A structure–function based approach to floc hierarchy and evidence for the non-fractal nature of natural sediment flocs. *Sci. Rep.* **11**, 14012 (2021).
52. Li, D. H. & Ganczarczyk, J. J. Stroboscopic determination of settling velocity, size and porosity of activated sludge flocs. *Water Res.* **21**, 257–262 (1987).
53. Droppo, I. G., Walling, D. E. & Ongley, E. D. The influence of floc size, density and porosity on sediment and contaminant transport. *Proceedings of a symposium held at Waterloo, Canada, IAHS*. 263 (2000).
54. Dean, D. J., Topping, D. J., Schmidt, J. C., Griffiths, R. E. & Sabol, T. A. Sediment supply versus local hydraulic controls on sediment transport and storage in a river with large sediment loads. *J. Geophys. Res. Earth Surf.* **121**, 82–110 (2016).
55. Rahman, M. & Ali, M. Potential causes of navigation problem in Pussur River and interventions for navigation enhancement. *Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development*. (ICCSD, 2018).
56. Toonen, W. H. J., Kleinhans, M. G. & Cohen, K. M. Sedimentary architecture of abandoned channel fills. *Earth Surf. Process. Landforms* **37**, 459–472 (2012).
57. Larsen, L. G., Harvey, J. W. & Crimaldi, J. P. Morphologic and transport properties of natural organic floc. *Water Resour. Res.* <https://doi.org/10.1029/2008WR006990> (2009).
58. Thrush, S. et al. Muddy waters: Elevating sediment input to coastal and estuarine habitats. *Front. Ecol. Environ.* **2**, 299–306 (2004).
59. Bastos da Silva, M. J., Fontoura, J. A. S., Correa, I. C. S. & Serpa, C. G. Sedimentation processes in the navigation channel of Patos Lagoon Estuary, southern Brazil. *Reg. Stud. Mar. Sci.* **61**, 102931 (2023).
60. Wu, N., Grieve, S. W. D., Manning, A. J. & Spencer, K. L. Flocs as vectors for microplastics in the aquatic environment. *Nat. Water.* **2**, 1082–1090 (2024).
61. Bellasi, A. et al. Microplastic contamination in freshwater environments: A review, focusing on interactions with sediments and benthic organisms. *Environments* **7**, 30 (2020).
62. Burns, E. E. & Boxall, A. B. A. Microplastics in the aquatic environment: Evidence for or against adverse impacts and major knowledge gaps. *Environ. Toxicol. Chem.* **37**, 2776–2796 (2018).
63. Kooi, M. & Koelmans, A. A. Simplifying microplastic via continuous probability distributions for size, shape, and density. *Environ. Sci. Technol. Lett.* **6**, 551–557 (2019).
64. Liu, J., Yang, Y., Ding, J., Zhu, B. & Gao, W. Microfibers: A preliminary discussion on their definition and sources. *Environ. Sci. Pollut. Res.* **26**, 29497–29501 (2019).
65. Monnanni, A. et al. Microplastics and microfibers contamination in the Arno River (Central Italy): Impact from urban areas and contribution to the Mediterranean Sea. *Sci. Total Environ.* **955**, 177113 (2024).

66. Mietta, F., Chassagne, C., Manning, A. J. & Winterwerp, J. C. Influence of shear rate, organic matter content, pH and salinity on mud flocculation. *Ocean Dyn.* **59**, 751–763 (2009).
67. Shakeel, A., Safar, Z., Ibanez, M., van Paassen, L. & Chassagne, C. Flocculation of clay suspensions by anionic and cationic polyelectrolytes: A systematic analysis. *Minerals* **10**, 999 (2020).
68. Nan, J., Wang, Z., Yao, M., Yang, Y. & Zhang, X. Characterization of re-grown floc size and structure: Effect of mixing conditions during floc growth, breakage and re-growth process. *Environ. Sci. Pollut. Res.* **23**, 23750–23757 (2016).
69. Rau, M. J., Ackleson, S. G. & Smith, G. B. Effects of turbulent aggregation on clay floc breakup and implications for the oceanic environment. *PLoS One* **13**, e0207809 (2018).
70. NEN 6484. *Water: Determination of the content of not dissolved material and its ignition residue*. (1982).
71. Mishra, A. K., Singh, J. & Mishra, P. P. Microplastics in freshwater ecosystem: A serious threat for freshwater environment. *Int. J. Environ. Sci. Technol.* **20**, 9189–9204 (2023).
72. Uguagliati, F., Zattin, M., Waldschläger, K. & Ghinassi, M. Optimising microplastic polyethylene terephthalate fibre extraction from sediments: Tailoring a density-separation procedure for enhanced recovery and reliability. *STOTEN* **957**, 177483 (2024).
73. Ali, W., Kirichek, A. & Chassagne, C. Flocculation of deep-sea clay from the Clarion Clipperton Fracture Zone. *Appl. Ocean Res.* **150**, 104099 (2024).
74. Manning, A. J., Friend, P. L., Prowse, N. & Amos, C. L. Estuarine mud flocculation properties determined using an annular mini-flume and the LabSFLOC system. *Cont. Shelf Res.* **27**, 1080–1095 (2007).
75. MacIver, M. R. *Safas: sedimentation and floc analysis software*. <https://github.com/rmaciver/safas> (2023).
76. Ali, W., Enthoven, D., Kirichek, A., Chassagne, C. & Helmons, R. Effect of flocculation on turbidity currents. *Front. Earth Sci.* <https://doi.org/10.3389/feart.2022.1014170> (2022).

Acknowledgements

This project was carried out with the support of Enel Green Power under the project titled: “Riconoscimento, quantificazione e modelli di distribuzione di microplastiche in sedimenti fluviali”. The authors gratefully acknowledge this support. F.U. also wishes to thank the Fondazione Ing. Aldo Gini for making this research possible through the award of a scholarship.

Author contributions

F.U.: Writing—original draft, Investigation, Formal analysis, Data curation, Conceptualisation, Methodology. A.W.: Writing—review & editing, Formal analysis, Conceptualisation, Methodology. C.C.: Writing—review & editing, Conceptualisation. K.W.: Writing—review & editing, Conceptualisation. M.Z.: Writing—review & editing, Conceptualisation, Project administration. M.G.: Writing—review & editing, Conceptualisation, Resources, Project administration.

Supplementary Information

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-026-52867-z>.

Correspondence and requests for materials should be addressed to F.U.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026