Shifting settling regimes of aquatic microplastics

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Abstract

Rivers are the major conveyor of plastics to the marine environment, but the mechanisms that impact microplastic (<5mm) transport, and thus govern fate of the material in the environment, are largely unknown. This prevents progress in understanding microplastic dynamics and identifying zones of high accumulation, as well as curtailing the evolution of effective mitigation and policy measures. Using a suite of novel settling experiments here we show, for the first time, how biofilm growth significantly increases settling velocity of a range of microplastics (fragments and fibres) by >130% and that significant increases can occur in only days. We also demonstrate how these impacts are both polymer and shape specific and that settling regimes also differ according to both salinity and sediment concentrations, which are typical of freshwater-marine boundaries found in estuaries. Our results demonstrate how existing transport formulae are inadequate to capture these impacts and highlight the importance of considering these processes within next generation predictive frameworks to understand and robustly predict the fate and impact of microplastic pollution within aquatic environments.

Introduction and Context

Estimates of plastic flux entering the ocean annually vary between 4.8 to 12.7 million metric tons, while floating marine plastic is calculated to be only 268,940 tons, accounting for just 2-6% of the estimated plastic entering aquatic systems every year\textsuperscript{1,2}. Land-based sources such as mismanaged waste, have resulted in rivers becoming a major pathway for plastic pollution to enter the marine environment\textsuperscript{1,3}. Yet, as microplastics (<5mm), move through a river basin and transfer to the marine environment, they will undergo a range of environmental gradients and physical, biological and chemical transitions, including changes
in salinity and sediment concentrations. Additionally, weathering and biofilm growth will also impact the vertical distribution of microplastics through the water column.

The likelihood that a given microplastic particle will settle out of suspension when entering an aquatic system varies depending on the physicochemical, hydrodynamic and biological conditions of the environment. First, microplastic distribution is dependent on the polymer properties (density, shape, size, etc.), but as subsequent growth of surficial biofilm occurs within minutes to hours of entering an aquatic system (Fig. 1) the microplastic density can change rapidly. This results in alterations to particle buoyancy and thus relative density to the ambient fluid, which has considerable implications in varying a particle’s trajectory in the water column. In addition, with surficial biofilms, microplastic particles can also become parts of hetero-aggregates (or flocs), which includes other naturally suspended sediment. The development of flocs, and further associated changes in density and particle size, is known to affect the settling velocity of particles. While silts and clays that undergo flocculation are typically 0.06 mm or smaller in size, flocculation can occur at larger grain sizes, including sand. The impact of floc formation on microplastic distribution, settling and fate is currently unquantified.

Changes in salinity and suspended sediment that occur across a freshwater-marine boundary is known to affect the development of flocs and thus overall settling velocity of particles, especially as the relative density of the particle changes as it moves into denser saline water. As water becomes more saline (and water density increases), particles are likely to stay suspended within the water column. Settling velocity is thus a key parameter used to predict sediment transport pathways, yet no comprehensive study has yet experimentally quantified these effects (biofilm, salinity and sediment concentration) for microplastics (extended data, table 1).

Here, we experimentally quantify how microplastic settling velocities vary through time as a function of biofilm growth and as they transition from freshwater to saline conditions typically found in estuarine environments. Using high-resolution measurements of particle settling
velocities, we demonstrate how biofilm growth and changes in salinity impact microplastic settling velocities, and show how these impacts are polymer and shape specific. Furthermore, our analysis reveals that widely applied sediment transport formulae\cite{33-36} are inaccurate for predicting microplastic fate and transport; microplastic interactions with- and relative density changes due to biofouling, as well as salinity and sediment concentration changes, are not well-constrained for microplastics in sediment transport laws.

**Biofilm and particle shape impacts**

To evaluate the controlling factors that influence microplastic transport, a series of settling experiments measuring particle settling velocity (see full Methods for details) were conducted; testing fragment and fibre polymer types and shapes, the impact of biofouling, salinity, and suspended sediment concentrations on settling velocity. Comparisons were
made between clean and biofilmed particles under varying salinity and clay concentrations to understand the effects of biofouling under different conditions. The impacts of salinity and clay concentrations were also evaluated for clean and biofilmed particles separately. Comparisons were considered significant when p < 0.05 and are summarised in the extended data. Biofilm time trials were also conducted to understand how quickly the impacts of biofilms on settling velocities are realised. Biofilm growth had the greatest impact on microplastic settling across all salinities and clay concentrations and increased the settling velocity on average by 40%. The magnitude of this change was different between polymer types (see extended data Table 2 for statistical summary). Settling velocity increased significantly between the clean and biofilmed PET at all salinities (ppm, SAL): by 73% at SAL 0, 29% at SAL18 and 55% at SAL30, and all clay concentrations: 83% at 0mg, 27% at 100mg, 67% at 400mg and 64% at 600mg clay (Fig. 2a). However, for PVC fragments, the significant increase in velocity between clean and biofilmed particles was seen for fewer scenarios: 25% at SAL30, 13.5% at 0mg and 68% at 600mg clay (Fig 2b). There was also a reduced effect of biofouling on nylon, polyester and acrylic (NP&A) fibres with a significant increase in settling velocity observed for two scenarios: 55% at SAL30 and 132% at 400mg clay (Fig. 2c).

Biofilm growth causes microplastics to settle faster due to an increase in particle specific density, not area (Extended data Fig.1-3), which has been observed before\(^4,29,37–39\). Biofouling was expected to cause microplastics to become stickier and form flocs, leading to an observable increase in particle size\(^40\), yet this was not seen. Previous studies have shown that the growth of biofilms and consequent hetero-aggregate formation is highly dependent on microplastic polymer chemical nature (polymer type)\(^12\). Polypropylene (PP) fragments are more likely to form heteroaggregates with freshwater algae compared to high-density polyethylene (HDPE), potentially due to different types of biofilm (EPS) being produced\(^12\). The chemical composition and surface texture of PET is also likely to have provided a preferred medium for microbes to grow on compared to PVC and NP&A fibres.
Compared to PET and PVC fragments, NP&A fibres were far less impacted by biofilm colonisation, likely due to their shape.

The impacts of biofilms on microplastic settling velocity occur quickly and is typically less than a week, as demonstrated by our time trials (see methods): PET fragments were biofouled and settling velocity measured over 0-8 weeks (Fig. 3). Settling velocity increased considerably by week 1 with average settling velocity of PET fragments being 16.85 ± 0.92 mm s\(^{-1}\) (± values represent standard error) at week 0 (clean), increasing to 29.38 ± 1.16 mm s\(^{-1}\) at week 1 and 36.67 ± 1.95 mm s\(^{-1}\) at week 2. In fact, biofilm growth significantly

**Figure 2: Main effects plot of condition, salinity and clay concentration on a) PET b) PVC and c) NP&A fibre microplastics. Solid lines indicate mean plots, while the shaded areas indicate confidence bands for all points within the range of data. Note that for c) the scale range is smaller as settling velocity was considerably lower for NP&A fibres.**
impacted PET settling velocity from week 0 to week 1 (p<0.001), week 2 (p<0.001), week 4 (p<0.001) and week 8 (p<0.001) and between week 1 and week 2 (p=0.04). This demonstrates how the dynamics of microplastics settling rates are fundamentally controlled by time; the longer a particle is exposed to biologically active aquatic environments, the more the particle properties will change.

Microplastic settling behaviour changes across the freshwater-marine salinity gradient

Our results reveal that microplastic settling velocity is influenced by changes in salinity and sediment concentration (Fig. 2) that would be experienced as microplastic particles cross the freshwater-marine boundary. It is clear that multiple environmental and biological conditions need to be considered when predicting microplastic transport. For clean PET fragments, settling velocity was significantly higher at SAL18 (15.8 mm s\(^{-1}\) ± 0.54), compared to SAL0.
(13.1 mm s\(^{-1}\) ± 0.40) and SAL30 (12.7 mm s\(^{-1}\) ± 0.49). However, for biofouled particles, settling velocity was considerably higher at SAL0 (22.74 mm s\(^{-1}\) ± 0.76) compared to SAL30 (19.68 mm s\(^{-1}\) ± 0.67). The influence of salinity was much more varied for PVC fragments, with clean particles settling rates significantly lower at SAL30 (17.67 mm s\(^{-1}\) ± 0.78) compared to SAL0 (24.90 mm s\(^{-1}\) ± 1.10) as expected. Biofilmed PVC fragments settled significantly faster at SAL0 (25.67 mm s\(^{-1}\) ± 0.98) compared to SAL18 (23.05 mm s\(^{-1}\) ± 0.97) but a lesser effect on settling velocity was observed due to salinity under these conditions. Finally, no significant effect on settling rate due to salinity was observed for NP&A fibres.

Polymer-specific salinity impacts have been shown previously, with higher salinity leading to lower settling velocities for certain polymers\(^{41}\). Salinity lowers settling velocity for polystyrene (PS) particles, yet for higher density polymers such as PET and PVC salinity had less of an impact \(^{31}\). Conversely, Wang et al., (2021)\(^{42}\) described how an increase in salinity only had minor impacts on PET but showed impacts on PVC, lowering the settling velocity. This is similar to our results, especially clean PET and PVC particles, with salinity having much more impact on clean PVC fragments compared to PET. However, our results show the much greater impact of biofilm growth on these relationships. As NP&A fibres have a lower density, a decrease in settling due to increase in salinity was expected, yet this was not seen perhaps due to the shape and surface area of fibres compared to spheres and fragments. These results indicate that the settling regimes for microplastics change as they move from a freshwater to marine environment, altering ecological risk and that these changes must be considered when sampling and predicting the transport and fate of microplastics within these environments.

Within the suspended sediment experiments, aggregation of microplastics and kaolinite was not observed as particle size did not increase (see extended data). However, settling velocity was still impacted. For PET and PVC fragments, overall settling decreased with higher sediment concentrations but for NP&A fibres the impacts were more variable (Fig. 2). Again, patterns differed between polymers and whether microplastics were
biofouled or not. Settling velocity remained similar for clean PET particles across all sediment concentrations and significant changes in settling velocity only occurred for biofilmed PET fragments, with highest settling rates at 0 mg (26.60 mm s\(^{-1}\) ± 1.21) and statistical significance between 0mg and 100 mg (19.50 mm s\(^{-1}\) ± 0.93) and 600 mg (21.73 mm s\(^{-1}\) ± 1.25). For clean PVC, settling rates were considerably higher at 0 mg (25.28 mm s\(^{-1}\) ± 0.77), compared to 400 mg (14.73 mm s\(^{-1}\) ± 0.81) and 600 mg (14.04 mm s\(^{-1}\) ± 1.00). For PVC, the highest settling rate was also observed at 0 mg for biofilmed PVC fragments (28.69 mm s\(^{-1}\) ± 1.13) compared to 100 mg (21.66 mm s\(^{-1}\) ± 1.06), 400 mg (21.12 mm s\(^{-1}\) ± 1.25) and 600 mg (23.60 mm s\(^{-1}\) ± 1.09). The decrease in settling velocity of PET and PVC fragments with clay mixing was unexpected. The surface properties of microplastics, such as charge and friction will play an important role in how they are transported\(^{43}\). The mixing of kaolinite and microplastics may have caused abrasion (extended data Fig.4) and also likely increased the drag of the particles, lowering their settling velocity. Also, the drag coefficient may have increased due to a small amount of clay attaching to the particles. Flocs may have also formed in the mixing procedure but as the rate of aggregation strength of flocs depends on electrical charge of particles, perhaps the forces between particles here were weak and caused flocs to break down during transfer or deposition in the settling column\(^{21}\), or the electrochemical forces between clay and polymer particles are not as strong and need to be studied further. For NP&A fibres, the impact of clay concentration was very different compared to the other polymers. The highest settling occurred at 100 mg for clean NP&A fibres, (7.20 mm s\(^{-1}\) ± 0.48) but was only significantly different to 400 mg (3.76 mm s\(^{-1}\) ± 0.22). However, for biofilmed NP&A fibres, settling rate was highest at 400 mg (8.44 mm s\(^{-1}\) ± 1.01) and lowest at 0 mg (3.25 mm s\(^{-1}\) ± 0.46) with significant differences between 0 mg and 100 mg (5.90 mm s\(^{-1}\) ± 0.51), 400 mg (8.73 mm s\(^{-1}\) ± 1.02) and 600 mg (7.12 mm s\(^{-1}\) ± 0.70). Kaolinite particles have been observed to adsorb onto the surface of polystyrene latex microspheres 1μm in diameter which may have occurred here, increasing density and settling, yet overall particle size/area was not altered significantly\(^{44}\). It should be noted that some fibres did clump (extended data, Fig.5) and this made calculation of settling difficult,
which may have impacted the results. Fibres may clump and tangle in turbulent conditions, so this should be considered for future studies. No PET or PVC particles were observed to clump together in this way.

**Comparison with empirical predictions**

It has been argued that microplastics in aquatic systems will behave in a way that is comparable to natural sediment and therefore microplastic fate can be predicted using the same methods available for natural particles. To assess this we compare our results to a widely applied universal sediment transport formula that resolves Stoke’s Law for fine grained sediment transport and turbulent fluid motion for larger grains to determine grain settling velocity (see methods). The theoretical settling velocity was calculated to be much higher compared to both clean and biofilmed experimental results for all sizes of PET (Fig. 4a). Any models using this formula will over-predict settling of PET microplastics resulting in a greater microplastic load in suspension than would be expected. For PVC microplastics, the formula both over and under-predicted settling velocities depending on particle size (Fig. 4b). Sediment equations could be used if the microplastics have hydraulically equivalent physical properties, however microplastics exist in a much wider range of shapes than natural sediment grains. The expected values were very different for observed fibre settling probably due to this reason (extended data). Despite Waldschläger and Schüttrumpf’s development of a new formula for settling of microplastics, we were unable to make comparisons using their predictions as they rely on needing 3-axis dimensions for individual particles and do not consider the impacts of biofouling, which we have shown as a first order control. Indeed, our physical experiments highlight the need for a new generation of transport formulae that consider irregular microplastic shapes, biofouling and the high sensitivity to changes in salinity.
Currently, the mechanisms that control microplastic transport and fate are poorly understood, which hinders our ability to manage and protect aquatic environments. Here we demonstrated that biofouling is a first order control on the settling velocity of microplastic, with impacts observed over only a few days. The effect varies by polymer type and ambient conditions (salinity/clay concentration), and evolves in time. This highlights that the changes in microplastic settling regimes from a riverine to marine environment must be appreciated to precisely predict microplastic fate and the formation of any high concentrations zones in the environment. Furthermore, while available sediment transport formulae might be useful for basic plastic transport predictions, we show they are largely inaccurate and must be urgently updated to incorporate these key factors into the predictive framework, particularly biofouling effects and time functions. This will ensure that our ability to model microplastic transport and fate in the environment is more accurate, allowing enhanced monitoring and sampling campaigns and future assessments of ecological impact of plastics through the freshwater-marine transition.

Figure 4: Expected settling velocity calculated using Ferguson and Church (2004) compared to our observed experimental values for clean and biofilmed microplastics of a) PET and b) PVC. Marginal histograms indicate the distribution of velocity and equivalent diameter data. Smaller particles were analysed during the experiments, especially for PVC fragments.
The settling velocity of the microplastic particles was determined through a series of non-intrusive sinking experiments conducted in a Laboratory Spectral Flocculation Characteristics (LabSFLOC) plexiglass column with dimensions of 12cm x 12cm x 33cm (Fig. 5, analogous to previous settling velocity experiments\textsuperscript{21,28–30,32,49}). The LabSFLOC settling column is combined with a LED light panel and high-resolution video camera (Fig.5) that collects particle settling video data that is processed to understand size, shape and velocity of individual particles and flocs. This is the first time a LabSFLOC water column has been used for microplastic settling experiments and allows individual particles to be easily analysed for their settling behaviour and aggregation. It is comparable to previous microplastic settling experiments that have utilised similar water columns.

The LabSFLOC water column was filled with distilled water of salinities ranging from SAL0-30 to represent the change in salinity from a freshwater to marine environment. Distilled water was utilised to ensure no impurities were impacting microplastic transport. Water temperature and pH was recorded at least 15 minutes before each experimental run and immediately after to ensure consistency. Fifteen minutes allows the water column to settle after any disturbances caused by measuring temperature and pH\textsuperscript{30}. Before each experiment, microplastics were immersed in water of the same salinity and temperature used in the experimental water column in glass petri dishes to ensure no electrostatic discharge from particles, which may prevent or alter sinking behaviour\textsuperscript{29}. For clean and biofilmed particles, microplastics were placed 0.01 m below the water surface of the LabSFLOC to prevent any restraint caused by surface tension and left to move freely. For microplastics that were being tested under different sediment concentrations, a glass pipette was utilised for transferring particles so not to disturb any formed flocs.

A series of images were taken of the particle movement. At least 100 particles per condition
were recorded for PET and PVC experimental series. However for fibres, particles tended to clump together which made analysis of movement difficult. Therefore at least 10 particles were recorded per variable for fibre analysis. Particles travelled at least 15cm before image recording took place to ensure microplastics had reached terminal settling velocity. This distance was chosen in accordance with measurements from other studies\textsuperscript{30–32}. For each polymer (PET, PVC and NP&A fibres), measurements were taken for clean and biofilmed particles under 3 salinities (SAL0, 18 and 30) and 3 sediment concentrations (100 mg, 400 mg and 600 mg), resulting in 54 scenarios. Finally, to assess the impact of biofilm growth on settling velocity, measurements were taken at 0,1,2,4 and 8 weeks for biofilmed PET fragments at SAL18. Images were analysed using a self-developed code in Matlab (R2020a)\textsuperscript{50}, see supplementary information. Particle detection was made using the ‘imbinarize’ function available in Matlab, using global thresholding\textsuperscript{51} or adaptive thresholding\textsuperscript{52} depending on image characteristics. Particle properties, including area, were obtained using the 'regionprops' function. The velocities were obtained with self-developed cross-correlation based Particle Tracking Velocimetry (PTV) routines.
Figure 5: Schematic of the Laboratory Spectral Flocculation Characteristics (LabSFLOC)

*experimental setup:* Pexiglass column of height 33 cm with a square cross section of 12 x 12 cm, filled with deionised water of varying salinities.

**Statistical analysis**

To understand the effects of microplastic condition (clean or biofilmed), salinity and clay concentration on settling velocity of microplastics, the combined interactions of [condition and salinity] and [condition and clay concentration] were assessed using generalised least square means analysis. All statistical analysis was conducted using R Studio (R Core Team, 2013). Interactions were considered statistically significant if $p < 0.05$. Post hoc analysis was conducted using the lsmeans package, Tukey adjusted to understand significant differences between the least-squares means of specific variables by fitting linear models. For biofilm growth analysis from 0-8 weeks, two-way ANOVAs were utilised after square root transformation to ensure equal variance (verified with Levene Test) and Tukey post hoc analysis.
Comparison to settling velocity predictions and formulae

As settling of microplastics has been related to the transitional flow regime, the formula of Ferguson and Church (2004) for smooth, varied and angular grains was chosen for comparison of measured settling velocities:

\[
 w = \frac{RgD^2}{C_1 v + (0.75C_2 RgD^3)} 
\]  (1)

Where \( w \) denoted the particle's settling velocity, \( R \) its submerged specific gravity, \( g \) the acceleration due to gravity, \( D \) its diameter, \( v \) the kinematic viscosity of the fluid and where \( C_1 \) and \( C_2 \) are constants with changing empirical values depending on the type of particle as described by Ferguson and Church. For our comparisons shown in Fig. 4, the values angular grains were utilised where \( C_1 = 24 \) and \( C_2 = 1.2 \). The measurements from the experiments and theoretical predictions were plotted in terms of settling velocity and equivalent diameter (\( D_e \)). This is to determine whether settling predictions of microplastics using formula based on sediment dynamics is applicable for microplastic transport.

Extended data
Table 1: Overview of previous microplastic settling experiments

<table>
<thead>
<tr>
<th>Source</th>
<th>Setup</th>
<th>Polymer(s)</th>
<th>Particle size range (mm)</th>
<th>Shape</th>
<th>Clean/Biofilm</th>
<th>Sinking rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagaev et al (2017)</td>
<td>50ml glass vial filled with distilled water, time taken for particle to sink 20cm measured with a stopwatch</td>
<td>Synthetic fibres, taken from field samples</td>
<td>N/A for all tested by uses 0.0mm as an example</td>
<td>fibres</td>
<td>Biofilm (field samples)</td>
<td>0.9 ± 0.8 mm/s.</td>
</tr>
<tr>
<td>Ballent et al (2012)</td>
<td>1m saltwater (36) column and video analysis</td>
<td>Non-buoyant High density preproduction (not specified)</td>
<td>~5.0</td>
<td>Pellets (spheres)</td>
<td>Unspecified (from a sample)</td>
<td>28 mm/s</td>
</tr>
<tr>
<td>Hoellein et al (2019)</td>
<td>Experimental stream: mean width 48 cm (±1.8) and depth of 3.7 cm (±0.2), lined with a substrate of uniformly-sized pea gravel (D50 = 0.5 cm) with constant discharge 1.45 L/s.</td>
<td>PP, PS, Acrylic</td>
<td>1.0-3.0</td>
<td>Pellets , fragments, fibres</td>
<td>Clean and biofilmed</td>
<td>0.61 (±0.48) mm/s.</td>
</tr>
<tr>
<td>Kaiser et al (2017)</td>
<td>Allergberg cylinders of 40 cm height and 7.5 cm internal diameter at a temperature of about 20 °C. Particles rested in water over night. Time taken to travel 2 x 10cm distance was measured</td>
<td>PS &amp; PE</td>
<td>1.0</td>
<td>Cylindrical</td>
<td>Clean and biofilmed</td>
<td>0.0059-0.017m s⁻¹</td>
</tr>
<tr>
<td>Khatmullina &amp; Isachenko (2017)</td>
<td>Glass column filled with distilled water with stopwatch</td>
<td>Polycaprolactone (PCL) &amp; aged fishing line</td>
<td>0.15-0.71</td>
<td>Spheres, cylinders &amp; fibres?</td>
<td>Clean</td>
<td>5-127mm/s</td>
</tr>
<tr>
<td>Kowalski et al (2016)</td>
<td>1m settling column of saltwater salinity 36. Aggregates (MP + diatom cells + river sediment) photographed every 2 seconds for 60 minutes.</td>
<td>PS, PA, polymethyl methacrylate (PMMA), PET, polycyemethylene (PDM, PVC)</td>
<td>0.3-2.6</td>
<td>Cylindrical, nodular, angular, think flakes, elongate</td>
<td>&quot;Non-aged&quot; (clean)</td>
<td>91 × 10⁻³ ms⁻¹</td>
</tr>
<tr>
<td>Mohlenkamp et al (2018)</td>
<td>1m settling column of North Sea water salinity 34.</td>
<td>Microbeads (polymer not specified) from cosmetics</td>
<td>0.022-1.589</td>
<td>Spherical, elliptical</td>
<td>Clean</td>
<td>53-559m d⁻¹</td>
</tr>
<tr>
<td>Waldschlaeger et al (2019)</td>
<td>Plexiglass water column with settling and rising velocity observed filled with DI water with digital camera</td>
<td>PE, PP, PS (EPS), PVC, PET, and PP&amp;A-fibers</td>
<td>0.3-5.0</td>
<td>Fibres, pellets</td>
<td>Clean</td>
<td>3.9-314mm/s</td>
</tr>
</tbody>
</table>

Table 2: Summary of statistical analysis (post hoc analysis with Imeans package, Tukey adjusted) between all variables and microplastic types

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Microplastic type</th>
<th>PET</th>
<th>PVC</th>
<th>NP&amp;A fibres</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BIOFOULING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean vs Biofilm SAL0</td>
<td>p=0.001</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean vs Biofilm SAL18</td>
<td>p=0.001</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean vs Biofilm SAL30</td>
<td>p=0.001</td>
<td>p&lt;0.001</td>
<td>p=0.0116</td>
<td></td>
</tr>
<tr>
<td>Clean vs Biofilm 0mg</td>
<td>p&lt;0.0001</td>
<td>p&lt;0.001</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean vs Biofilm 100mg</td>
<td>0.0215</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean vs Biofilm 400mg</td>
<td>0.0001</td>
<td>-</td>
<td>-</td>
<td>p&lt;0.0001</td>
</tr>
<tr>
<td>Clean vs Biofilm 600mg</td>
<td>0.0001</td>
<td>p&lt;0.001</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>SALINITY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean SAL0 vs Clean SAL18</td>
<td>p=0.0108</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean SAL0 vs Clean SAL30</td>
<td>-</td>
<td>p=0.301</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean SAL18 vs Clean SAL30</td>
<td>p=0.0084</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Biofilm SAL0 vs Biofilm SAL18</td>
<td>-</td>
<td>p=0.0167</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Biofilm SAL0 vs Biofilm SAL30</td>
<td>p=0.0089</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Biofilm SAL18 vs Biofilm SAL30</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td><strong>CLAY CONCENTRATION</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean 0mg vs 100mg</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean 0mg vs 400mg</td>
<td>-</td>
<td>p=0.0142</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean 0mg vs 600mg</td>
<td>-</td>
<td>p&lt;0.001</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean 100mg vs 400mg</td>
<td>-</td>
<td>-</td>
<td>p&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Clean 100mg vs 600mg</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Clean 400mg vs 600mg</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Biofilm0mg vs 100mg</td>
<td>p=0.0001</td>
<td>p=0.0001</td>
<td>p=0.0058</td>
<td></td>
</tr>
<tr>
<td>Biofilm0mg vs 400mg</td>
<td>-</td>
<td>p&lt;0.0001</td>
<td>p=0.0001</td>
<td></td>
</tr>
<tr>
<td>Biofilm0mg vs 600mg</td>
<td>p=0.0270</td>
<td>p=0.0181</td>
<td>p=0.0008</td>
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<tr>
<td>Biofilm100mg vs 400mg</td>
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<tr>
<td>Biofilm100mg vs 600mg</td>
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<tr>
<td>Biofilm400mg vs 600mg</td>
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</table>
Figure 1: The settling velocity of clean and biofilmed PET fragments a) under different salinities from SAL0-30, b) various sediment concentrations from 0-600mg/L and c) verses particle area under all salinity and clay conditions.
Figure 2: The settling velocity of clean and biofilmed PVC fragments a) under different salinities from SAL0-30, b) various sediment concentrations from 0-600mg/L and c) versus particle area under all salinity and clay conditions.
Figure 3: The settling velocity of clean and biofilmed fibres a) under different salinities from SAL0-30, b) various sediment concentrations from 0-600mg/L and c) verses particle area under all salinity and clay conditions.
Figure 4: Clean PET fragment after clay mixing

Figure 5: Example of fibres clumping together: clean, SAL30, 600mg clay
References


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**Supplementary Information**

Please find attached pdf.
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SettlingMPsCode.pdf