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First-line detection of PET and PVC microplastics in water using a portable fluorescence lifetime platform

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ABSTRACT

The widespread presence of micro- and nanoplastics (MNPs) in aquatic environments raises increasing environmental and health concerns, highlighting the need for fast, portable, and accessible detection methods. While fluorescence lifetime analysis coupled with phasor analysis has shown promise for monodispersed polystyrene (PS) detection, its applicability to other prevalent MNPs remains underexplored. Here, the aqueous suspensions of polyethylene terephthalate (PET) and polyvinyl chloride (PVC) microplastics (0.01–0.05 mg/mL) were examined without labeling or preprocessing. Time-correlated single-photon counting data were transformed into phasor plot to extract their fluorescence lifetime (τ_Φ) and modulation. Both polymers exhibited stable fluorescence lifetimes (2.38±0.12 ns for PET and 2.50±0.21 ns for PVC) across the concentration range tested. Despite the fluorescence lifetimes of PET and PVC overlap with those of other common polymers, such as PS (2.34±0.14 ns), the photon counts and modulation increased approximately linearly with microplastic concentration. In summary, the consistent signal and the relationships among concentration, photon counts, and phasor fingerprints make the portable, label-free FLA system reliable for detecting MNPs in water within minutes, with a limit of detection of 0.01 mg/mL. This system's capability is particularly valuable for its deployment as a first-line screening tool in remote or resource-limited communities, enabling timely interventions and trigger targeted advanced polymer-specific analysis.

1. Introduction

The ubiquity of micro- and nano- plastics (MNPs) in global aquatic ecosystems has gained significant scientific attention due to their enduring environmental impact and potential human health implications (Enfrin et al., 2019). Recent statistics indicate that millions of tons of these plastics are produced annually, with a significant fraction failing to be recaptured through recycling efforts and ultimately ending up in natural water systems (Geyer et al., 2017). This persistence is further compounded by the potential of these plastics to leach harmful additives (Li et al., 2024), underscoring the necessity for robust, sensitive detection technologies (Wu et al., 2018). In particular, polyethylene terephthalate (PET) and polyvinyl chloride (PVC) are among the most abundantly produced and discarded plastics worldwide. These plastics are frequently identified in marine and freshwater environments as well as within industrial wastewater discharges (Smith, 2022; Lu et al., 2023; Monteleone et al., 2021) . The detection and quantification of these specific types of MNPs are critical not only for environmental monitoring but also for mitigating potential pollution sources from industrial processes.

Current detection methods including pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS) (Okoffo et al., 2020), Fourier-transform infrared (FT-IR) and Raman spectroscopies (Ivleva, 2021), often costly and face time-consuming workflows (Mahapatra and al., 2024; Sharma et al., 2024). In contrast, a newly emerged technology – fluorescence lifetime imaging microscopy coupled with phasor analysis (FLIM-phasor) provides a fast and non-invasive microplastics (MPs) identification and differentiation by exploiting polymer autofluorescence (Monteleone

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et al., 2021; Sancataldo et al., 2020). However, the dependence on bulky microscopy limits its applications. In fluorescence lifetime analysis (FLA), a laser pulse excites the sample, the emitted photon was detected by a single-photon detector and a time-tagger records the emitted light decay. The resulting fluorescence decay curve is converted into phasor coordinates (g, s) on a 2D plot, with each coordinate reflecting the fluorescence lifetime of the sample. Many plastics possess intrinsic fluorescence (Monteleone et al., 2021), so autofluorescent microplastics form distinct clusters on the phasor plot, providing intuitive visualization and quantification of their presence.

A fluorescence lifetime analysis (FLA) system was recently presented for the detection of monodispersed PS MNPs. In that system, PS particles with different sizes and surface modifications were successfully detected and mapped effectively on phasor plots. Each PS sample produced a characteristic cluster, and their position on the plot shifted systematically with particle concentration[15]. Although the FLA system does not provide images, it provides precision, sensitive and affordable measurement for fluorescence lifetimes. Expanding on this groundwork, this work addresses the open question of whether this established FLA system can be effectively applied to more environmentally dominant microplastics. Specifically, this study applied the portable, stand-alone FLA system to polydisperse PVC and PET MPs in aqueous suspension, thereby extending its scope beyond frequently studied PS particles (Ekvall et al., 2022). PVC and PET were chosen due to their substantial prevalence in the environment, especially in agricultural soils where accumulation is often intensified using contaminated irrigation waters (Dawson et al., 2023). Given their prevalence and environmental significance, the ability to monitor these plastics is not merely a scientific endeavor but a necessity for environmental protection and pollution control strategies (Sancataldo et al., 2020; Huang et al., 2023). This inquiry is driven by the need for versatile and broadly applicable environmental monitoring tools that can adapt to various types of plastic pollutants without requiring extensive reconfiguration.

This work aims to validate and demonstrate the capability of the portable FLA system for the rapid, label-free detection of PET and PVC MPs in aqueous samples. The FLA measurements demonstrate that these polymers exhibit fluorescence lifetime characteristics closely resembling those of PS under the tested conditions. Although the chemical composition and physical structure of these plastics differ, their fluorescence lifetime signals converge within a similar range when measured in a label-free, aqueous environment. This overlap implies that fluorescence lifetime alone does not enable discrimination among different polymer types such as PS, PET, and PVC. Nevertheless, the autofluorescence signal and phasor fingerprint response vary predictably with particle concentration, confirming the capability of this compact FLA system for rapid, label-free detection of widely distributed MNP in aqueous suspension.

2. Materials and methods

2.1. Preparation and characterization of PET and PVC samples

Polyethylene terephthalate (PET) and polyvinyl chloride (PVC) microplastic particles were purchased from Suyuan plastic material and Tesulang chemical material respectively (Guangdong, China) in the form of powder. The particles were weighed and suspended in water to prepare stock solutions. Serial dilutions were performed to achieve final concentrations ranging from 0.01 mg/mL to 5 mg/mL. It's worth noting that all materials were used as received, without further treatment, such as purification and labeling. Prior to DLS and FLA measurement, suspensions were shake-mixed and started right away to minimize gravitational settling.

The plastic powders used in this study were characterized using an ALPHA II compact Fourier-Transform Infrared Spectroscopy (FTIR) spectrometer (Bruker), equipped with an attenuated total reflection (ATR) module (Eco-ATR). Specifically, plastic powder was loaded on a high-throughput ZnSe crystal and the IR spectra were acquired in the wavelength range of 4000 to 600 cm^{-1}, and for each spectrum 24 scans, at a resolution of 4 cm^{-1} was averaged. The background was acquired before the measurements and then subtracted from each sample spectra. The spectra were registered and preprocessed using the commercial OPUS 8.5 SP1 software, dedicated to the analysis of IR spectral data.

The hydrodynamic size, polydispersity index (PDI), and zeta potential of the samples were measured at room temperature with Zetasizer Ultra Red (ZSU3305, Malvern Panalytical, U.K). The results were presented as the mean ± standard deviation of three independent measurements.

2.2. FLA experiments

A portable Fluorescence Lifetime Analysis (FLA) system developed with FLIM LABS (Rome, Italy) was used to investigate the fluorescence lifetimes of the samples (Xiao et al., 2024). The system includes a time-resolved laser-induced fluorescence lifetime spectroscopy and customizable software for data acquisition and analysis. A 445 nm picosecond pulsed laser with a repetition rate of 40 MHz was used to excite the samples. The emitted fluorescence signals were collected through a 500 nm long-pass filter using a Single-Photon Avalanche Diode (SPAD) detector, which records time-correlated single-photon counting (TCSPC) data. The system's components, including the laser and SPAD detector, are housed in a portable 30 cm × 30 cm box, enhancing the system's suitability for on-site inspections. The FLA system was first calibrated with coumarin 153 (C153) in methanol, which exhibits a single exponential decay with a fluorescence lifetime of approximately 4.3 ns (Boens et al., 2007). Then, the sample suspensions were excited and the TCSPC data were recorded and processed using custom-written software in a Jupyter Lab notebook and Matlab, as detailed in the previous work (Xiao et al., 2024). The software reconstructed the fluorescence intensity decay curves and they were transformed to vectors (g, s) on phasor plots, forming phasor fingerprints and providing information on fluorescence lifetime and modulation parameter. The vectors (g, s) were calculated as following:

$$g(\omega) = \frac{\int I(t)\cos(\omega t)dt}{\int I(t)dt} \tag{1}$$

$$s(\omega) = \frac{\int I(t)\sin(\omega t)dt}{\int I(t)dt} \tag{2}$$

where ω is the angular frequency for a laser of repetition rate f, i.e., $\omega = 2\pi f$ (in this case $f = 40$ MHz). Two parameters, modulation and phase angle were used to compute the fluorescence lifetime τϕ:

$$m = g^2 + s^2 \tag{3}$$

$$\varphi = arctan\left(\frac{s}{g}\right) \tag{4}$$

$$\tau_\phi = \frac{1}{h\omega} tan\phi \tag{5}$$

where h represents the harmonic parameter. In this case, we performed a first-harmonic analysis. Then, $h = 1$.

3. Results

The chemical identity of the purchased PET and PVC microplastic powders was first assessed using ATR-FTIR spectroscopy. Representative FT-IR spectra for PET and PVC are shown in Fig. 1, confirmed the presence of the expected vibrational signatures for each polymer. In both spectra, weak but noticeable absorption bands were observed around 2352 and 2362 cm^{-1}, most likely due to atmospheric carbon dioxide interference during measurements, as commonly reported in

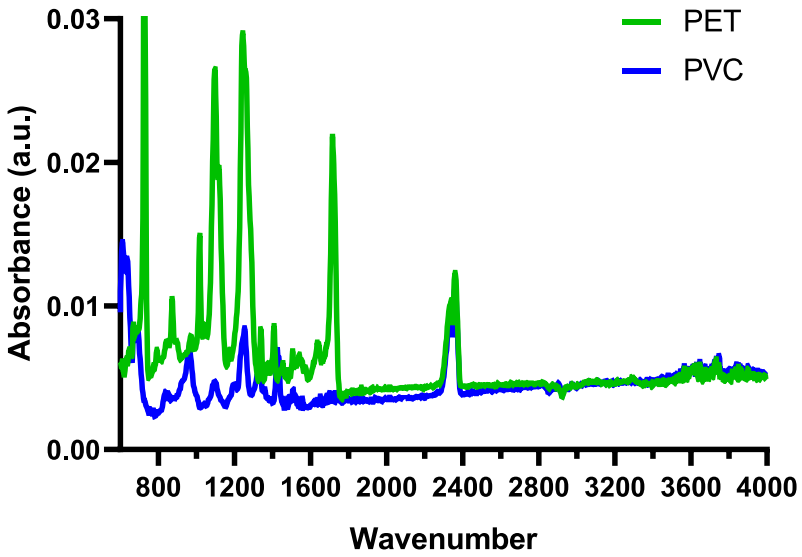

Fig. 1. ATR-FTIR characterization of PET and PVC microplastics. Representative FT-IR spectra of PET and PVC MPs recorded using attenuated total reflectance Fourier-transform infrared spectroscopy. The spectra display the characteristic absorption bands for each polymer, confirming their chemical identity. Common features in both spectra around 2352–2362 cm^{-1} are attributed to atmospheric CO_2 interference. PET shows strong peaks associated with ester and aromatic groups, while PVC presents distinctive C–Cl and CH–Cl vibrational modes, consistent with reference polymer profiles.

ATR-FTIR analysis of environmental samples (Reggente et al., 2019). Despite this minor overlap, the spectral profiles clearly displayed the characteristic functional group vibrations of PET and PVC. In the case of PET, the well-defined absorption peaks at 725 cm^{-1} (assigned to out-of-plane C–H bending in the aromatic ring), 876 cm^{-1} (CH_2 rocking), 1016 cm^{-1} (in-plane C–H stretching), and intense bands at 1100 and 1248 cm^{-1} attributed to the C–C–O stretching of ester groups were observed. The carbonyl ($C = O$) stretching band of the carboxylic ester moiety was located at 1718 cm^{-1}, in agreement with reference spectra in the literature (Park et al., 2021). The spectrum of PVC similarly revealed distinct bands corresponding to its chlorinated structure: peaks at 613, 636, and 689 cm^{-1} were assigned to C–Cl stretching, while bands at 960 cm^{-1} (CH_2 rocking), 1102 cm^{-1} (C–C stretching), and 1252 and 1330 cm^{-1} (CH—Cl bending modes) confirmed the presence of polyvinyl chloride. A broad signal at 1428 cm^{-1}, corresponding to CH_2 wagging, was also observed, completing the spectral fingerprint of PVC MPs (Park et al., 2018).

To complement the chemical identification, the physical properties of the suspensions were also characterized by dynamic light scattering (DLS) and zeta potential measurements. As reported in Table 1, both PET and PVC MPs exhibited high Z-average sizes, in the range of 7–8 μm, consistent with a fragmented microplastic population. The polydispersity index (PdI) was equal to 1 for both materials, indicating a highly heterogeneous particle distribution, which is not unexpected given the non-uniform fragmentation processes typically involved in MP generation. Zeta potential values were significantly negative for both polymers, –44.3 mV for PET and –61.5 mV for PVC, confirming that the particles are colloidally stable in aqueous suspension and are likely to exhibit limited aggregation under the conditions used in subsequent fluorescence measurements (Ali et al., 2010; H Muller et al., 2011).

Table 1
Chemical-physical characterization of PET and PVC MPs.

MP	Z-Average (nm)	PdI	Peak 1 Mean by Intensity (nm)	Peak 1 Area by Intensity (%)	Zeta Potential (mV)
PET	7908.3 ± 1483.2	1	1220.6	100 %	−44.3 ± 1.5
PVC	6923.3 ± 476.5	1	1306.0	100 %	−61.5 ± 1.6

Following this physical-chemical characterization, the possibility of direct detection without any form of sample pre-treatment or labeling was investigated using previously developed FLA system. The system was first calibrated using C153, a standard fluorophore with a well-characterized single exponential decay. PET and PVC suspensions were then analyzed across a wide concentration range, from 0.01 to 5 mg/mL, under label-free conditions. The reconstructed fluorescence decay profiles for both materials are shown in Fig. 2a and 2b It's worth noting that slow precipitation was observed at high concentration (> 1 mg/mL). As a result, the photon counts deviation was larger at high concentration tested (Fig. 2c-d). Whereas, no large shift was detected at lower concentrations, confirming that the suspensions remain stable throughout the measurement. In both cases, the total number of detected photons increased with concentration, confirming that MPs emit detectable autofluorescence under the chosen excitation and detection settings. Linear regression of photon counts versus MP concentration yield good fits for PET (R^2= 0.98; Fig. 2c) and PVC (R^2= 0.96; Fig. 2d). The corresponding phasor plots, shown in Fig. 2e and 2f, provided further insight into the fluorescence decay behavior of the particles. Across all concentrations, phasor coordinates from both PET and PVC suspensions followed a nearly linear trajectory in the (g,s) phasor space, suggesting similar fluorescence lifetime dynamics. Interestingly, the phasor fingerprints of PET and PVC overlapped almost completely, suggesting that the two materials exhibit very similar intrinsic lifetime features under these conditions. Although this spectral convergence limits the ability to discriminate between PET and PVC based solely on fluorescence lifetime, the stability and reproducibility of the phasor signatures across the tested concentration range demonstrate that FLA can be used reliably to detect the presence of MPs in aqueous samples, even when specific polymer identification is not feasible.

To better quantify the optical behavior of the suspensions several key parameters were extracted from the phasor analysis, shown in Fig. 3 The fluorescence lifetime τ_Φ across concentrations shown do not exhibit significant variation (Fig. 3a and b), with an averaged value around 2.38 ns for PET, and 2.50 ns for PVC, indicating stable fluorescence lifetime characteristics irrespective of particle concentration. Conversely, the modulation parameter (m), shown in Fig. 3c and d, which represents the distance of the phasor fingerprints from the origin in the phasor plot, exhibited a clear increasing trend as particle concentration increased. A slight drop in m was observed around 1 mg/mL, which can be attribute

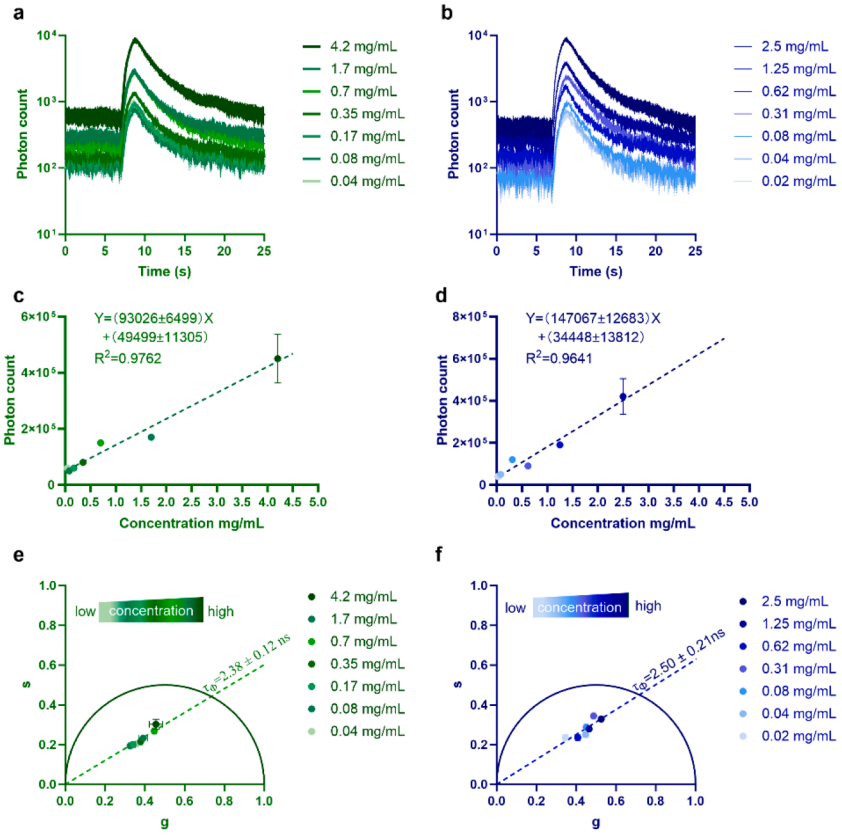

Fig. 2. Fluorescence lifetime analysis of suspensions of PET and PVC MPs. Fluorescence decay profiles of (a) PET and (b) PVC MPs measured at various concentrations (0.01–5 mg/mL) under label-free conditions. Photon counts versus (c) PET and (d) PVC concentration with linear fits (dashed lines). Corresponding phasor plots for (e) PET and (f) PVC show a linear distribution of data points across concentrations, indicating stable fluorescence lifetime (τ_Φ). The overlapping phasor fingerprints for PET and PVC suggest similar lifetime behavior under the experimental conditions, highlighting the feasibility of MP detection but not their discrimination based solely on fluorescence lifetime.

to inner-filter effect at elevated concentrations (Panigrahi and Mishra, 2019). In highly concentrated samples, excitation light is attenuated near the surface of the cuvette, and fluorescence emitted from deeper regions is partially re-absorbed by the particles (Wenzel, 2021), thereby reducing the apparent m value.

Furthermore, it is important to note that in the phasor approach, the modulation parameter is inherently influenced by sample brightness. Lower brightness enhances the relative contribution of background signals, which shifts the phasor coordinates toward the origin ($g = 0$, $s = 0$). In the present study, sample brightness correlates strongly with particle concentration; Thus, any reduction in brightness—whether arising from lower concentrations or from attenuation and reabsorption caused by inner-filter effects at higher concentrations—renders the phasor representation more susceptible to background noise. This interplay between brightness, inner-filter effects, and background contribution provides additional context for the observed modulation behavior at extreme concentrations.

Taken together, these results confirm that FLA can detect PET and PVC microplastic particles suspended in water across a broad range of concentrations. However, it is important to note that the similarity in fluorescence lifetime characteristics among these polymers—and their overlap with values previously reported for polystyrene—suggests that fluorescence lifetime alone is not sufficient for polymer-specific identification. Nonetheless, the sensitivity, label-free nature, and minimal sample preparation requirements of FLA make it ideally suited as a first-level screening tool for the presence of MNPs in complex aqueous matrices. Once the presence of contamination is established, complementary and more resource-intensive analytical techniques can be employed to determine the specific chemical composition of the particles.

4. Discussion

Plastic pollution is one of the biggest environmental problems of the 21st century, several studies have highlighted their presence in aquatic ecosystems (Mutuku et al., 2024). UNEP suggests up to 23 million tons of plastic waste seep into the world's water systems every year (UNEP 2025), where it degrades into MNPs gradually (Ali et al., 2024). While laboratory techniques like FT-IR, Raman spectroscopy and Py-GC/MS offer precise polymer identification, their dependence on infrastructure, skilled operators, and lengthy sample preparation limits their utility for rapid, field-deployable application (Lv et al., 2020). This gap underscores the critical need for easy-to-use, low-cost, and portable detection systems (Iri et al., 2021). Furthermore, a rapid detection of MNPs in water system is crucial (Thompson et al., 2024) for understanding their prevalence, potential health impacts and for developing effective mitigation strategies.

The FLIM-phasor technique addresses this need by exploring the use of FLA for detecting and differentiating MPs in a fast, non-destructive, and label-free way (Monteleone et al., 2021; Sancataldo et al., 2020; Zhou et al., 2022; Wohlschläger et al., 2024). However, its dependence on bulk microscopy limits its application for field investigations. To broaden its application, a portable FLA system without the aid of microscope was developed. In this prior study, its applicability to PS MPs and NPs has been validated. Those PS MNPs were successfully detected in water as low as 0.01 mg/mL. Moreover, their phasor fingerprints follow a single trajectory on the phasor plot, and move far from the origin as concentration increases (Xiao et al., 2024), suggesting the

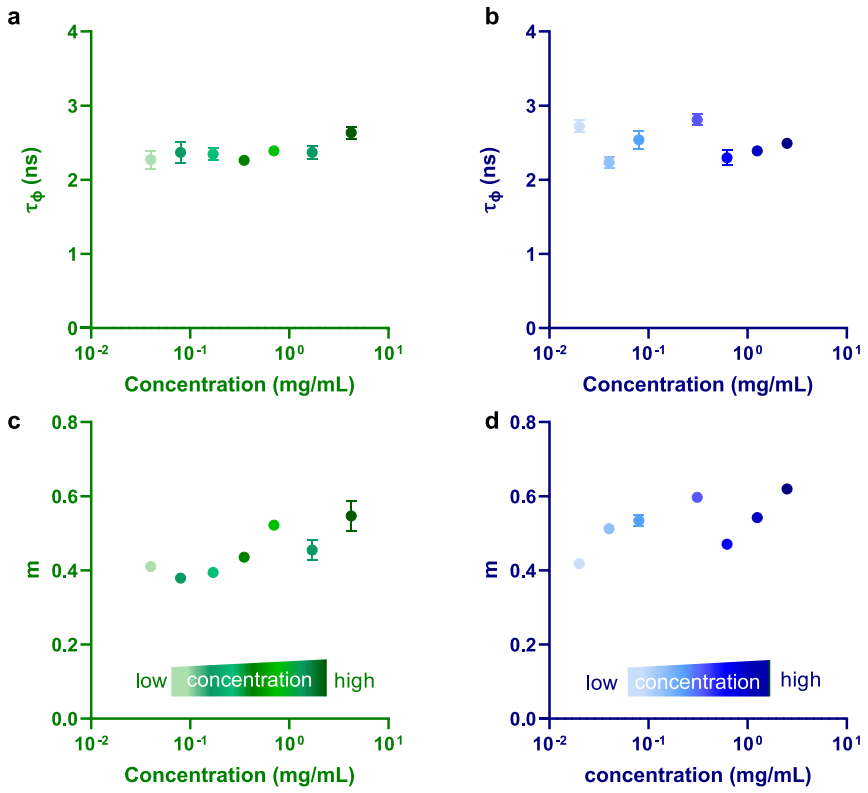

Fig. 3. Quantitative analysis of key FLA parameters as a function of particle concentration for PET and PVC MP suspensions. Fluorescence lifetime (τ_Φ) shows a slight fluctuation for both (a) PET and (b) PVC MPs; while modulation (m) increases with concentration for (c) PET and (d) PVC MPs. These trends confirm the robustness of FLA for detecting MPs over a broad dynamic range, even when fluorescence lifetime-based discrimination is not feasible.

identification and quantification potential of the developed FLA system. It's worth noting that those PS particles were purchased in form of homogenous suspensions, while MNPs in the aquatic systems often display heterogeneous distributions.

In this work, the applicability of the FLA system was broadened to two other common plastic types, PET and PVC, with high polydispersity (PdI = 1), mirroring real-world fragmented MPs. These results demonstrate that the FLA system reliably detects them over a wide concentration range. In consistent with previous findings, their phasor fingerprints follow a single trajectory, suggesting a stable fluorescence lifetime (τ_Φ) across concentrations. In addition, the linearity between photon counts and MP concentration, regardless of polymer type, enabling rapid estimation of total MP concentration in unknown water samples. The fluorescence lifetime for PET MPs was 2.38±0.12 ns, and PVC was 2.50±0.21 ns in water suspensions, which fell within the range previously observed for PS MNPs ($\tau_\Phi \approx$ 2.34±0.14 ns). For PET, the result match Zhou et al., who reported fluorescence lifetime around 2.2 ns for PET in water under 440 nm excitation (Zhou et al., 2022). Interestingly, their fluorescence lifetime for PVC is around 1.6 ns diverged from the value tested here. This variation may come from additives or manufacturing differences, as well as the combined effects of intrinsic material properties and environmental factors such as refractive index, scattering, and solvent interactions. Indeed, Wohlschläger et al. demonstrated that the fluorescence lifetime of a same particle shifts under different excitation wavelengths (405 or 445 nm), for example, PET shifts from 1.59 ns to 2.49 ns, and PVC shifts from 2.56 ns to 3.28 ns (Wohlschläger et al., 2024). This result suggests the excitation wavelength and the spectral window may influence the actual value. Notably, the fluorescence lifetimes of these common plastic types range from 1.5 to 3.2 ns when excited around 440 nm (Monteleone et al., 2021; Monteleone et al., 2021; Zhou et al., 2022; Wohlschläger et al., 2024). Interestingly, these studies suggest that phasor-based differentiation is possible for some MP types with the aid of microscope (Monteleone et al., 2021; Monteleone et al., 2021; Zhou et al., 2022; Wohlschläger et al., 2024). Unfortunately, without the help of microscope, their similar fluorescence lifetimes result in overlapping in their phasor fingerprints. And therefore, the FLA system does not able to provide sufficient resolution for polymer-specific identification under tested conditions. Additionally, field MNPs are often in the ug/L range (Xu et al., 2022) and natural aqueous environments often contain organic matters, which exhibits intrinsic fluorescence that may interference with MPs (Stedmon et al., 2003). Although, fluorescence lifetime-based phasor analysis is far less sensitive to spectral overlap than intensity-based method (Datta et al., 2020), simple pre-concentration and pre-treatment are needed before applying field aquatic samples to current FLA platform. A study has reported Fenton's reagent ($Fe^{2+} + H_2O_2$) can isolate MPs from organic-rich matrices in a rapid and efficient way (Tagg et al., 2017). On the other hand, vacuum filtration (Tse and al., 2022), ultrafiltration (Okoffo and Thomas, 2024), and emerging microfluidic concentrators (Hu et al., 2025; Zhang et al., 2023) can be used out of the lab to enrich environmental samples for microplastics; while vacuum filtration and microfluidic devices are readily field-deployable, ultrafiltration can also be adapted for on-site use through portable cartridge-based systems or pressurizable setups. These methods enable fast pre-concentration of MNPs for downstream screening.

Despite these limitations of current FLA platform, the τ_Φ values were consistent across replicates and concentrations, demonstrating the robustness of the FLA system for detecting unstained MNPs in water. This highlights a key advantage of the FLA system as an ideal first-line screening tool, which requires minimal experimental effort. Once the presence of MNPs is detected, follow-up identification of specific polymers can be performed using complementary techniques such as Raman or FTIR spectroscopy, or MS-based approaches (Monteleone et al., 2021; Monteleone et al., 2021; Sancataldo et al., 2020). In other words, the FLA system can be integrated into a layered workflow allows for more

efficient use of analytical resources (Organization, 2017), as time- and cost-intensive techniques can be reserved for selected, positively screened samples. In real-world applications such as water treatment facilities and municipal supply networks, early detection of MNP contamination enables prompt intervention before affected water reaches consumers. Similarly, in remote or resource-limited environments—such as rural water sources, mountain lakes, or coastal aquaculture farms—portable detection systems can flag contamination in the absence of laboratory infrastructure. Furthermore, in industrial settings, real-time monitoring of effluents helps prevent environmental release of MNPs and reduces regulatory risks. Screening applications also extend to bottled water production, hydroponic farming, and clinical or biomedical studies, where the presence of MNPs in biological fluids can be linked to environmental exposure. In all these contexts, a reliable yes/no answer on the presence of MNPs is often sufficient to trigger action, with polymer-specific identification left to a second analytical tier. In a nutshell, the deployment of FLA at the front end of such workflows not only improves responsiveness and cost-efficiency, but also empowers timely decision-making in sectors where MP pollution poses both environmental and socioeconomic risks.

5. Conclusion

The developed portable FLA system was successfully applied to detect polydisperse suspensions of PET and PVC MPs at concentrations close to 0.01 mg/mL under fully aqueous and unstained conditions. The results align with previous studies on monodispersed PS MNPs: the observed fluorescence lifetime (τ_ϕ) values exhibited minimal fluctuations, while the modulation parameter (m) increased with concentration, confirming the system's sensitivity and robustness. The linearity between MP concentration and photon counts further supports the use of this portable FLA system as a concentration estimation tool in first-line screening scenarios. Although current FLA system has limitations in identifying and differentiating plastic types, newly emerging simple enrichment and pretreatment methods provide a realistic route to on-site FLA of MNPs at environmentally relevant levels. Once MNP contamination is detected, polymer-specific identification can follow using Raman, FTIR or Py-GC/MS techniques (Monteleone et al., 2021; Dawson et al., 2023; Huang et al., 2023).

In summary, this study contributes to this landscape by applying the FLA system to detect common MNPs in fully aqueous suspension, under label-free conditions and independent of polymer type, highlighting its potential for early warning MNP detection. Its portability, speed, and reliability in detecting common MNPs, irrespective of polymer type, make it as an ideal tool needed in many real-world scenarios where laboratory infrastructure is lacking and timely intervention is essential. Such as in remote coastal zones, aquaculture facilities, agricultural runoff areas, and low-resource communities managing water safety. By enabling real-time, in situ monitoring, the FLA system can guide timely decision-making, trigger targeted analyses, and reduce reliance on costly, time-consuming techniques unless truly needed. Moreover, the integration of FLA into tiered analytical workflows for MNPs may offer a cost-effective framework for large-scale MNP surveillance, aligning with both economic and societal priorities.

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CRediT authorship contribution statement

Siyao Xiao: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Luca Digiacomo:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Cristina Marchini:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Cristina Miceli:** Supervision, Funding acquisition, Conceptualization. **Massimiliano Papi:** Supervision, Methodology, Investigation. **Giulio Caracciolo:** Writing – review & editing, Supervision, Conceptualization. **Alessandro Rossetta:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Conceptualization. **Daniela Pozzi:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Alessandro Rossetta reports a relationship with FLIM LABS Srl that includes: board membership and equity or stocks. 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.

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Data availability

Data will be made available on request.

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