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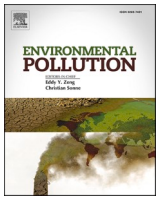

Review

# Suspension of micro- and nanoplastic test materials: Liquid compatibility, (bio)surfactants, toxicity and environmental relevance☆

Dónal van Uunen [a,1], Maria Kloukinioti [a,b,1], Ingeborg M. Kooter [a,b], Elena M. Höppener [a], Laurine E.A. Yoe [a], Andrea M. Brunner [a], Arjen Boersma [c], Luke A. Parker [a,*]

[a] TNO Environmental Modelling, Sensing and Analysis, Princetonlaan 6-8, 3584 CB, Utrecht, the Netherlands
[b] School of Nutrition and Translational Research in Metabolism (NUTRIM), Department of Pharmacology and Toxicology, Maastricht University Medical Center+, Maastricht, the Netherlands
[c] TNO Materials Solutions, HTC 25, 5656 AE, Eindhoven, the Netherlands

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ABSTRACT

Micro- and nanoplastics have been detected in environmental compartments from the highest mountains to the deepest seas. They have been shown to be present at almost all trophic levels, and within humans they have been detected in numerous organs and human stool. Whilst their ubiquitous nature is indisputable, little is known about the health risks they may present. Much current research is focussed on the production of test materials with which to perform the necessary health studies. An important aspect of this is the correct storage and suspension of the materials to ensure they remain stable both chemically and with regards to size and shape. In this review, we look at the chemical stability of nine common polymers in a range of liquids; first with the use of commercial compatibility charts and then with a more quantitative approach using Hansen solubility parameters. We then look at stability with regards to particle agglomeration, whether and how stable compositions can be predicted, and which dispersants can be added to increase stability. Finally, we discuss the role of biosurfactants and the eco-corona and how these may offer a route to both better stability and environmental relevance.

## 1. Introduction

Since their first commercialisation in the 1950s, plastics have become an essential part of modern living due to their unique properties and low cost. The annual global production has been continuously rising and was estimated at 390.7 million tons in 2021 Bouwmeester et al., 2015; Janssens, 2022; Wright and Kelly, 2017). Plastic use, as well as mismanaged plastic waste, lead to small plastics known as micro- and nanoplastics (MNPs). These particles are <5 mm and <0.1 μm in size, respectively. MNPs originate from numerous sources: they are intentionally added to products such as cosmetics, production pellets or for cloth production (Boucher and Friot, 2017; Kannan and Vimalkumar, 2021), they can be formed by wear during use (Cai et al., 2020; Jan Kole, 2017; Luo, 2022) or they can also be formed by degradation of plastic in the environment through exposure to biotic (bacteria, fungi etc) or abiotic (UV, waves heat etc) stresses (Andrady, 2022; Tirkey and Upadhyay, 2021). Numerous reports have shown the presence of MNPs in oceans, rivers, water bodies, surface soils, both indoor and outdoor air and human samples (urine, blood, placenta, stool etc.) (Danopoulos et al., 2020; Dusza, 2022; Horton, 2020; Lahive, 2022; Leslie et al., 2022; Pironti et al., 2023; Romano et al., 2018; Schwabl, 2019).

Due to the exposure potential of MNPs, ongoing research aims at elucidating their potential toxicological effects on organisms from different trophic levels, including humans (Burns and Boxall, 2018; Castro-Castellon, 2022; Wang et al., 2021). Such research relies on relevant MNP test material that is standardised, but still reflects particles found in the environment. Spherical polystyrene microbeads are currently the most widely used MNP model particles, while little is known about fragments from commonly used plastic types. Additionally, these spherical particles are not representative of the complex MNPs found in the environment that have been subjected to various ageing processes such UV-irradiation, oxidation and fragmentation

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* Corresponding author.
*E-mail address:* luke.parker@tno.nl (L.A. Parker).

[1] These authors contriubuted equally to this work.

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(Bosker et al., 2019; Kühn et al., 2018; Seghers, 2022; Stock, 2021; von der Esch, 2020). Finally, these particles often contain surface groups or surfactants not commonly found in nature that should be taken into consideration when performing a laboratory study (Brachner, 2020; Gruber, 2022).

One potentially determining factor of the uptake and toxicity of MNPs is particle size, therefore MNP test materials of all plastic types with clearly defined size distributions are desired. More and more research groups are trying to produce their own test materials, through different processes such as milling or precipitation (Eitzen et al., 2019; Gouin, 2019a; Hildebrandt and Thünemann, 2023). By optimising techniques such as precipitation, or combining milling with fractionation through sedimentation or sieving, MNPs in numerous size fractions have been produced (Tanaka et al., 2023; Parker, 2023). In parallel with the preparation of test materials, attention should be given to the suspension of these MNP test materials to ensure that the particle properties, in particular the size distribution, are not affected by the suspension. Prepared suspensions should be stable, not allowing for agglomeration, swelling or dissolution/chemical breakdown of the polymers during (long-term) storage and use. Care should also be taken with surfactants, solvents and other dispersants used in the process. Such compounds could potentially alter the surface of the particles and thus modify their way of interacting with the biological models and organisms used for toxicity screening. In some cases, the toxicity could even derive from these additives rather than the particle itself (Balakrishnan et al., 2019; Paul, 2020; Stock, 2022). This is also true for toxic substances such as plasticizers and heavy metals that are (non-)intentionally added to plastics during production to enhance polymer properties or adsorbed by the plastics during and after use. These substances can leach from plastic particles into the media during storage and experiments (Petersen et al., 2022). While toxicity from chemical leaching needs to be seriously considered and distinguished from particle toxicity, a detailed analysis is out the scope of this review.

The aim of this review is to provide an overview of potential liquids and dispersants for MNP test materials, also taking into account biocompatibility of both, such that a model system can be tailored for each plastic type. In order to achieve this, an overview of the chemical compatibility of nine plastics with a number of common lab liquids is given followed by an assessment of the toxicity of the most promising candidates. Factors influencing particle agglomeration are then discussed and progress towards predicting particle suspension stability is presented. The use of (bio)surfactants, their environmental relevance and toxicity is discussed before ending with a number of approaches that do not utilise a liquid/dispersant system. Hopefully, this review can act as a guide for those that pursue to develop new or improved MNP test materials and to standardise/harmonise the evaluation of microplastic toxicity.

## 2. Dispersion liquids

To correlate MNP size to potential toxicity, a well-defined size distribution is a prerequisite. Changes in the size distribution and surface chemistry due to suspension need to be minimized. It is therefore crucial that the suspension system (liquid + potential dispersant) is compatible with the materials used. This preferably means that 1) the plastic does not dissolve in the chosen liquid; 2) the liquid is not absorbed in the plastic (a.k.a. swelling); 3) particles do not agglomerate and 4) the system does not affect metrics relevant for interpretation related to the study's purpose.

In this section, potential suspension liquids for nine common plastics (PMMA, HDPE, LDPE, PA, PC, PP, PVC, PS and PET) are investigated. First, a shortlist of potential liquids is composed based on their chemical compatibility. Then, using Hansen solubility parameters the solubility of common polymers in the selected liquids is examined (Díaz de los Ríos and Hernández Ramos, 2020; Hansen, 2000, 2004; HANDBOOK of Surface and Colloid Chemistry, 2009). In the context of this review, solubility is exclusively defined as dissolution of the solid test materials into a liquid solvent and does not refer to dispersion stability as in colloidal sciences.

### 2.1. Chemical compatibility

Many companies publish chemical compatibility charts that grade the effect of liquids/solvents on their material. Using several chemical compatibility charts and other references (Bel-Art; CDF Corporation; Curbell Plastics; dominique Dutscher; Equistar,; Graco; HCS-Lab; Inc; ISMa; ISMb; National Polystyrene Systems; PerkinElmer; Pipestock; Schulman; Scientific; Ultratech International; Polyethylene Terephthalate), a shortlist of promising liquids with minimal effects on commonly used plastics was compiled. The list is presented in Table 1. For conciseness, salt solutions listed in compatibility charts are omitted from the table as these do not differ from water for the plastics in scope of the present study. In general, the selected plastics show good compatibility with aqueous solutions. The exception is PET which one source deemed incompatible with warm water but good in cold water (Curbell Plastics). A reason is not given but this may be due to the potential for hydrolysis of PET. Ethanol, (iso)propanol and (iso)butanol also seem suitable for most plastics, however there are large discrepancies between sources; e.g. some sources deem alcohols to be compatible with polystyrene, but others give them the least resistance (PerkinElmer; Inc; National Polystyrene Systems; HCS-Lab). The polyols appear to be even more suited for the selected polymers, with the exception of PVC. The aliphatic alkanes, hexane and cyclohexane, are only compatible with PA. Many oils were found to be somewhat compatible with most plastics, however it is important to note that oils are less practical to work with due to their immiscibility with aqueous cell media.

### 2.2. Solubility

The first factor that will contribute to a stable MNP suspension is solubility. The suspension can be altered by either dissolution of the polymer into the liquid (solvent), or by the absorption of liquid into the polymer, a.k.a. swelling. While these effects should to some extent be contained in the chemical compatibility charts, a more concrete approach to predict the solubility of the common polymers in the promising liquids is desired. A simplistic view to predict solubility is "like dissolves like", i.e. polar solvents dissolve polar solutes and non-polar solvents dissolve non-polar solutes. The Hansen solubility parameter (HSP) approach takes this a step further and accounts for the three major types of interactions between molecules: 1) dispersion forces (D), 2) permanent dipole forces (P) and 3) hydrogen bonding (H) (Hansen, 2007). The energy of each interaction is described by their respective parameter $E_D$ (dispersion), $E_P$ (polarity), $E_H$ (hydrogen bonding). The parameters can be represented in three-dimensional space as the centre of a sphere. Good solvents will be located within the sphere, while bad solvents will lie at the boundary of the sphere or beyond. Ra is the distance between two species based on their solubility parameter components and is a measure of how "alike" they are, with the old adage "like dissolves like" here being quantified. Ra is calculated using the following formula:

$$Ra^2 = 4(\delta D1-\delta D2)^2 + (\delta P1-\delta P2)^2 + (\delta H1-\delta H2)^2 \quad (1)$$

Ro is the boundary of the HSP sphere and is determined through experimental measurements of "good" and "bad" solvents. The Ro for many common materials is available in numerous reference books. The relative energy difference (RED) of two species can be calculated with:

$$RED = Ra/Ro \quad (2)$$

A RED value of less than 1 indicates a substance will dissolve, while a value $> 1$ indicates progressively lower affinities. Therefore, for stable

**Table 1**
Compatibility of various liquids with nine common polymers (Bel-Art; CDF Corporation; Curbell Plastics; dominique Dutscher; Equistar,; Graco; HCS-Lab; Inc; ISMa; ISMb; National Polystyrene Systems; Perki-nElmer; Pipestock; Schulman; Scientific; Ultratech International; Polyethylene Terephthalate). Values from the chemical compatibility charts have been converted to 1: Good 2: Some effect 3: Not suitable. Value shown is an average of all available sources. *Indicates that values vary widely (from 1 to 3) between sources.

| Liquid | HDPE | LDPE | PP | PC | PS | PVC | PA | PMMA | PET |
|---|---|---|---|---|---|---|---|---|---|
| Water | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2* |
| Urea | 1 | 1 | 1 | 1 | 2 | 3* | 1 | - | 1 |
| Acetic Acid | 1 | 1 | 1 | 2* | 2* | 2* | 2* | 2* | 2* |
| Ethanol | 1 | 1 | 1 | 2 | 2 | 3* | 1 | 3 | 1 |
| 1-Propanol | 1 | 1 | 1 | 2* | 2* | 1 | 2* | 3 | 1 |
| Isobutanol | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2* | 2 |
| Glycerol | 1 | 1 | 1 | 1 | 1* | 1 | 1 | 2 | 1 |
| Ethylene Glycol | 2* | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 |
| Propylene Glycol | 1 | 1 | 1 | 2 | 1 | 3 | 1 | 2 | 1 |
| Diethylene glycol | 1 | 1 | 1 | 2 | 1 | 3 | - | 2* | 1 |
| Cyclohexane | 3* | 2* | 3* | 2* | 3 | 2* | 1 | 2* | 2* |
| Hexane | 2 | 3 | 2 | 3 | 3* | 2 | 2 | 2* | 1 |
| Vegetable oils | 1 | 2* | 1 | 1 | 2 | 1* | 1 | 3* | 1 |

MNP suspensions, high RED values are desired. Table 2 shows the calculated RED values for selected liquid/plastic combinations (Díaz de los Ríos and Hernández Ramos, 2020; Hansen, 2000, 2004; HANDBOOK of Surface and Colloid Chemistry, 2009). From this table it is evident that for most plastics, aqueous liquids are suitable from a solubility standpoint. Other promising liquids include glycerol and ethylene glycol (although not compatible with PA) and 1- or 2-propanol (not compatible with PMMA). This table also suggests that PC, PA and PMMA are the most challenging to keep stable. These are three relatively polar polymers and as such any solvent that has polar or hydrogen bonding groups will show a non-negligible interaction with these polymers. This may increase diffusion and swelling. For PC and PMMA this is enhanced by the non-crystalline nature of the two polymers that causes a decreased resistance against swelling. If these polymers start to swell, agglomeration can occur when they start sticking together.

### 2.3. *Liquid toxicity*

Performing toxicological studies with biological systems (cell cultures, tissue, organs or organisms) requires the use of multiple buffers and growth media. Toxicity screening of MNPs in these systems is challenging, as their water-insoluble nature prevents the creation of a homogeneous exposure suspension. The suspension and stability of each material depends not only on the particle's unique properties and the desired exposure concentration but also on the medium used in each study (different types of cell medium, fresh or salted water for aquatic

**Table 2**
Calculated RED values for selected liquids and common plastics.

| Type | Liquid | HDPE | LDPE | PP | PC | PS | PVC | PA | PMMA | PET |
|---|---|---|---|---|---|---|---|---|---|---|
| Aqueous | Water | 21.8 | 13.2 | 7.4 | 6.8 | 7.8 | 7.8 | 6.3 | 4.0 | 5.7 |
| | Urea | 15.6 | 9.7 | 5.3 | 4.4 | 5.3 | 5.3 | 4.2 | 2.5 | 3.7 |
| | Acetic Acid | 7.8 | 4.1 | 2.7 | 1.8 | 2.6 | 1.4 | 3.8 | 1.2 | 1.6 |
| Alcohols | Ethanol | 10.0 | 5.8 | 3.5 | 2.5 | 3.4 | 3.4 | 1.7 | 1.6 | 2.1 |
| | 1-Butanol | 7.7 | 4.3 | 2.7 | 1.8 | 2.6 | 2.6 | 3.3 | 1.3 | 1.6 |
| | 2-Butanol | 7.2 | 4.0 | 2.6 | 1.6 | 2.4 | 2.4 | 3.6 | 1.2 | 1.4 |
| | Iso-Butanol | 8.1 | 4.4 | 2.8 | 2.0 | 2.8 | 2.8 | 3.3 | 1.4 | 1.7 |
| | 1-Propanol | 8.7 | 4.9 | 3.0 | 2.1 | 2.9 | 2.9 | 2.6 | 1.4 | 1.8 |
| | 2-Propanol | 8.1 | 4.6 | 2.9 | 1.9 | 2.8 | 2.8 | 3.0 | 1.4 | 1.7 |
| Polyols | Glycerol | 14.9 | 9.0 | 5.1 | 4.2 | 5.2 | 5.2 | 2.0 | 2.6 | 3.6 |
| | Ethylene Glycol | 13.2 | 7.9 | 4.6 | 3.6 | 4.6 | 4.6 | 0.9 | 2.2 | 3.1 |
| | Propylene Glycol | 8.3 | 4.8 | 2.9 | 1.7 | 2.6 | 2.6 | 3.0 | 1.1 | 1.5 |
| | Diethylene Glycol | 11.2 | 6.6 | 3.9 | 2.8 | 3.7 | 3.7 | 1.2 | 1.7 | 2.4 |
| | Dipropylene Glycol | 9.6 | 5.6 | 3.3 | 2.2 | 3.1 | 3.1 | 2.1 | 1.4 | 1.9 |
| | Triethylene Glycol | 10.6 | 6.1 | 3.7 | 2.6 | 3.5 | 3.5 | 1.9 | 1.5 | 2.2 |
| Alkanes | Cyclohexane | 1.5 | 1.0 | 0.4 | 1.7 | 1.2 | 1.2 | 8.8 | 1.3 | 1.5 |
| | Hexane | 3.3 | 1.1 | 1.0 | 2.0 | 1.7 | 1.7 | 8.8 | 1.4 | 1.7 |
| Fatty Acids | Oleic Acid | 3.0 | 1.1 | 1.1 | 0.9 | 1.0 | 1.0 | 6.7 | 0.9 | 0.8 |

organisms etc.) (Meiner et al., 2009). To achieve that, MNP suspensions are created in various liquids with the possible addition of surfactants and other dispersants (discussed in depth in later sections), whose toxicological profile should also be known and taken into consideration (Balakrishnan et al., 2019).

While using dispersing agents seems the solution for creating stable suspensions these added components in cell culture media can be problematic from a biological aspect. Any addition of external components changes the "normal" cellular environment, with the cells seeing them as extra antigens and potentially altering their response. In addition, these materials may change the chemistry of the cell surface/membrane which can alter the way chemicals interact with cells and transport through the monolayer. The degree of toxic effects induced can vary among the different liquids and is time, concentration, and cell type dependent. For instance, recent studies have shown that in the majority of cells, DMSO seems to induce high toxicity and even at low concentrations is able to stimulate retinal apoptosis, whereas ethyl acetate and methanol have significantly lower toxicity (Koc et al., 2022), (Galvao et al., 2014). However, this response could vary a lot based on the readout chosen to validate the toxic effect, and the cell type used. Regarding the endpoint used for the assessment, Forman et al. showed that cytotoxicity induced by DMSO in HeLa cells is significant at concentrations above 2% while growth inhibition was observed even at concentrations below 1% (Forman et al., 1999). Differences in responses of multiple cell lines are reported by Timm et al. where 0.25 and 0.5% of DMSO had a stimulatory effect for the Mono Mac cells, and HL-60 cells but reduced the response of RAW 264.7 cells. While if toxicity is examined among different solvents, then, for example, ethanol affects cell viability at a concentration of 5% for HeLa cells, which is significantly higher than the threshold of 2% for the DMSO (Timm et al., 2013a). Based on these observations, the final concentration of each component in the suspension medium should be known and controlled to eliminate potential toxic side effects (Table 3).

Based on their chemical compatibility and solubility (presented in Tables 1 and 2), the most promising liquids for creating MNP suspensions were further investigated for their suitability for toxicological studies using potential toxicity in multiple cell lines. This is shown in Table 3. Toxicity data from previous cell studies show that most of the potential liquids used in particle suspensions or drug delivery studies are capable of inducing significant toxic effects only in high concentrations of 2–4% in the final solution (Gonzalez-Suarez, 2017; Komura, 2022; Mochida and Gomyoda, 1987; Timm et al., 2013). In MNP exposure studies, it seems unlikely that such high doses of the additive compounds are reached, if serial dilutions of a concentrated stock solution are used to achieve the lower environmentally relevant concentrations of particles. However, another factor that should be taken into consideration in biological studies is the presence of potential metabolites of these liquids that could be produced and released during the exposure. These metabolites could be more toxic than the original compound, something that could potentially be an obstacle for chronic exposures or animal studies. This effect has shown to be the case for diethylene glycol (DEG) and its two metabolites: diglycolic acid (DGA) and N-(2-Hydroxyethyl) ethylenediamine (2-HEEA) (Reed et al., 2021). Studies have shown that DGA can be concentrated in the kidney, brain and liver, playing a significant role in the induction of cell death and nephrotoxicity. In these cases, time and concentration ranges play a significant role in the DEG and its metabolites-induced toxicity. The DGA metabolite in high concentrations seems to have similar effects as the DEG but unlike DEG can induce apoptosis in much lower concentrations as well. Therefore, it is likely that repeated dosing experiments could enhance metabolite accumulation to higher concentrations in targeted tissues causing unwanted toxicity in later time points.

Similar examples can be also found in literature for suspensions made in water, the so-called "aqueous" suspensions. A characteristic example is the case of the C60 aqueous aggregates produced in a mixture of Tetrahydrofuran (THF) and water. Studies performed in zebrafish have found effects in the THF-C60 and THF-water exposure groups while no effects have been observed for the C60-water groups. Further analysis of the composition of the water revealed that the use of THF as a vehicle generated new substances in the water which were responsible for the observed mortality (Henry et al., 2007). Based on this evidence it is important to highlight that even "aqueous" suspensions should be tested for extra toxicity of their solvents when introduced in a biological system. Multiple commercial PS suspensions are supplied as aqueous

**Table 3**
Toxic effects of liquids potentially used in MNPs suspensions, in multiple cell lines or organisms.

| Liquid | Toxicity study | IC50/EC50[(1)] | Exposure time (h) | Source | Recommended final concentration | Comments |
|---|---|---|---|---|---|---|
| **Ethanol** | HepG2, MDA-MB-231, MCF-7 and VNBRCA1 cells | – | 72 h | Nguyen et al., 2020 | 0.15%–1.5% v/v | Toxicity dependent on the cell line. Low toxic effects for the HepG2, MDA-MB-231, MCF-7 and VNBRCA1 cell lines but higher for the K562, HL60, HCT-116 and H929 cells (Koc et al., 2022), (Nguyen et al., 2020) |
| **Methanol** | K-562, HL-60, HCT-116 and H929 cells | 10% v/v | 24, 48 and 72 h | Koc et al., 2022 | 1–2% v/v | |
| **Ethyl acetate** | K-562, HL-60, HCT-116 and H929 cells | >10% v/v | 24–72 h | Koc et al., 2022 | 1–2% v/v | |
| **Glycerol** | SAECs cells | 3–4% v/v | 24 | Komura et al., 2022 | 0.01%–2% v/v (if exposure is up to 24 h) 1% if exposure is up to 48 h | Toxicity affected by temperature (e.g. less toxic effects at 21 °C than 37 °C) |
| **Ethylene glycol** | KB cells | 0.45 M | 72 | Mochida and Gomyoda, 1987 | 0.01%–1% v/v | |
| **Propylene glycol** | KB cells | 0.31 M | 72 | Mochida and Gomyoda, 1987 | 0.01%–1% v/v | |
| | NHBE cells | 3.41% v/v | 24 | Gonzalez-Suarez et al., 2017 | | |
| | SAECs | 2% | 24 | Komura et al., 2022 | | |
| **Diethylene glycol (DEG)** | SH-SY5Y (Neuron cells) | 0.1 M | 24–120 h | Reed et al., 2021 | <1% v/v | Can be metabolized into compounds proven to induce cell death in vitro. Higher toxicity shown in chronic (animal) studies correlated to exposure time and concentration range |
| | KB cells | 0.18 M | 72 | Mochida and Gomyoda, 1987 | | |
| **n-hexane** | Hepatocytes | 297 mM | 2 | Zapór et al., 2002 | – | |

[1] EC50 values represent the effective concertation of the components, able to induce an effect at 50% of its maximal response.

solutions or a mixture of ethanol/water. The uncertainty of the composition of the final product regarding dispersant or other additives used could lead to misinterpretation of the observed data (Gouin et al., 2019b). Stock et al. investigated the effect of the aqueous dispersants that commercial PS is supplied in by separating the particles from their liquid vehicle. Then exposures to intestinal and liver cell models proved that commercial "ready-to-use" suspensions of PS were stored in relevant amounts of toxic dispersants while the particles on their own were mostly nontoxic (Stock et al., 2022). Furthermore, it shouldn't be ignored that different cell lines and organisms present different sensitivity to compounds, so it is necessary to be also aware of the specific characteristics of the biological model used in order to find the optimal concentration needed.

## 3. Agglomeration

While water appears to be a viable liquid for microplastics research based on the chemical compatibility, limited solubility with various polymers and low toxicity (as shown in Tables 1–3), it is known that many polymers such as polystyrene tend to agglomerate in water (Eitzen et al., 2019). It is important to minimise agglomeration of test materials for toxicity testing as agglomeration can lead to larger particles with a broader size distribution (see Fig. 1A). This has direct implications for toxicity assessments as the particles exposed to cells/organisms maybe larger or more heterogeneous than the as-prepared materials making it hard to draw accurate conclusions as to the relationship between particle and effect.

Agglomeration occurs when the repelling forces between particles are weaker than the attractive forces and can greatly affect the size distribution of a MNP test material in suspension, as shown in Fig. 1A. The three most important forces governing agglomeration are 1) van der Waals, 2) electrostatic and 3) steric forces. Van der Waals forces are attractive forces between atoms caused by fluctuating polarisation (Ninham and Parsegian, 1970), (Moore et al., 2015). Repulsive electrostatic forces arise when a particle is suspended in a liquid; an electrical double layer is formed around the particle as a result of the surface charge and a cloud of counterions. Steric forces are caused by the adsorption of bulky molecules on the surface of a particle and can be achieved by the use of additives such as surfactants or dispersants, that create a layer of molecules around the particles that repel each other. These molecules prevent the particles from forming attractive van der Waals interactions (Ortega-Vinuesa et al., 1996). Many paints are stabilized using this type of surface modification. As changing the attractive van der Waals forces is not trivial, controlling the repulsive electrostatic and steric forces is key to create a stable suspension.

Electric stabilisation is realized by the electrostatic repulsion of similarly charged colloidal particles. Particles with very high surface charge (zeta-potential) can cause a coulombic repulsion that is sufficient to ensure dispersion stability (Mo et al., 2016). Important influencing factors are the thickness of the electric double layer, the size of the particle, the ionic strength of the solution and the surface charge (zeta potential) (See Fig. 1A) (Jiang et al). With a thicker double layer the repulsive forces are more dominant, allowing a good dispersion of the particles. With a thinner double layer on the other hand, the repulsive forces are weaker, potentially leading to agglomeration of particles. This charge stabilisation can be broken by increasing the ionic strength of the dispersion (e.g. add salt or changing pH). The charges become shielded and repulsion breaks down to form agglomerates. The effect of the ionic strength of aqueous solutions on agglomeration has been demonstrated in the literature. Agglomeration in solutions with higher ionic strength can be explained by shielding of the electrostatic repulsion (Moore et al., 2015). This has been clearly demonstrated by Hildebrandt and Thünemann, who presented a method to prepare an aqueous dispersion of ≈180 nm polypropylene by using a mechanical disperser (Hildebrandt and Thünemann, 2023). However, in the presence of sodium chloride (NaCl), agglomerates of hundreds of nanometres are formed within 60 min. Similarly, agglomeration of polystyrene microplastics with increased concentrations of various salts has been observed by Shuocong Li et al. (2018) (See Fig. 1B). Additionally, Shams et al. investigated the aggregation of polystyrene and polyethylene nanoscale particles (Shams et al., 2020). Their results show that aqueous suspensions of polyethylene nanospheres were more readily destabilised than polystyrene in the presence of salts. This effect should be considered when adding or transferring a microplastic suspension to a cell medium containing salts. However, as agglomeration also depends on the concentration, when low concentrations are used for toxicity studies that use cell medium, the effect may be less significant (Parker, 2023).

The surface charge (or zeta potential) may also give an indication of which MNP/liquid combinations are promising. Commonly used in colloidal sciences, a zeta potential with a magnitude of 30 mV (negative

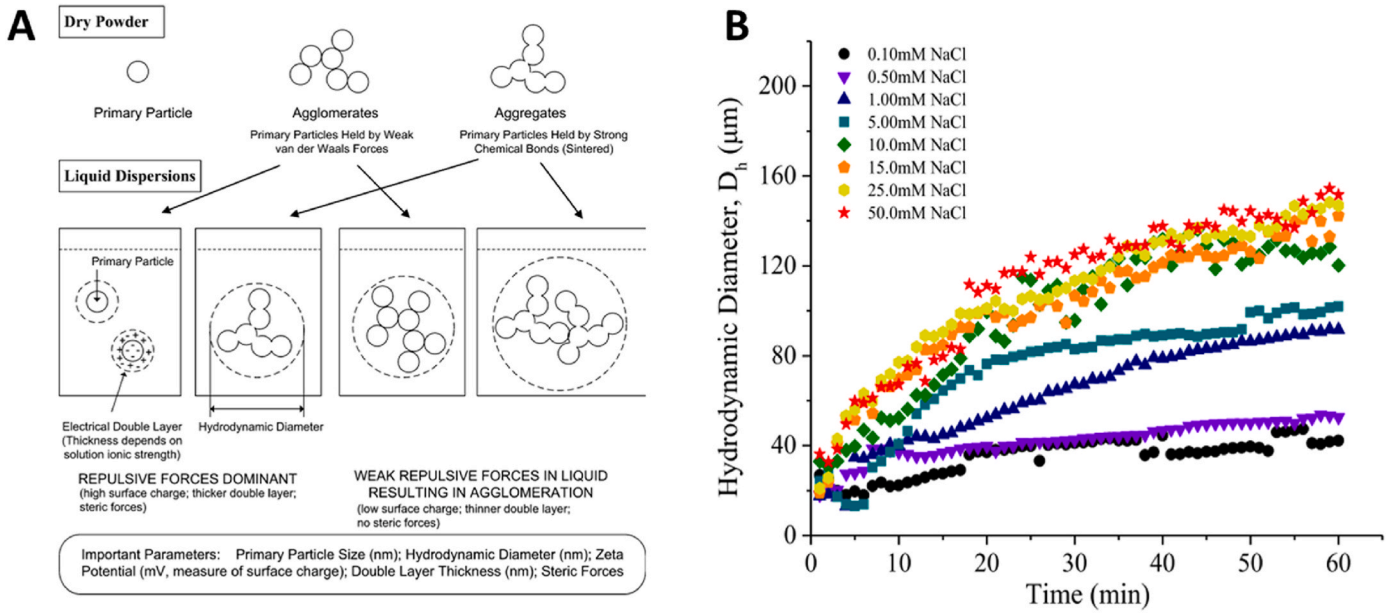


**Fig. 1.** A) Schematic depiction of particles and agglomerates and the forces that govern this (Reproduced from Ref. (Moore et al., 2015) with permission from the Royal Society of Chemistry); and B) the effect of ionic strength on particle agglomeration (Reproduced from Ref. (Li et al., 2018) with permission from Elsevier).

or positive) or higher is expected to indicate fair stability, while a zeta potential of ±60 mV or greater yields excellent stability (Freitas and Müller, 1998; Kovacevic et al., 2011; Shah et al., 2014). The surface charge, and therefore the zeta potential, of a microplastic particle depends on the liquid that the particle is submerged in. Unfortunately, limited sources are available that report the zeta potential of microplastics in different liquids or describe the agglomeration of plastic particles for various liquids. It would therefore be interesting to compare the zeta potential of MNPs in promising liquids like propanol, glycerol and ethylene glycol.

With the Hansen Solubility Parameters and zeta potential, we have ways of predicting both chemical (dissolution) and physical (agglomeration) stability, respectively. By plotting these against each other for different combinations of plastic and liquid, it may be possible to predict which combinations offer the best suspensions for MNP test materials. In Fig. 2, we demonstrate how such a Hansen-Zeta plot would look. By plotting the absolute zeta potential ($|\zeta|$) on the (logarithmic) y-axis and the Relative Energy Difference (RED) calculated by Hansen's solubility parameters on the (logarithmic) x-axis, with the axes crossing at RED = 1 and $|\zeta| = 10$, we form a plot with four distinct regions. The general rule of the plot is that the further right a suspension is, the more chemically stable it is, whilst the higher up on the plot it is, the more physically stable it is. In the bottom left (red), RED=<1 and $|\zeta|$=<10, therefore suspensions would show both agglomeration and dissolution behaviour and therefore be completely unsuitable for test materials. In the bottom right and top left (yellow), suspensions will either show agglomeration or dissolution, however showing just one of the behaviours still makes the suspension unsuitable for test materials. Finally, the top right region (green), shows suspensions with RED = >1 and $|\zeta|$=>10 mV. These suspensions should be both chemically and physically stable, with suspensions further to the right and higher being the most stable and thus most suitable.

To demonstrate the use of such a plot, we have tested six different microplastic suspensions (PET, PS and PP in both 1-propanol and water) for both zeta potential and physical stability. Experimental details of suspension preparation, static light scattering and zeta potential measurements are available in the Supporting Information. In 1-propanol, all plastics are chemically compatible. PS and PET both have a $|\zeta|$> 30 mV, whilst PP has a $|\zeta| = 10.5$ mV, therefore all suspensions are in the upper-right (green) region. As mentioned previously, in colloidal sciences a $|\zeta|$ >30 mV shows good stability, whilst $|\zeta|$ >60 mV shows phenomenal stability against agglomeration. This is also reflected in static light scattering (SLS) to determine particle size distribution (Fig. S1 in the Supporting Information). PS and PET show a singular peak ~25 μm, whereas PP, prepared in the same way, shows a small second peak ~200–300 μm that likely represents agglomerates. Upon exchange into water, all suspensions move further to the right and down. This suggests that while chemical stability is enhanced in water, physical stability is reduced and the risk of agglomeration increases. For PP this also results in the suspension moving into the bottom-right segment of the diagram, indicating the insoluble-agglomerated regime. This is reflected in the particle size distributions (PSD) of the suspensions. For PS and PET the PSD is almost identical in both water and 1-propanol, however for PP the distribution shifts noticeably towards larger particle sizes. The peak *ca.* 200–300 μm also grows considerably in water, suggesting large-scale formation of large agglomerates. PET also exhibits a second peak around 300–400 μm when dispersed in water that may indicate agglomeration, however this is much smaller (<1%).

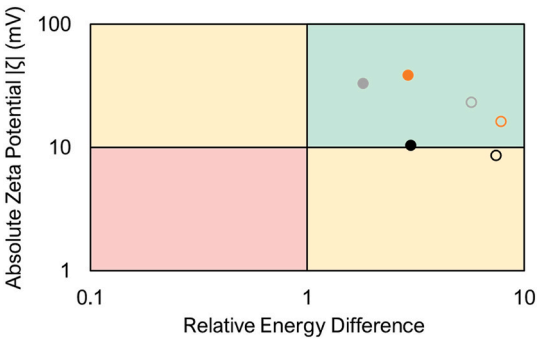


**Fig. 2.** Hansen-Zeta Plot demonstrating four possible interaction regimes: insoluble-non-agglomerated (green), insoluble-agglomerated and soluble-non-agglomerated (yellow) and soluble-agglomerated (red). Six plastic suspensions are plotted to illustrate use of the plot. PP (black), PET (grey) and PS (orange) in 1-propanol (closed circles) and water (open circles). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

### 3.1. Surfactants

Both the zeta potential and steric forces may be influenced by adding dispersants. One class of dispersant that can alter the zeta potential and/or increase the steric repulsion of MNPs are the so-called surface active-agents (surfactants) (Guo et al., 2018), (Kowalczyk and Kaminska, 2020). These generally consist of a hydrophilic "head" and hydrophobic "tail" allowing them to interact at the interface of two substances. Surfactants are used to stabilise a wide variety of systems, including coatings, paints (Hellgren et al., 1999), colloidal nanoparticles (González-Rubio et al., 2020), mesoporous material templates (Holmberg, 2004) and emulsions (Kalaitzaki et al., 2014), (Wu et al., 2020). Surfactants can stabilise particles through two pathways: electrostatic stabilisation and steric stabilisation.

Electrostatic stabilisation is achieved when a charged surfactant is attached to the surface of a particle, increasing the surface charge and thus the repulsive electrostatic forces. This is commonly used for the dispersion of pigments in paints (Hellgren et al., 1999). Dastbaz et al. prepared PS microplastics through phase inversion and investigated the effect of surfactant and co-surfactants on stability. By using a sodium dodecyl sulphate (SDS) surfactant they achieved a stable aqueous nanoplastic suspension (Dastbaz et al., 2021). Jódar-Reyes et al. also showed that PS beads can be stabilized electrostatically using sodium dodecylbenzenesulfonate (NaDBS) and domiphen bromide (DB, a quaternary ammonium compound), however at very high surfactant concentration the system becomes less stable (Jódar-Reyes et al., 2006). One of the disadvantages of electrostatic stabilisation is that it is mostly limited to aqueous systems due to the high dielectric constant of water. In other liquids with a lower dielectric constant the electric double layer will be much thinner.

Steric stabilisation occurs through the use of long-chain non-charged surfactants. These are bound to the particle surface and the highly solvated long chains that protrude from the surface induce steric hindrance between particles. Many common surfactants, such as Triton X-100 (2-[4-(2,4,4-trimethylpentan-2-yl)phenoxy]ethanol) and Tween-80 (polysorbate-80), work through steric stabilisation (Li et al., 2016), (Zhang et al., 2013). Structures of common surfactants are presented in Fig. S2 in the Supplementary Information. 3-(trimethoxysilyl)propyl methacrylate (TPM) is a non-charged surfactant that has been demonstrated to stabilise PMMA-CS/ZnO composite nanoparticles through the steric pathway (Petchthanasombat et al., 2012). Many surfactants act through both pathways, so-called electrosteric stabilisation, with an example being polyethyleneimine (PEI) which has been used by Inphonlek et al. to stabilise PMMA/CS nanocomposites. PEI is both cationic and has a long branching structure leading to stabilisation through both electrostatic and steric pathways (Inphonlek et al., 2010).

### 3.2. Surfactant toxicity

While surfactants can potentially be used to improve the stability of microplastic suspensions, their effect on toxicity studies should be considered. Environmental hazards of the chemically synthesized

surfactants have been studied extensively since they are highly present in aquatic environments and are poorly degradable. Other commonly used surfactants seem to induce chronic and sublethal toxicity to aquatic organisms or have cytotoxic effects in concentrations higher than 0.1 mg/L (Lewis, 1991), (Rebello et al., 2014). These side effects reported in aquatic environments should also be considered as potential hazards for the in vitro exposures in a laboratory setting. The toxicity of commonly used surfactants is shown in Table 4. Detergents like SDS and Triton X-100 can induce disorder in the bilayer of cells and can cause lysis in high concentrations (Inácio et al., 2011), (Arechabala et al., 1999). The potential toxicity of the surfactants could change based on the cell type used (non-polarized vs polarized cells) while the toxic effect seems to be dependent on the polar head of the surfactant, with the cationic ones being the most toxic (Inácio et al., 2011).

Besides the potential effects of surfactants themselves, the alteration to the surface properties by the surfactants might pose a problem. The results of Ramsperger et al. and Musyanovych et al. indicated that the surface properties of polystyrene microplastic particles can have an effect on the particle cell interactions and the uptake of particles (Ramsperger et al., 2022), (Musyanovych et al., 2011). In a study by Hillery et al. it was also proven that poloxamer surfactants can convert the hydrophobic surface of PS particles into a hydrophilic one, changing this way the kinetic profile of the particles. In particular, the uptake of poloxamer-PS particles seems to take place only in the large intestine and in low percentages while uncoated PS particles could be taken up throughout the gastrointestinal tract of rats and in higher rates (Hillery and Florence, 1996). Additionally, Voigt et al. found that the presence of non-ionic surfactants improves the passage of nanoparticles through the blood-brain barrier, while anionic surfactants on the other hand prevent it (Voigt et al., 2014). In a case study on Daphnia magna, some types of microplastic resulted in a higher mortality and mortality rate when surfactant was added. It has to be noted that the surfactant (Triton X-100, 0.001% v/v) itself also increased the rates (Renzi et al., 2019). This alteration could affect what is considered the “targeted organ of concern” and give false data on the kinetics of the particles in a realistic exposure scenario.

### 3.3. Biosurfactants and the eco-corona

Biosurfactants are amphiphilic substances with surface active properties that are produced or inspired by micro-organisms (yeast, fungi or bacteria) (Sockett et al., 2022), (Kumar Duddu et al., 2015). Four major classes of biosurfactants are: (1) glycolipids, (2) phospholipids and fatty acids, (3) lipopeptide/lipoproteins, (4) polymeric surfactants (Patel and Kharawala, 2022). These biosurfactants are currently of interest for applications where biocompatibility or customization is required such as drug delivery systems (Kalaitzaki et al., 2014). In addition, their low cytotoxicity on mammalian cells could expand their applications. In the study of Voulgaridou et al. two biosurfactants tested on keratinocytes and hepatocytes appear to be safe at concentrations up to 0.25 mg/ml. On the contrary, traditional surfactants induced cytotoxicity at much lower concentrations (0.002 mg/ml) under similar exposure conditions (Voulgaridou et al., 2021). These findings suggest that biosurfactants could potentially be a more suitable alternative for the creation of stable MNP suspensions to be used in toxicological studies. One example of natural compounds with surface activity are steviol glycosides such as stevioside. These have been used by Wan et al. in combination with soy protein isolate to stabilise resveratrol nanosuspensions (Wan et al., 2016). Biosurfactants could also be utilised to stabilise microplastic suspensions. Balakrishnan et al. prepared PE particles of 200–800 nm using an emulsion of toluene in water with biosurfactant from freshwater algae that were stable in aqueous solution for at least 3 months (Balakrishnan et al., 2019). Hazra et al. used rhamnolipids, surfactin and trehalose lipids of microbial origin to synthesize core–shell nPMMA–biosurfactant nanoparticles (Hazra et al., 2014). Microbial surfactants seem more applicable for creating MNP suspensions used in research since they are more ecologically compatible, and stable at several temperatures, pH, and salinities, thus promoting their use in various biological systems and conditions (Abbot et al., 2022).

Under realistic environmental conditions MNPs can act as absorbants or vectors for several impurities and contaminants such as salts, heavy metals, DNA, proteins, carbohydrates and degradation products like humic acid (Liu et al., 2022a). This layer of bound matter on the surface of MNPs is called an eco-corona. Much like with surfactants, the eco-corona may affect the surface properties of microplastic particles, which in turn may influence their aggregation, mobility, settling, cellular internalisation and environmental toxicity. Witzmann et al. performed direct force measurements on polystyrene particles with and without an eco-corona and detected repulsive forces when an eco-corona was present (Witzmann et al). An (artificial) eco-corona of extracellular polymeric substances around polystyrene nanoplastics resulted in a lower toxic effect in terms of oxidative stress (Natarajan et al., 2020). On the other hand, aggregation on the inner surface of the intestines of zebrafish as a consequence of bovine serum albumin (BSA) on the surface of polystyrene caused reduced food intake (Luo et al., 2022). The eco-corona effect seems to be strongly correlated with other properties of the MNPs such as size, shape, and origin (Liu et al., 2022). For instance, in a study performed by Liu et al. the presence of humic acid in PS suspensions of 0.1 and 0.25 μm reduced the toxicity of the particles on algae cultures while the same concentration of humic acid in suspensions of 1 and 2 μm of PS did not alter the observed effects (Liu et al., 2020). It is interesting to note the effect of an eco-corona on suspension stability. The effect of humic acid and salinity was investigated by J. Wu (Wu et al., 2019) and an interactive effect was found, where the stability of negatively charged polystyrene in the presence of NaCl was improved. This was, however, not the case for positively charged polystyrene-$NH_2$. Following the same trend, Li et al. observed increased stability of polystyrene nanoparticles in the presence of (higher concentrations of) BSA for negatively charged polystyrene (PS-bare and PS-COOH) but adverse effects for positively charged particles (PS–$NH_2$) (Li et al., 2021). This may suggest that the use of biosurfactants will not only promote better dispersion, but may also

**Table 4**
Cytotoxicity of surfactants on multiple cell lines. Recommended final concentrations taken as those that have similar response to the control groups in the referenced literature. For surfactants with n/a not enough data could be found.

| Surfactant | Cell type | IC50/EC50[1] | Exposure time | Source | Recommended final concentration |
|---|---|---|---|---|---|
| **Tween 80** | Human fibroblasts | 210 μg/ml | 4 h | Arechabala et al., 1999 | n/a |
| **Triton X-100** | Human fibroblasts, Caco-2, Hela, FSDC | 34 μg/ml<br>$3.87*10^{-2}$ M | 4 h and 24 h | Arechabala et al., 1999, Inácio et al., 2011 | 10−3 g/L |
| **Texapon N40** | Human fibroblasts | 290 μg/ml | 4 h | Arechabala et al., 1999 | n/a |
| **Benzethonium chloride** | Human fibroblasts | 8 μg/ml | 4 h | Arechabala et al., 1999 | $10^{-4}$ g/L -$10^{-3}$ g/L |
| **Sodium dodecyl sulphate (SDS)** | Caco-2, Hela, FSDC | 3, 28 * $10^{-2}$ M | 24 h | Inácio et al., 2011 | 0.1 mol/L |
| **N-dodecyl-N,N-dimethylammonium-propanesulfonate (DDPS)** | Caco-2, Hela, FSDC | 7 * $10^{-2}$ M | 24 h | Inácio et al., 2011 | <1.2 M |

increase the environmental relevance of test materials. However, it should be noted that all of these studies used polystyrene spheres which may not be representative of MNPs found in the environment. Other challenges include the role of organism interaction in eco-corona formation (Mao et al., 2016) and, if aiming to produce standardised test materials, how a standardised eco-corona can be achieved.

The benefit of more environmental relevance and fewer chances for acute toxicity when using bio-surfactants should not take our attention away from their disadvantages. While synthetic surfactants have a well-characterized structure and properties this information may lack for the biosurfactants. The various and complex characteristics of the organic matter existing in nature cannot be solely represented by the properties of the natural organic matter (NOM) currently used in toxicological studies (Handy et al., 2012). Literature regarding the toxicity of bio-surfactants is scarce and the environmental hazards deriving from their use remain to be clarified. A study from Edwards et al. where the toxicity of bio and synthetic surfactants on aquatic species was studied showed an intermediate toxicity of biosurfactants without this being consistent (Edwards et al., 2003). So it seems that the toxic effects in this case are compound-specific and cannot be generalized among other compounds of the same category. Apart from their potential immediate toxicity, we should take into consideration their biologically active nature. Most biosurfactants are naturally anti-microbial agents, are proven to reduce the toxicity of engineered nanomaterials, and control the bioavailability of compounds to aquatic organisms (Handy et al., 2012), (Vecino et al., 2017). These properties could affect the toxic profile of the test compound dissolved in a solution containing biosurfactants and result in false positive or negative results.

## 4. Other methods

Finally, it is worth mentioning some alternative routes to stabilise test materials that have been investigated. These often do not utilise surfactants and some do not even utilise liquids. Methyl cellulose and related compounds, such as hydroxypropyl-methylcellulose (a propylene glycol ether of methylcellulose), have been studied for their potential applications in drug formulations. These compounds can serve as additives to inhibit crystallization (Raghavan et al., 2003), potentially enhance solubility (Mitchell et al., 2003), (Kiortsis et al., 2004), or provide better control over drug delivery/release (Tundisi et al., 2021), (Siepmann and Peppas, 2012). Hydroxypropyl methyl cellulose is mentioned as a stabilizer in seeded dispersion polymerisation with polystyrene seeds (Shahsavari et al., 2015), and for carbon nanotubes for cement composites (Du and Chen). However, limited literature exists on the use of methyl cellulose specifically for microplastic stabilisation. Interestingly, a paper by S.L. Raghavan et al. discusses how the addition of anionic carboxymethyl cellulose (CMC) reduces the interaction between polystyrene latex particles (which are negatively charged) and yeast cells, similarly to the surface effects described in the surfactant section (Yumiyama et al., 2018).

A number of studies have investigated stabilisation using carbohydrates. Müller et al. used a sucrose solution with a calculated density of 1.3 g/ml to stabilise a microplastic stock solution for at least 1 min, such that the microplastic particles remained suspended during transfer to subsequent flasks (Müller et al). Starch nanoparticles can be used to stabilise graphene sheets with low oxygen content as shown by Zhao et al. (2021). No papers were found applying starch as dispersant for microplastics, however, a paper by Onyianta et al. shows the use of cellulose nanocrystals in a similar fashion to formulate a stable dispersion of polypropylene (see Fig. 3) (Onyianta et al., 2022). It should however be noted that cellulose is considered a potential control substance for MNP effect studies.

Another way to store microplastic test material is the solid phase. De Vries et al. suggest that rapid freezing followed by freeze-drying reduces the amount of agglomeration for proteins (De Vries et al., 2017). Seghers et al. have proposed a similar method to reduce agglomeration in

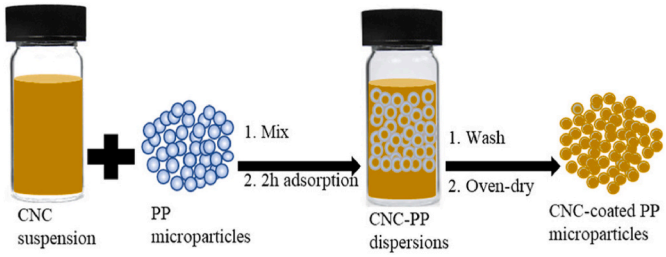


**Fig. 3.** Schematic representation of the adsorption process of cellulose nanocrystals onto PP microparticles. Reproduced from Ref. (Onyianta et al., 2022) licensed under CC BY 4.0.

microplastics (Seghers et al., 2022). PET microparticles were created with cryo-milling and after sieving the particles were suspended in a 29.5% (w/v) NaCl solution with a low concentration of surfactant. The suspension was then freeze-dried to obtain a dry cake. While this strategy can be applied to microplastics, work by Tian et al. indicates that degradation of the microplastics is increased during freezing which they ascribe to the formation of singlet oxygen ($^1O_2$) between ice crystals accelerating oxidation of the plastic (Tian et al., 2022). It is worth noting that while these methods are useful to avoid agglomeration during storage, health effect experiments carried out aqueous media may still lead to agglomeration after suspension of dry-stored particles.

## 5. Conclusions

The aim of this review is to provide an overview of liquids and dispersants that could be used for toxicity evaluations of micro- and nanoplastic test materials with a defined size distribution. In the liquid section, we have seen that based on chemical compatibility charts as well as Hansen solubility parameter calculations, water and glycerol are expected to be the best dispersing liquids for most of the common plastics. Short chain alcohols such as ethanol and propanol also show reasonable compatibility with many plastics. PC, PMMA and PA exhibit the least chemical compatibility due to their polar nature, for these water is still an option but many other liquids such as alcohols are not. PA shows better compatibility with apolar solvents such as alkanes than the other plastics.

Most plastics however tend to agglomerate in water, especially in the presence of ions. This is a challenge for toxicity testing as it results in larger particles with a broader size distribution making it harder to draw concrete conclusions about the relationship between particle size and effect. Studies on the dispersion and agglomeration of MNPs in glycerol are limited, however, the higher viscosity of glycerol can potentially improve the dispersion compared to water (Vashisth et al., 2022). Whilst there is no “one-size-fits-all” solution for suspending MNPs, by utilising a combination of zeta potential and the Hansen solubility parameters we have shown that suitable plastic-liquid combinations can be chosen which are stable both chemically and physically. The toxicological considerations when choosing a suspension liquid should not be overlooked. We have identified that the critical exposure concentration is both readout and cell line dependent, a challenge and consideration that should be take into account when selecting and preparing testing materials.

Additionally, dispersants could be used in conjunction with liquids to decrease the amount of agglomeration. There are many different dispersants to choose from, including surfactants (ionic, anionic and non-ionic), biosurfactants and eco-corona related molecules such as humic acid and bovine serum albumin. However, we have also shown that use of such dispersants can have a large effect on the toxicity and bioavailability of test materials.

Methods have also been investigated to create stable suspensions by ultrasonication, phase inversion or without additives. Alternatively, freeze-drying (with and without NaCl) has been proposed as a method to

create a dry powder where less agglomeration occurs than other drying methods.

Most of the stabilising approaches investigated rely on changing the surface properties of the microplastic particles, as those will determine the extent of agglomeration. This poses a new question that needs to be answered: What do we want to measure? Toxicity of microplastics is complex and multiple modes of action might be at play. If a response to MNPs of various sizes is to be measured a defined distribution is desired, but adding dispersants to prevent large changes to the distribution can also change the surface properties of the microplastic particles and in turn affect the response. If, however, we want to relate the potentially harmful effects to real world situations, a test material with an (artificial) eco-corona might be the solution as this serves to both stabilise the particles and make their surface more environmentally relevant. Future work focussed on understanding how to make particles simultaneously more stable and more environmentally relevant would be very valuable, as well as understanding the most important source of toxicity in such systems – in this review we have shown how this could be down to liquid, plastic, eco-corona or leachate compounds, among others.

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## Consent for publication

All authors consent to publication.

## Ethics approval and consent to participate

Not applicable.

## Definitions

Agglomeration – The reversible clumping of particles caused by physical forces.

Biosurfactant – A surface active agent derived from natural sources such as algae.

Colloid (colloidal particles) – Dispersion of microscopic insoluble particles in a liquid.

Coulombic repulsion – see Electrostatic forces.

Dispersant – A substance added to the suspension to improve separation of particles and stabilise against agglomeration.

Eco-corona – The surface coating of proteins and adsorbed chemicals that can form when particles are exposed to natural environments.

Electric double layer – Parallel layers of charge that occur at an interface (in the context of this review solid-liquid) consisting of a surface charge layer of ions and a second screening layer that is attracted to the charge of the first layer.

Electrostatic forces – attractive and repulsive forces between charged molecules.

In vitro – Studies performed using biological material (e.g. cells, bacteria etc) that have been isolated from their original biological environment and are now grown in a laboratory.

Solubility – The dissolution of a solid material into liquid solvent.

Steric forces – Repulsive forces caused by overlapping electron clouds.

Surfactant – Surface active agent, an amphiphilic substance that acts at the interface of solid and liquid. The most common type of dispersant.

Van der Waals forces – weak, distance dependent intermolecular interactions.

Note: the term liquid is consciously used instead of solvent throughout as it is a requirement that the liquid-phase does not dissolve the test particles.

## CRediT authorship contribution statement

**Dónal van Uunen:** Writing – original draft, Visualization, Investigation, Data curation. **Maria Kloukinioti:** Writing – original draft, Investigation, Data curation. **Ingeborg M. Kooter:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Elena M. Höppener:** Writing – review & editing. **Laurine E.A. Yoe:** Writing – review & editing, Investigation. **Andrea M. Brunner:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition. **Arjen Boersma:** Writing – review & editing, Conceptualization. **Luke A. Parker:** Writing – original draft, Visualization, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Luke Parker reports financial support was provided by PlasticsEurope AISBL. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.124306.

List of Abbreviations

| | |
|---|---|
| **2-HEEA** | N-(2-Hydroxyethyl)ethylenediamine |
| **ABS** | Acrylonitrile Butadiene Styrene Copolymer |
| **BSA** | Bovine Serum Albumin |
| **Caco-2** | Epithelial cells isolated from colon carcinoma |
| **DB** | Domiphen Bromide |
| **DDPS** | N-dodecyl-N,N-dimethylammonium-propanesulfonate |
| **DEG** | Diethylene Glycol |
| **DGA** | Diglycolic Acid |
| **DMSO** | Dimethyl Sulfoxide |

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(*continued*)

| | |
|---|---|
| **FSDC** | Murine dendritic cell line |
| **H929 B** | lymphocytes |
| **HCT-116** | Human colorectal carcinoma cell line |
| **HDPE** | High Density Polyethylene |
| **HeLa** | Epithelia cell line derived from adenocarcinoma of the uterus |
| **HeoG2** | Human liver cancer cell line |
| **HL-60** | Promyeoloblasts isolated from the peripheral blood |
| **HSP** | Hanson Solubility Parameters |
| **K562** | Lymphoblast human cells |
| **KB cells** | Epithelial cell line |
| **LDPE** | Low Density Polyethylene |
| **MCF-7** | Hman breast cancer cell line |
| **MDA-MB-231** | Human breast cancer cell line |
| **MNPs** | Micro- and Nanoplastics |
| **NaDBS** | Sodium dodecylbezene sulphonate |
| **NHBE** | Human bronchial epithelial cells |
| **PA** | Polyamide |
| **PC** | Polycarbonate |
| **PEI** | polyethyleneimine |
| **PET** | Polyethylene Terephthalate |
| **PMMA** | Poly (Methyl Methacrylate) |
| **PP** | Polypropylene |
| **PS** | Polystyrene |
| **PSD** | Particle Size Distribution |
| **PVC** | Polyvinyl Chloride |
| **RED** | Relative energy difference |
| **SAECs** | Human small airway epithelial cells |
| **SDS** | Sodium Dodecyl Sulphate |
| **SH-SY5Y** | Human neuroblastoma cell line |
| **SLS** | Static Light Scattering |
| **TPM** | 3-(trimethoxysilyl)propyl methacrylate |

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