Modelling and Application of Dissolved Air Flotation for Efficient Separation of Microplastics from Sludges and Sediments

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Introduction

The longevity of plastics, which makes them a widely used material in our society, is disadvantageous once introduced into the environment. Rather than decomposing, plastics will become smaller by physical, chemical and biological processes(Akdogan and Guven, 2019). In addition, sludge streams containing microplastics are formed during the mechanical recycling of plastic waste (Go et al., 2022; Guo et al., 2022) and in wastewater treatment plants (Cheng et al., 2021; Horton and Dixon, 2018; Tang, 2023; Ziajahromi et al., 2021). The presence of microplastics in the environment poses a variety of concerns. For example, microplastics floating on the aquatic surface reduce light penetration to the underlying aquifers (Arthur et al., 2009), and the accumulation of microplastics on the seabed can inhibit gas exchange between the surface water and interstitial water of the sediments and hinder the oxygen transfer (Zeng et al., 2008). Furthermore, microplastics have been detected in the stomachs, intestines, and tissues of more than 690 animal species (Provencher et al., 2017). The provided non-exhaustive compilation of environmental concerns associated with the presence of microplastics underscores the imperative to extract these particles from the environment, encompassing sludges and sediments. This is, however, a complicated endeavor.

Unfortunately, many techniques are not industrially relevant for the separation of microplastics and sediment; for example, it is not possible to separate them based on particle size due to the overlapping range (Akdogan and Guven, 2019; Crawford and Quinn, 2017). Sedimentation is also not industrially relevant due to the range of particle sizes, combined with the range of densities (Spellman, 2016). Flotation of microplastics with a dens medium is done in the laboratory, but is also industrially less relevant due, amongst others, to the high cost of the media (Cheng et al., 2021; Crawford and Quinn, 2017; Nabi et al., 2022). Consequently, Dissolved Air Flotation (DAF) is one of the few applicable techniques that is capable of separating microplastics by flotation. Here the air bubbles attach to the more hydrophobic microplastics, and not to the hydrophilic sediment particles (Lesaine, 2018; Van Melkebeke et al., 2020; van Oss, 2006). Consequently, the microplastics will float and the sediment particles will sink and thus be separated.

Several models have already been developed to describe the bubble-particle attachment in the contact zone of a DAF (Edzwald, 2010; Fukushi et al., 1995; Tambo et al., 1986; Tambo and Watanabe, 1979). These models typically use various system properties, such as bubble size, particle size and densities, to describe the attachment. However, these models consistently rely on the bubble-particle attachment efficiency as the only empirical factor, necessitating experiments to determine this factor before it is possible to dimension a DAF unit. In this study, an empirical and semi-deterministic model based on the Extended Derjaguin-Landau-Verwey-Overbeek (XDLVO) theory was established to predict the attachment efficiency of bubbles and microplastics in water. This involved a Design of Experiments (DoE) to generate a data set, considering various polymer types, solid loads, particle sizes and air flow rates, using the White-Water Blanket Model (WWBM) to determine the corresponding experimental bubble-particle attachment efficiencies. The potential descriptors for the attachment of air bubbles and particles were examined in literature and subsequently considered during the establishment of predictive models by partial least squares (PLS) and multiple linear regression (MLR). Finally, a case study was performed on an industrial sludge fraction from a plastic recycling facility, to assess the developed models and demonstrate their applicability to support industrialization of froth flotation as cleaning technique for contaminated sediments and sludges.

Materials and methods

The establishment of the predictive models involved a series of successive steps. In this process, microplastics were first created and characterized. Therefore, commercially available rigid plastic packaging was purchased in polyvinylchloride (PVC), high-density polyethylene (HDPE), polyethylene terephthalate (PET), polystyrene (PS) and polypropylene (PP). Besides, flexible low-density polyethylene (LDPE), being garbage bags, and ethylene propylene diene monomer (EPDM) rubber, a widely used material with different properties than the previous polymers, were also used. Based on literature, it was determined which system and particle properties were expected to have an impact on the attachment efficiency. Since it was uncertain whether the presence of sediment and the solid load would have an impact, an initial screening was performed. Next, a Design of Experiments was generated and executed to create a diverse data set, each time determining the experimental attachment efficiency. After subjecting the resulting data to a correlation and outlier analysis, an empirical model using PLS regression, and a semi-deterministic model based on the XDLVO theory using MLR were established. These were validated and ultimately subjected to a case study on an industrial sludge fraction. First, the predicted attachment efficiency between air bubbles and the microplastics in the industrial sludge was validated. Next, it was demonstrated that a DAF can be dimensioned based on the predicted attachment efficiency.

Results

Our findings reveal that sediment does not undergo bubble attachment, and its presence does not impede the attachment of air bubbles to microplastics. Nevertheless, the solid load exerts a significant influence on attachment efficiency. Consequently, an empirical model is established by PLS, incorporating various parameters such as particle size, bubble size, density, Hamaker constant, contact angle, solid load, aspect ratio, circularity, and sphericity. The resulting model is able to describe the attachment efficiency with an MSPE of 0.011 and adjusted-R^2 of 0.64. Thereby, the coefficient plot indicated that bubble size, contact angle, density and Hamaker constant are the main predictors of the attachment efficiency.

Next, a semi-deterministic model, based on XDLVO theory, describing the attachment efficiency in terms of the natural logarithm of Van der Waals, electrostatic and hydrophobic forces on the potential barrier distance was established. This model was extended, including factors not considered by XDLVO theory, such as density, solid load and shape factors. Only solid load was found to be significant, resulting in an RSE of 0.067 and an adjusted R^2 of 0.63. From this model, it can be observed that an increase in solid load negatively affects the attachment efficiency, which can be attributed to the increased friction between the particles. On the other hand, it was shown that an increase in potential barrier promotes the attachment efficiency. Thereby, it was confirmed that aggregate stability is crucial in the separation of microplastics by froth flotation.

Finally, the models' applicability is validated through a case study on industrial sludge. Both the empirical and semi-deterministic models successfully predict the bubble-microplastic attachment efficiency, eliminating the need for case-specific experimental determinations. This modelling approach provides valuable insights into the potential and prerequisites of DAF as a viable technology for microplastics separation from sediments and sludges on a broader scale.

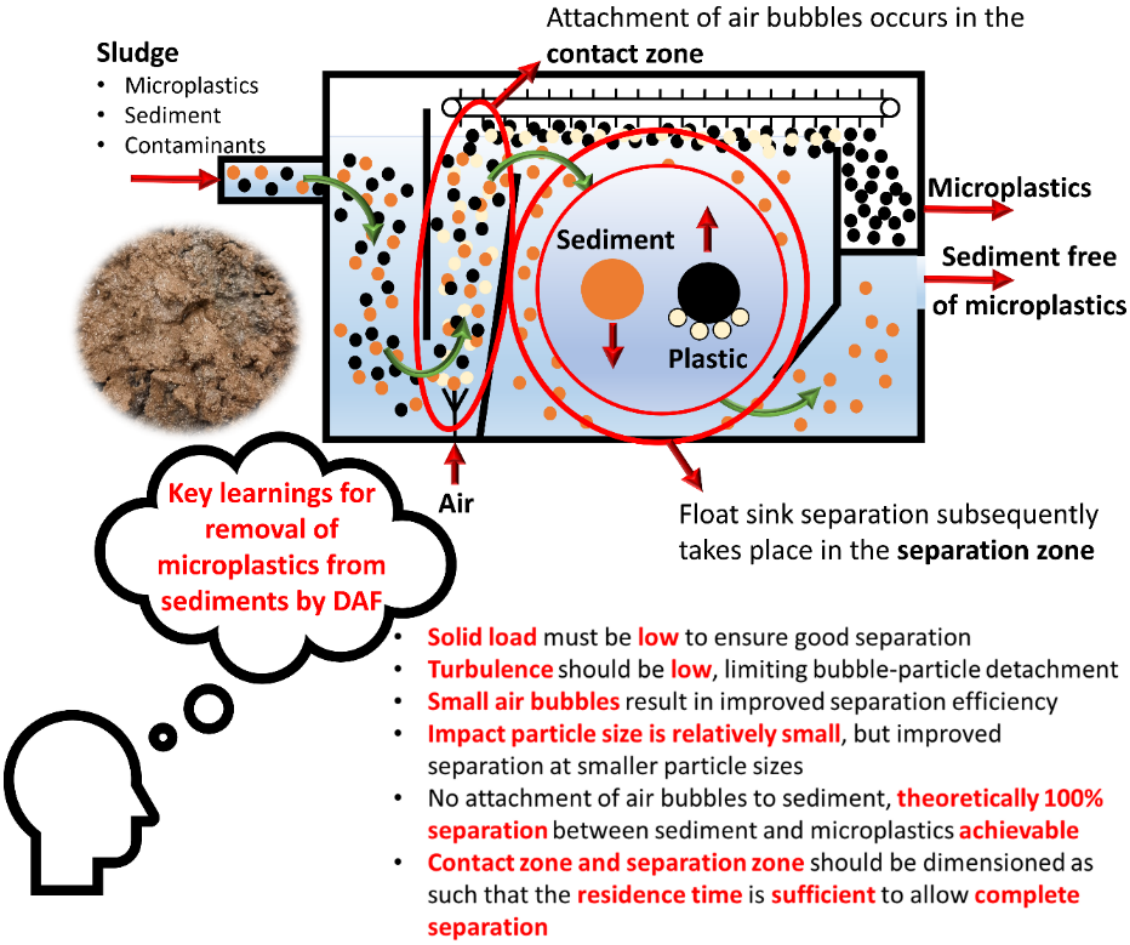

Figure 1: Key learnings for the application of Dissolved Air Flotation (DAF) as a technology to separate microplastics from sediment/sludge.

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