

Monitoring and health impacts substances of concern: micro(nano)plastics and pathogens

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Airborne emerging risks, including ultrafine particles (UFPs), micro- and nanoplastics (MNPs), and pathogenic microorganisms, pose increasing challenges for environmental and public health. Although chemically and biologically distinct, these agents share key features: they are small, pervasive, and difficult to detect, yet capable of inducing systemic effects upon inhalation or exposure. Current monitoring approaches remain fragmented, slow, and insufficiently sensitive, limiting our capacity to trace exposure pathways, assess risks, and implement preventive actions. Optical and photonic technologies present a unifying analytical platform for detecting both particulate pollutants and biological hazards with high precision and real-time capability.

The UPRISE project exemplifies this approach by investigating how maternal exposure to UFPs and MNPs influences fetal development and contributes to adverse birth outcomes. A central challenge lies in the detection and quantification of MNPs at low concentrations within complex biological matrices such as air, placenta, and blood. Optical techniques, particularly Raman spectroscopy, enable chemical fingerprinting and morphological characterization of these particles, even at micro- and nanoscales [1,2]. Advanced photonic technologies are increasingly stepping in to overcome these hurdles. For instance, portable optical sensors based on Raman and infrared spectroscopy, and fluorescence tagging now enable *in situ* characterization of microplastic pollutants [3]. Combined with *in vitro* lung-placenta models, these tools support mechanistic insights into MNP translocation and toxicity.

Similarly, airborne pathogen detection suffers from limitations of culture-based and molecular techniques, which are time-consuming and require centralized infrastructure. In contrast, photonic biosensors, including surface-enhanced Raman scattering (SERS) [4], plasmonic and interferometric systems, offer rapid, sensitive, and culture-independent detection of bacteria, fungi, and viruses [5]. These technologies are increasingly adaptable to portable and automated platforms, supporting

environmental monitoring in clinical, urban, or industrial contexts [6].

In parallel to the challenges posed by micro- and nanoplastics, pathogen monitoring remains a critical priority within the One-Health framework. Recent advances in optical and photonic biosensing technologies have enabled highly sensitive, rapid, and label-free detection of bacteria and viruses, significantly reducing analysis time compared to conventional culture-based methods. Surface Plasmon Resonance (SPR) and Localized SPR (LSPR) platforms provide real-time monitoring of binding events down to femtomolar levels and have been successfully applied to detect viral antigens, bacterial membrane proteins and whole virions [7,8]. Likewise, nanophotonic micro-ring resonators and photonic crystal slabs have demonstrated exceptional refractive-index sensitivity, enabling multiplex detection of clinically relevant pathogens such as *E. coli*, *Salmonella spp.* and SARS-CoV-2 in complex matrices [9]. Raman-based techniques, including SERS, further allow molecular fingerprinting with high specificity, and recent studies have shown their integration into portable and point-of-care devices for environmental pathogen surveillance [10-11]. Fluorescence-based biosensors, particularly those employing quantum dots, upconversion nanoparticles (UCNPs) and Förster resonance energy transfer (FRET) pairs, have expanded the analytical window for pathogen detection by enhancing signal-to-noise ratios and enabling multi-wavelength multiplexing [12]. By leveraging some of these optical and photonic transduction mechanisms as a unified sensing strategy, we aim to address major gaps in pathogen detection, including time-to-result, analytical sensitivity, operational simplicity and adaptability to on-site environmental monitoring.

By converging the study of micro- and nanoplastics (MNPs) with pathogenic microorganisms within a unified photonic sensing platform, this work addresses critical gaps in quantification, mechanistic insight, and health impact assessment of these emerging environmental contaminants. Utilizing advanced optical and photonic biosensing approaches, we enhance detection sensitivity and analytical resolution for MNPs in complex environmental matrices while enabling rapid, multiplexed, and label-free monitoring of clinically and environmentally relevant pathogens. This integrated strategy provides a holistic perspective on the interactions and potential synergistic effects between physical and biological stressors, offering a comprehensive view of environmental exposure risks. The resulting datasets will not only strengthen

biosensor design and operational performance but also generate robust evidence to inform policy and regulatory decisions. In particular, our findings aim to support the development of European air quality standards and maternal-fetal health protection strategies, facilitating proactive measures to mitigate the combined impacts of MNPs and pathogens on vulnerable populations. Overall, this approach bridges methodological, mechanistic, and translational gaps, positioning photonic biosensor technology at the forefront of environmental health research.

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