Environmental Sciences Europe

RESEARCH Open Access

Characterization of polyethylene and polyurethane microplastics and their adsorption behavior on Cu^{2+} and Fe^{3+} in environmental matrices

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Abstract

As the world faces growing environmental challenges, understanding the nature of microplastics—such as Low-Density Polyethylene (LDPE) and Polyurethane (PU)—and their transformation in water-based environments is necessary for predicting and mitigating their effects. In this study, we investigated their physicochemical characteristics, presence of impurities, colloidal behavior, and sorption capacity to understand better how microplastics behave and transform in the environment, including their role in transporting heavy metals. The two types of microparticles investigated fall into distinct size ranges, approximately 70 microns for PE particles and around 5 microns for PU particles. Both samples showed a spherical morphology and an evident surface micro-roughness. The elemental and thermal analysis did not show the presence of any significant metal impurities. The zeta-potential measurements as a function of pH provided insights into the dispersion behavior of microplastics (MPs) in freshwaters, suitable for the growth of Zebrafish (Egg water) and Daphnia magna (Elendt M7 Water). Both materials showed in bidistilled water negative zeta potential (ZP) at natural pH (ZP = − 51.0 ± 4.3 mV at pH = 6.6 and ZP = − 29.5 ± 1.4 mV at pH = 5.6 for LDPE and PU, respectively), justified by the presence of surface-active charged impurities. In saline media, ZP vs. pH curves were flatter, with ZP values near 0 mV, confirming the reduced colloidal stability from higher ionic strength and double-layer compression. Finally, we assessed the metal adsorption capacity to establish the role of microplastics in the transport of heavy metals in the environment. We observed selective adsorption for Cu^{2+} ions, which was both medium-dependent (more ions adsorbed in Elendt M7) and plastic-dependent, with PU showing a stronger affinity for Cu^{2+} in MilliQ and Egg water. On the contrary, both plastics showed similar adsorption capacity for Fe^{3+} ions across all media.

Keywords Microplastic, Environmental medium, Characterization, Colloidal behavior, Adsorption capacity

Introduction

Every year, between 5 and 13 million tons of plastic enter the environment worldwide [1]. Plastic pollution is a major environmental issue, especially in ocean waters, where it causes extensive damage to ecosystems, the species living there, and, indirectly, humans through the food chain. More specifically, microplastics (MPs) have gained significant attention as potential pollutants in aquatic environments, because they have become widespread throughout

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the natural environment, impacting terrestrial, aquatic, and atmospheric systems. Depending upon their source, microplastics can be classified into primary and secondary MPs. The primary MPs are deliberately manufactured and added to printing inks, paints spray, cosmetics, injection moldings, and abrasives, which enter the environment at this size directly. The secondary MPs are originated from the mechanical, chemical, and light-induced breakdown of larger plastics, released into the environment as a result of inadequate wastewater treatment, transportation, and, especially, improper disposal of plastic waste, such as bags, bottles, toys, and household items. The distinction between microplastics, nano-plastics, meso-, and macroplastics is not standard practice in the field; nevertheless, in September 2023, the International Standardization Organization published the first internationally recognized microplastic testing standard (ISO 24187), providing also the definition of MPs, as solid plastic particles, insoluble in water with at least one dimension between 1 μm and 1 mm [2]. International scientific organizations [i.e., World Health Organization (WHO), European Food Safety Authority (EFSA), and Science Advice for Policy by European Academies (SAPEA)] have emphasized the need for data on the human health impact of MNPs that provides the necessary evidence base for effectively supporting policy-making [3–7].

The main problems related to the pollution caused by MPs include their potentially harmful effects on wildlife, fish, and humans, either directly (contaminated water where they persist for many years) or through the food web [8–10]. Additionally, MPs can act as vectors for absorbing, concentrating, and transporting waterborne chemical pollutants from invertebrates to higher trophic levels. They also serve as a "Trojan horse" for the ingestion of harmful plastic additives and as carriers of bacteria. Finally, microplastics contribute to air pollution, further amplifying their negative environmental and human health impact [11].

Characterizing MPs dispersed in aqueous media (colloidal characterization) is fundamental in understanding the interaction mechanisms between MPs and the surrounding environment [12]. Notably, environmental factors, such as pH, salinity, and coexistent ions, affect the interaction and, consequently, the sorption mechanism [13, 14]. The large surface area exposed, the hydrophobicity, and the overall surface chemistry make MPs very effective in adsorbing many pollutants from the environment [15, 16]. More specifically, the sorption capacity of MPs to heavy metals can be altered by weathering due to the formation of anion active sites and increased porosity [17]. In any case, MPs with adsorbed matter, including heavy metals, may pose potential toxicity due to the high concentration of surface-bound ions. These adsorption characteristics should be carefully considered when evaluating microplastics' environmental and health impacts. In the absence of exhaustive and quantitative information regarding MPs toxicity and exposure, issues related to their dispersion, transportation, and transformation in relevant environmental matrices are crucial for predicting their potentially direct and indirect adverse effects [18–20]. Considering this need, protocols, toxicological studies, and adequate analytical techniques for physicochemical characterization have recently been improved to understand better the MPs risks [21, 22]. For these reasons, we focused our attention on the characterization of two classes of industrially relevant microplastics exposed to environmental matrices, with the ultimate aim of supporting the interpretation of ecotoxicological data. We chose primary plastics, low-density polyethylene (LDPE) and polyurethane (PU) plastics, as they are commercially available materials found in a variety of products, including packaging, medical devices, construction for LDPE [23], and coatings, films, insulation, construction foams, furniture, and packaging for PU [24], respectively. We investigated their behavior in brackish water (Egg water) proper for the growth of *Zebrafish* embryos (freshwater fish) and in synthetic water (Elendt M7 Water) enriched with salts and nutrients to support the growth, survival, and reproduction of *Daphnia magna* (freshwater crustacean). Both Egg Water and Elendt M7 are high-hardness media currently recommended for Organization for Economic Cooperation and Development (OECD) testing [25, 26]. We specifically looked at (1) physicochemical identity, (2) colloidal behavior, and 3) adsorption capacity to understand how microplastics transport heavy metals in the environment.

Methods

Materials

The low-density polyethylene (LPDE) microplastic (certified size of 10–150 μm, additives by the safety data sheet, approximately 30% by weight) was purchased by Cospheric LLC (Santa Barbara, CA, USA), while the polyurethane (PU) microplastic (certified size of 5.0–8.0 μm) was purchased by Lamberti SpA Chemical Specialties (Fiorano Modenese, MO, Italy). Egg water medium was purchased by Fisher Scientific (Thermo Fisher Scientific–Canada). The theoretical concentrations of dissolved ions in mg L^{-1} are: 18.2 Na^{+}; 0.630 K^{+}; 2.17 Mg^{2+}; 0.646 Ca^{2+}; 0.0285 Sr^{2+}; 0.0111 Al^{3+}; 31.7 Cl^{-}; 1.26 $SO4^{2-}$. All the Elendt M7 medium salts were purchased from Sigma-Aldrich (Italy), the approximate concentration of the main salts in mg L^{-1} is 1.250 $Na_2EDTA*2H_20$, 293.800 $CaCl_2*2H_2O$, 123.300 $MgSO_4*7H_20$, 5.800 KCl, 64.800 $NaHCO_3$, 10.000 $Na_2SiO_2*9H_20$, 0.274 $NaNO_3$, 0.143 KH_2PO_4, 0.184 K_2HPO_4 [27]. Nitric acid (65%), sulfuric

acid (96%) and ICP-OES standards were purchased from Sigma-Aldrich (Italy).

Microplastics characterization

Morphological characterization of LDPE and PU microplastics was performed by Field Emission Scanning Electron Microscopy (FE-SEM) instrument (Carl Zeiss Sigma NTS Gmbh, Oberkochen, DE), coupled with Scanning Transmission Electron Microscopy (STEM) detector. The SEM images were analyzed with the ImageJ software (version 1.52p), calculating the size of at least 500 microspheres per sample. Thus, the size distribution was evaluated; in the specific, the average diameter, the mode, and the median were calculated with the values obtained; a 95% confidence interval was chosen for the statistical analysis of the results. The SEM analysis was also replicated on LDPE and PU microplastics after exposure to environmental media. The results (Figures S3-S6 and Table S4) and relative comments are reported in ESI.

Fourier transform infrared spectroscopy with attenuated total reflection (ATR-FTIR) analysis was performed on the previously dried microplastics in an oven at 110 °C for 15 min to remove residual traces of water. The measurements were obtained using a Nicolet iS5 spectrometer (Thermo Fisher Scientific Inc.—Waltham, MA, USA). A wave number range between 400 and 4000 cm^{-1} was set for the analysis using the ATR accessory (model iD7). The positions of the peaks were identified using the OMNIC software, and values were compared with the data in the literature [28, 29]. The ATR-FTIR analyses were also replicated on LDPE and PU microplastics after exposure to environmental media. The results (Figures S7 and S8) and relative comments are reported in ESI.

The thermogravimetric analysis (TGA), coupled with the differential scanning calorimetry analysis (DSC), of microspheres was performed by the STA 449 F3 Jupiter instrument (NETZSCH Group—Selb, Germany). The analyses were conducted first in nitrogen and then in air: the analysis in nitrogen was set with a gas flow of 50 mL min^{-1}; while for the analysis in air was chosen a mixture of N_2 and O_2 in the ratio 92:8 by volume and using a gas flow of 50 mL min^{-1}. All the samples were heated at 10 °C min^{-1} up to 700 °C. The thermograms were analyzed using the Proteus software.

Metal impurities

The metal impurities content of microplastics before and after the exposure to environmental media were evaluated by inductively coupled plasma optical emission spectroscopy (ICP-OES 5100—vertical dual view apparatus, Agilent Technologies—Santa Clara, CA, USA). In particular, the microspheres were digested by acid treatment, 250 mg of material were treated with 3 mL of nitric acid (HNO_3—65%) and 3 mL of sulfuric acid (H_2SO_4—96%) concentrated and the mixture was heated by microwaves. The acid mixture was used for sample mineralization comprised HNO_3 (65%) and H_2SO_4 (96%), in a 1:1 ratio. The acid mixture (6 mL) was added in Teflon tubes with ca. 250 mg of microplastics samples. The microwave system EM-45/A Milestone (Milestone Helping Chemists Srl—Sorisole, Italy) was used to digest the samples following the procedure reported in Table S1. Afterward, the samples were allowed to cool down for 30 min in vent mode at room temperature. The obtained solutions were diluted to 10 mL and analyzed without another treatment. All samples were obtained in triplicates; the detection limit was 0.01 mg L^{-1}.

Colloidal characterization

Following NanoReg dispersion protocol [30–32], usually applied in the nanotoxicology field, 2560 mg L^{-1} stocks of LDPE and PU microplastic in bi-distilled MilliQ water were prepared and then diluted in environmental media. A concentration range of 100–1000 mg/mL was considered, in agreement with what is reported in the literature. Ferraz et al. (2020) reported an average microplastic content in river water of 330.2 particles per L, corresponding to a concentration range of 1 to 15,000 mg/L, assuming spherical particles with an average density of 1 g cm^{-3} and diameters ranging from 200 to 1000 μm [33]. However, considering the instrumental limits of the various techniques, the range was arbitrary restricted, and samples diluted in Egg Water and Elendt M7 media at the concentrations of 100, 500 and 1000 mg L^{-1}. The suspensions were incubated for 1 h, 24 h, and 240 h at 20° C under dynamic conditions within an oscillating bath (SB 35, ArgoLAB) coupled to a chiller (F12, Julab). These conditions were chosen to replicate the natural exposure conditions, simulating both the average temperature and the currents to which the microplastics in the rivers are subjected. The colloidal behavior of microplastics was evaluated in MilliQ water, in Egg water and Elendt M7 media, monitoring Zeta Potential (ZP) by ELS measurements, using a Zetasizer Nanoseries (Malvern Instruments, Malvern, UK). ZP titrations as a function of pH were performed, to identify the pH point where ZP is neutralized (isoelectric point, IEP). The titration was carried out in a pH range between 1.5 and 8.0 using 1, 0.1 and 0.01 M HCl (for the acidic range) and 0.01 and 0.001 M KOH M (for basic range). The microspheres were suspended in media at a concentration of 100 and 1000 mg L^{-1} and subjected to titration, while the 500 mg L^{-1} samples were analyzed by mean of single ZP analysis. Each sample was prepared and analyzed in triplicate.

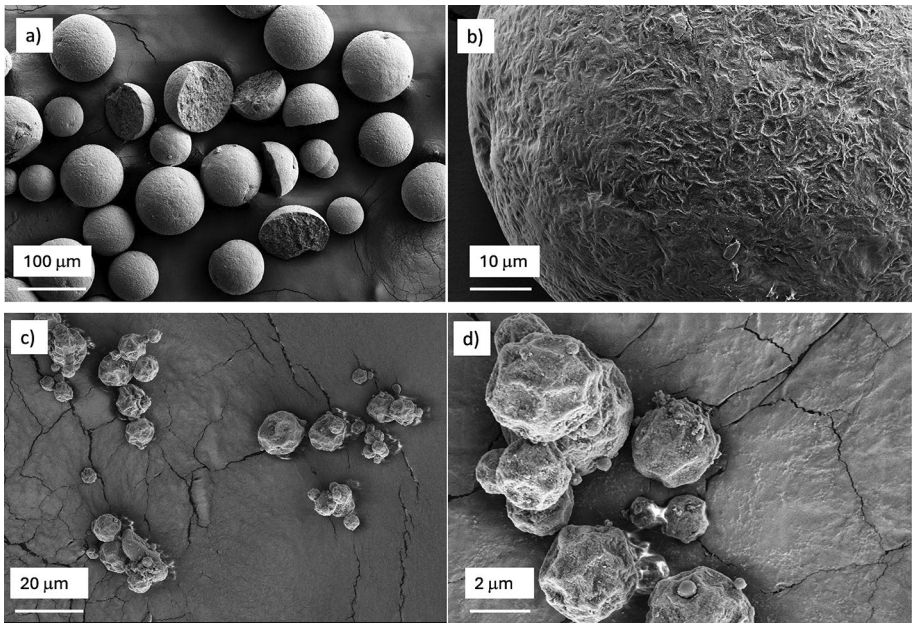

Fig. 1 FE-SEM images of the microspheres and relative size distribution of LDPE (**a**, **b**), and of PU (**c**, **d**)

Heavy metal adsorption capacity

The adsorption capacity of microplastics was evaluated against Cu^{2+} and Fe^{3+} ions used as heavy metal probes. The MPs were dispersed at a concentration of 1000 mg L^{-1} in Egg Water and Elendt M7 media. A stock solution of $CuCl_2$ at 100 mg L^{-1} was added to the suspensions to have a total concentration of Cu equal to 10 mg L^{-1}. A stock solution of $Fe(NO_3)_3$ at 100 mg L^{-1} was added to the suspensions to have a total concentration of Fe equal to 2 mg L^{-1}. These values were chosen assuming that, during a hypothetical spill, the concentrations of Cu and Fe reached values 10 times higher than the legal limit for water intended for human consumption, set at 1 mg L^{-1} for Cu and 0.2 mg L^{-1} for Fe by Italian Legislative Decree 31/2001 [34].

As negative control, MPs were dispersed in MilliQ water to check for any release of ions by the microspheres. All the samples were prepared in triplicate and incubated for 6 days in the dynamic thermostatic bath. After the incubation period, the suspensions were filtered with PES syringe filters 0.22 µm, and the recovered media were acidified by adding nitric acid (10% by volume of HNO_3—65%) and analyzed by ICP-OES. Adsorption was calculated by the difference between Cu and Fe ions recovered from filtration and the administered concentrations in the medium. All samples were obtained in triplicates; the detection limit was 0.01 mg L^{-1}.

Results and discussion

Microplastics characterization

FE-SEM size distribution and morphology of pristine powders are reported in Figs. 1 and S1. From the morphological point of view, the LDPE microparticles (Fig. 1a) appear spherical and, at higher magnifications, the surface exhibits micro-roughness (Fig. 1b). The LDPE microspheres present an average diameter of 70 ± 2 µm (mode equal to 62 µm; median equal to 65 µm), and are characterized by a bimodal size distribution, as shown in Figure S1a. The PU microparticles also show a spherical shape, but with irregular morphology (Fig. 1c, d). In terms of size, the microparticles have an average diameter smaller than LDPE, equal to 5.8 ± 0.2 µm (mode and median are equal to 5 µm) with a narrow dimensional distribution, but tailed toward higher diameter values, as shown in Figure S1b. The size distribution of both target MPs determined by FE-SEM confirmed the certified size declared by the manufacturers, that are reported in the "Materials" section.

We investigated the elemental composition of the microparticles through ICP analysis, checking the presence of eventual metal/inorganic additives or impurities. The concentrations of the ions expressed in mg of metal on g of plastic are shown in Table S2. In general, the concentrations of the investigated ions are quite low, all below 0.1 mg g^{-1}, except for sodium in PU microplastics, which have values above 4 mg g^{-1}. The presence of sodium could justify these data as a counter ion of

surfactants or neutralizing agents used during the synthesis [35].

The chemical structure of the microplastics was investigated using FTIR spectroscopy, and the spectra were consistent with those of corresponding macro-plastics. Figure 2a of the LDPE microplastics shows the peaks at 2914 and 2847 cm^{-1}, attributable to the stretching of the C–H bond, while those at 1472 and 1462 cm^{-1} were attributable to the bending of -CH_2 and -CH_3 [36]. Figure 2b of the PU microplastics shows the peak at 3340 cm^{-1} attributable to the stretching of the N–H bond, typical of the urethane group. The series of peaks between 2867 and 2969 cm^{-1} are attributable to the stretching of the C–H bond of the methyl group, probably due to an alkyl chain. Finally, the peaks at 1720, 1633, and 1556 cm^{-1} are attributable to the stretching of the C=O bond, the stretching of the C–N bond, and the bending of the N–H bond, respectively [36].

The thermal characterization of microplastics was performed to investigate the presence of additives. Figure 3 shows the thermograms relating both to the TGA and the DSC analysis of the two MPs. LDPE presented an onset degradation temperature of about 285 °C in air and 410 °C in nitrogen, observable by TGA measurements (Fig. 3a). Furthermore, the complete degradation of the polymer in both cases suggests the absence of inorganic additives (mass degradation 100%). The DSC analysis of LDPE showed an endothermic transition at 111 °C, attributable to the polymer's melting. While the TGA of PU microspheres presented an onset degradation temperature of ca. 295 °C in air and of 315 °C in nitrogen. In addition, we observed a weight loss of about 3% at 164 °C associated with an exothermic transition only in the analysis in the air (Fig. 3b). This event is attributable to an oxidative phenomenon, with the probable development of CO_2 [37]. Also, in this case, the complete degradation at the end of the analysis confirms the absence of inorganic additives [38].

Colloidal characterization

The zeta potential (ZP) as a function of the pH in MilliQ water of LDPE and PU is reported in Fig. 4. Both materials have negative zeta potential at natural pH (ZP = − 51.0 ± 4.3 mV at pH = 6.6 and ZP = − 29.5 ± 1.4 mV at pH = 5.6 for LDPE and PU, respectively). The LDPE curve presents the characteristic inverse sigmoid shape, with an isoelectric point (IEP) at a pH value of 3.8, while PU showed a relatively lower ZP across the whole pH range investigated, with IEP set at 2,7. The high negative ZP values at natural pH of microplastics with a strong hydrophobic character and insolubility in water is a topic debated in the research field. Among the controversial explanations for the negative zeta potential (ZP) of hydrophobic particles are the adsorption of hydroxyl ions (OH^-) [39], interfacial polarization [40], adsorption of bicarbonate ions (HCO_3^-) [41], charge transfer between water molecules [42], and surface-active

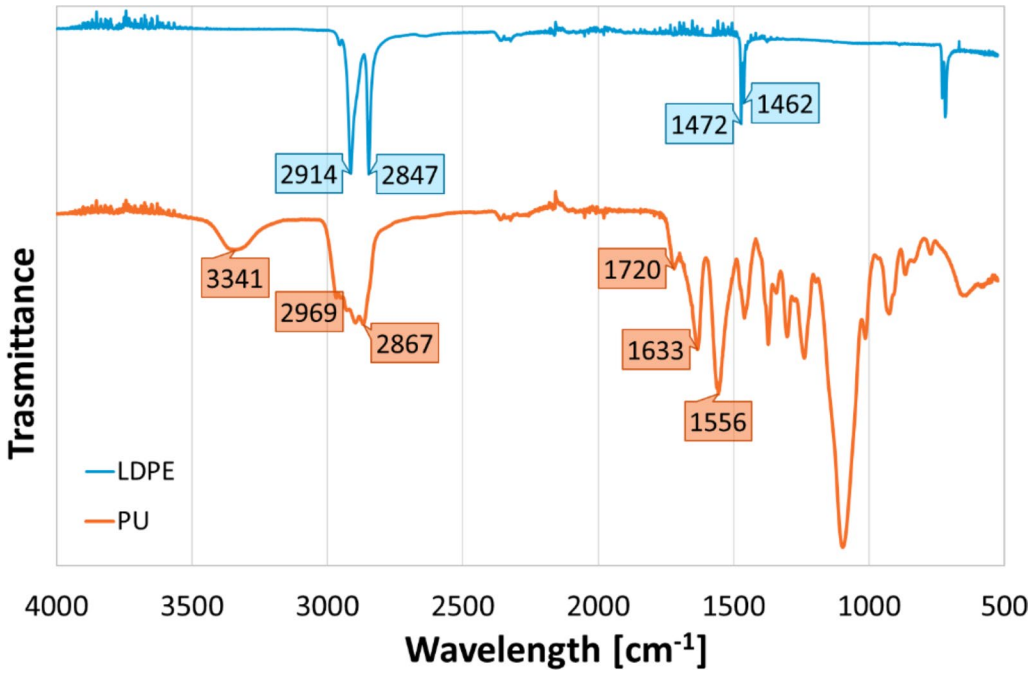

Fig. 2 AT-FTIR spectra of LDPE and PU microplastics

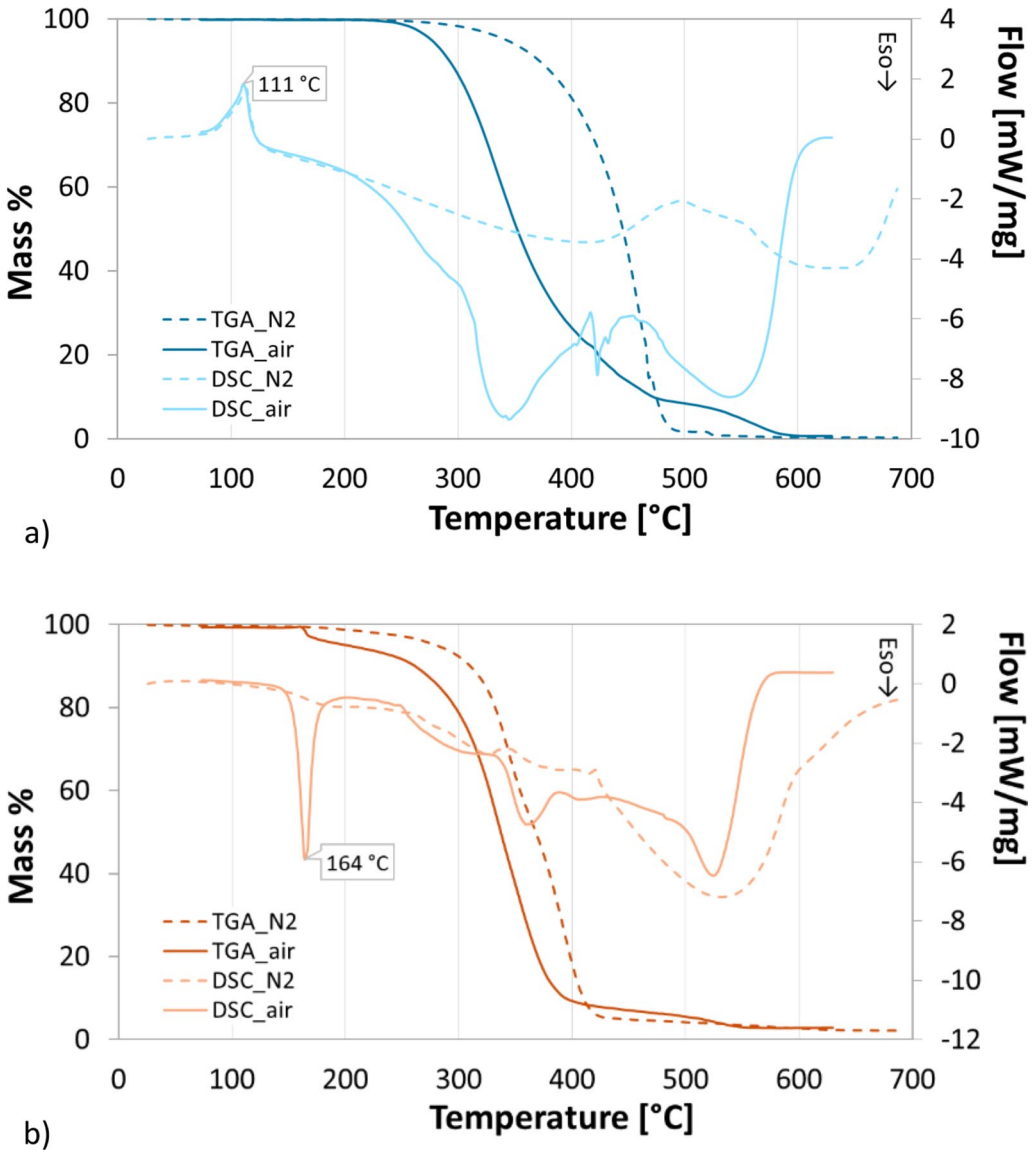

Fig. 3 TGA and DSC thermograms of the pristine **a** LDPE and **b** PU MPs under nitrogen (N_2) and air (air) atmosphere

charged impurities, predominantly anionic surfactants, at the air/water interface [43, 44], well justified by the presence of additives, often added to improve processability, elasticity, flame retardancy, and mechanical or chemical resistance [45, 46].

Zeta-potential (ZP) values of microplastics dispersed in Egg Water and Elendt M7, which mimic freshwater media at different salt concentrations (higher in Elendt M7), are reported in Tables S3 and S4.

For both microplastics, we measured ZP vs pH curves at different concentrations and different incubation times, comparing the results with the corresponding suspensions in MilliQ water (see Figs. 5 and 6). As expected, the curves of the LDPE samples dispersed in saline media (Fig. 5) were more flattened than in water, and the ZP values approached 0 mV. This trend is reflected in a decrease in colloidal stability due to the increase in ionic strength and the consequent compression of the double layer [47]. The phenomenon is more pronounced in the Elendt M7 medium than in the Egg water medium due to the presence of higher amounts of salt. The PU samples (Fig. 6) showed most likely the exact behavior of LDPE ones, presenting a less-pronounced destabilization trend in Egg water compared to Elendt M7. This was further confirmed by the shift in the isoelectric point (IEP), which in Elendt M7 was set at values lower than 1.5 for all the concentrations and exposure times investigated. The PU samples exhibited a behavior like that of the LDPE samples, reaching

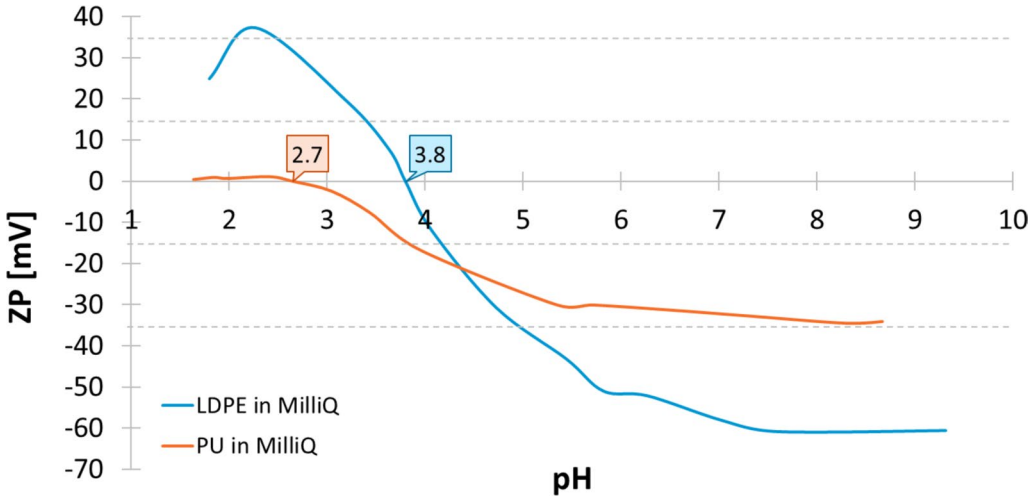

Fig. 4 Zeta potential vs. pH for LDPE (●·) and PU (●) dispersed in MilliQ water

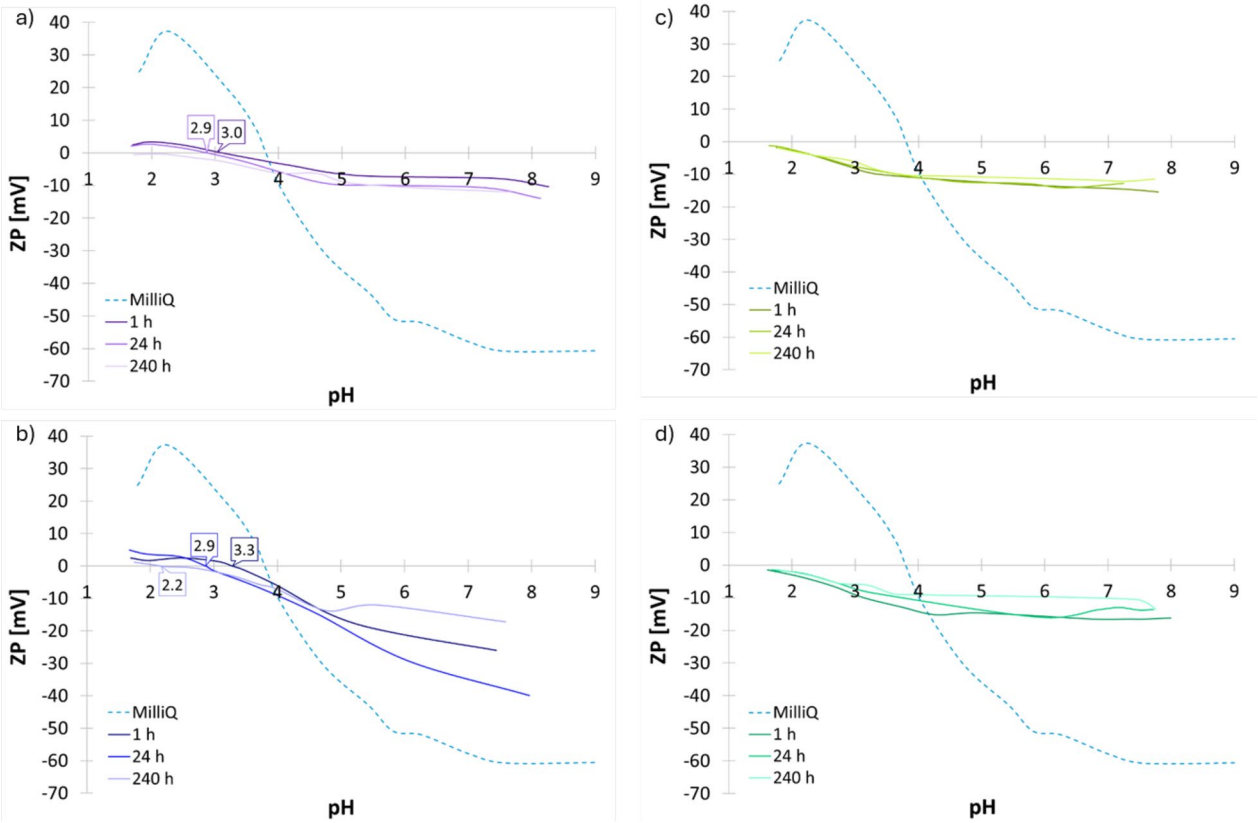

Fig. 5 Zeta Potential vs. pH curve for LDPE in Egg Water **a** 100 mg L^{-1}, **b** 1000 mg L^{-1} and in Elendt M7 **c** 100 mg L^{-1}, **d** 1000 mg L^{-1}, at different exposure times. Samples incubated in environmental media were compared with the corresponding dispersion in water at 100 mg L^{-1}

an equilibrium within 1 h. Nevertheless, after 240 min of exposure in Elendt M7 medium, PU samples showed a slight increase in negative zeta-potential (ZP) values, likely due to the specific adsorption of polyvalent ions [48], as sulfate anions SO_4^{2-}, present in high quantity in Elendt M7 water. The hypothesized mechanisms involved in the colloidal destabilization in saline media are schematized in Figure S2.

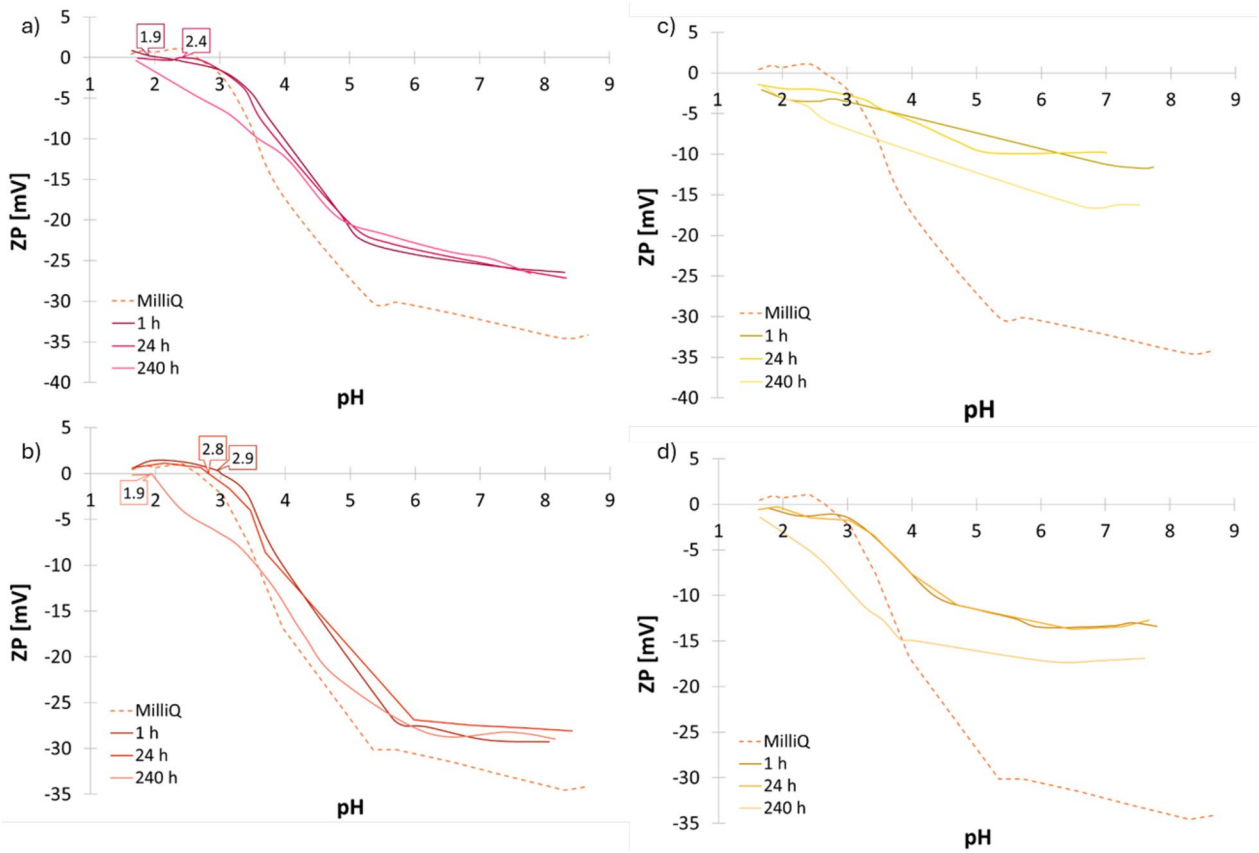

Fig. 6 Zeta potential vs pH curves for PU in Egg Water, **a** 100 mg L^{-1}, **b** 1000 mg L^{-1} and in Elendt M7 **c** 100 mg L^{-1}, **d** 1000 mg L^{-1}, at different exposure times

(Heavy) metal adsorption capacity

To verify if the exposure to environmental media influenced the content of metal ions present on MPs, we compared the elemental analysis of mineralized MPs before and after the exposure (see Fig. 7). The LDPE samples showed a significant increase in the total amount of detected cations (Fig. 7a), suggesting a tendency of the MPs to adsorb the ions present in the medium. By contrast, the PU plastics exhibited a significant loss of sodium in both media (Fig. 7b), most likely because there was an excess in the pristine PU plastic due to synthesis by-products.

Finally, we investigated the metal adsorption capacity for copper and iron added to aqueous media, using MilliQ water as a reference alongside Egg Water and Elendt M7 (Fig. 8). Regarding the adsorption of Cu (Cu^{2+} cations) (Fig. 8a), we detected a significant difference between the amount of Cu adsorbed in Elendt M7 compared to the other media, both for LDPE and PU. The influence of the medium as the main driver of the adsorption capability was already observed for different heavy metals, like Hg and Pb [13, 14]. In our work, this finding suggests that the adsorption of copper in Elendt M7 is promoted by its high affinity with the SO_4^{2-} groups specifically adsorbed on plastic surfaces [49]. Furthermore, if in Elendt M7, the adsorption seems independent of the type of material, in MilliQ water and Egg water, it varies according to the polymer, and in particular, it is higher for PU, suggesting selective adsorption of copper ions for this plastic. This finding agrees with the study of B. Acemioğlu and M.H. Alma, which demonstrated a high affinity of PU to Cu^{2+} ions, promoting it as a new adsorbent and alternative to activated carbon in Cu^{2+} removal [50]. In general, the greater adsorption capacity of PU could be attributable to its polarity. In fact, Xu et al. found that the adsorption on polar MPs was significantly greater than that on nonpolar MPs, such as LDPE [51]. Instead, the morphology seems not to play a key role, as could be assumed. In fact, the micro-roughness that characterizes the LDPE MPs did not significantly promote metal adsorption. A different behavior was observed for Fe^{3+} cations, as reported in Fig. 8b, where we detected

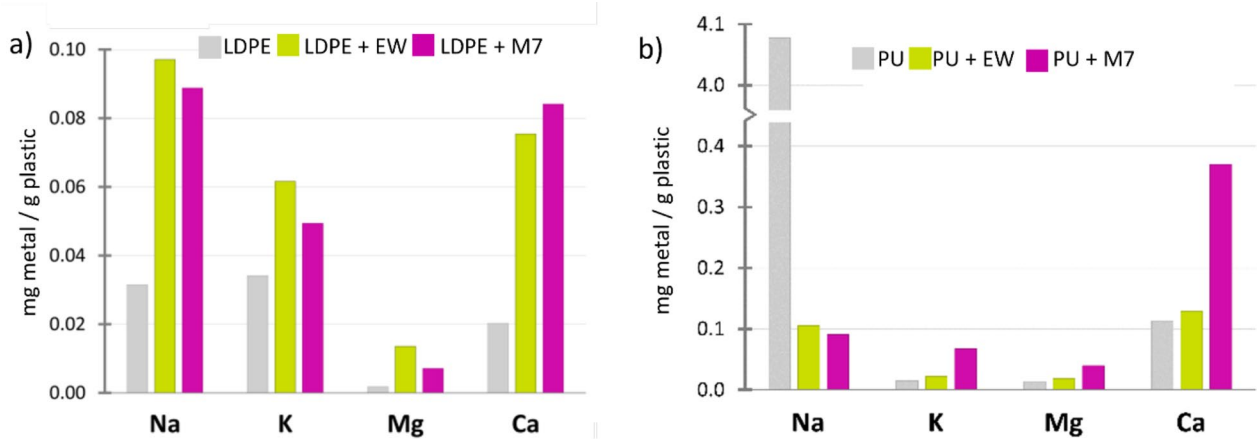

Fig. 7 Metal content of **a** LDPE and **b** PU after exposure to MilliQ water, Egg Water (EW) and in Elendt M7 (M7)

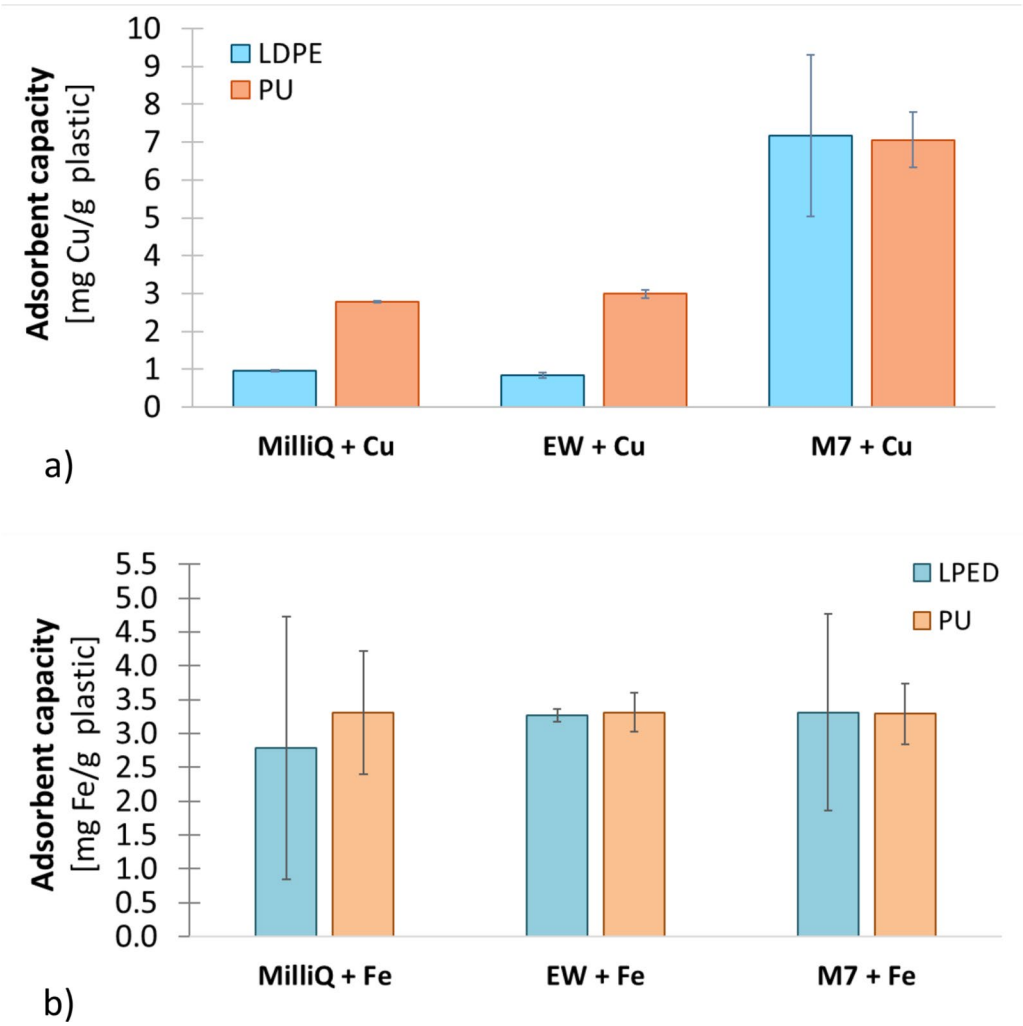

Fig. 8 Adsorbent capacity of LDPE and PU MPs to **a** Cu and **b** Fe ions in aqueous media, Milli Q water, Egg water (EW), and Elendt M7 (M7)

almost comparable adsorbent capacity for both plastics in all the media.

Conclusions

Establishing the physicochemical identity of microplastics is the first step for the interpretation of their safety profile. As a representative class of microparticles, we investigated LDPE and PU primary microplastics characterized by a spherical morphology, a micrometric surface roughness, and different sizes, with LDPE particles diameters around 70 microns and PU microparticles around 5 microns. FTIR spectra confirmed that the chemical structures of the microparticles match their respective macro-plastics. The absence of residual mass at the end of thermal analysis indicated that no inorganic additives were present.

Zeta-potential measurements in aqueous suspensions allowed to assess the potential transformation occurring in environmentally relevant media, providing indications of their biological identity and colloidal stability. Both pristine LDPE and PU dispersed in MilliQ water showed a negative zeta potential at natural pH, likely due to the presence of surface-active charged impurities such as synthesis by-products or additives. Dispersion in saline media caused a compression of the electrical double layer, leading to a decrease in negative zeta potential and a shift of the isoelectric points toward lower pH, as a consequence of the adsorption of oxyanions such sulfate from the media. Metal adsorption tests with copper and iron ions provided insights into the capacity of microplastics to transport heavy metals in the environment. Selective adsorption of Cu^{2+} ions was observed, which was both medium-dependent, driven by SO_4^{2-}-rich Elendt M7, and plastic-dependent, with PU showing a stronger affinity for Cu^{2+} in MilliQ and Egg water. In contrast, both plastics showed similar adsorption capacity for Fe^{3+} ions across all media. Overall, these findings enabled us to understand the transformation occurring at the MPs/water interface, especially some adsorption phenomena that significantly influence their hazardous potential.

Abbreviations

ATR-FTIR	Fourier transform infrared spectroscopy with attenuated total reflection
DSC	Differential scanning calorimetry analysis
ELS	Electrophoretic Light Scattering
FE-SEM	Field Emission Scanning Electron Microscopy
ICP-OES	Inductively coupled plasma optical emission spectroscopy
IEP	Isoelectric point
LDPE	Low-Density Polyethylene
MPs	Microplastics
MNPs	Micro- and nano-plastics
OECD	Organization for Economic Cooperation and Development
PU	Polyurethane
STEM	Scanning Transmission Electron Microscopy
TGA	Thermogravimetric analysis
ZP	Zeta potential

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-025-01061-5.

Supplementary Material 1.

Acknowledgements

This work was supported by the "PlasticsFatE" (Plastics Fate and Effects in the human body) H2020 European project (H2020—GA 965367).

Author contributions

Conceptualization: I.Z., M.B., S.A., and A.L.C.; methodology: I.Z., L.B., M.C., and G.M.; investigation: I.Z., L.B., L.F., and S.O.; data curation: I.Z., L.B., L.F., S.O., M.C., and G.M.; writing—original draft preparation: I.Z. and L.B.; writing—review and editing: S.O. and A.L.C.; supervision: M.B., S.A., and A.L.C.; funding acquisition: A.L.C. All authors have read and agreed to the published version of the manuscript.

Funding

This work was funded by European Commission, H2020 - GA 4965367.

Data availability

Data are provided within the manuscript or supplementary information files.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 29 October 2024 Accepted: 26 January 2025
Published online: 06 February 2025

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