

PERSPECTIVE

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Research infrastructures as engines of integration for micro- and nanomaterial research: a European perspective inspired by FHERITALE

Elisa Murgioni¹, Ondřej Adamovský², Nastasia Belc³, Michel Boër⁴, José Maria Carazo⁵, Marcos Gragera⁵, Laurens D.B. Mandemaker⁶, Francesca Morelli¹, Gabriel Mustatea³, Valeria Poscente⁷, Harald Schwalbe^{8,9}, Subha Lakshmi Sharma¹⁰, Joseph Timkovsky⁴, Joris Van Loco¹⁰, Roel C.H. Vermeulen⁶, Claudia Zoani⁷ and Antonio Rosato^{1,11*} 

Abstract

Micro- and nanomaterials have become pervasive across ecosystems, food systems, and human environments, raising urgent questions about exposure, toxicity, and long-term impacts. Yet despite rapid scientific advances, the research landscape remains fragmented, with inconsistent terminology, heterogeneous methodologies, and uneven technological capabilities across laboratories. The FHERITALE initiative—*Food, Health and Environment Research Infrastructures to Tackle Emerging Priorities*—offers a unique cross-domain analysis of these challenges and outlines a roadmap for coordinated European action. Drawing on the FHERITALE Policy Brief and White Paper, this perspective synthesizes current gaps, emerging priorities, and the strategic role of Research Infrastructures (RIs) in enabling a One Health approach. We argue that Europe is poised to lead globally in micro- and nanomaterial research if it can integrate RI capabilities, harmonize standards, and shift from descriptive studies toward mitigation, remediation, and policy-relevant solutions.

Keywords Microplastics and nanoplastics, One health, European research infrastructures, Analytical standardization, Interoperability

Main text

Artificial micro- and nanomaterials, including microplastics and nanoplastics, are becoming increasingly prevalent in environmental, food and human systems. This raises concerns about exposure and long-term impacts. Despite the growing body of research in this area, the

field remains fragmented due to inconsistent terminology, heterogeneous methods and uneven technological capacities. While there have been advances in detection and characterization, key gaps in our understanding of biological interactions, exposure pathways and associated risks persist.

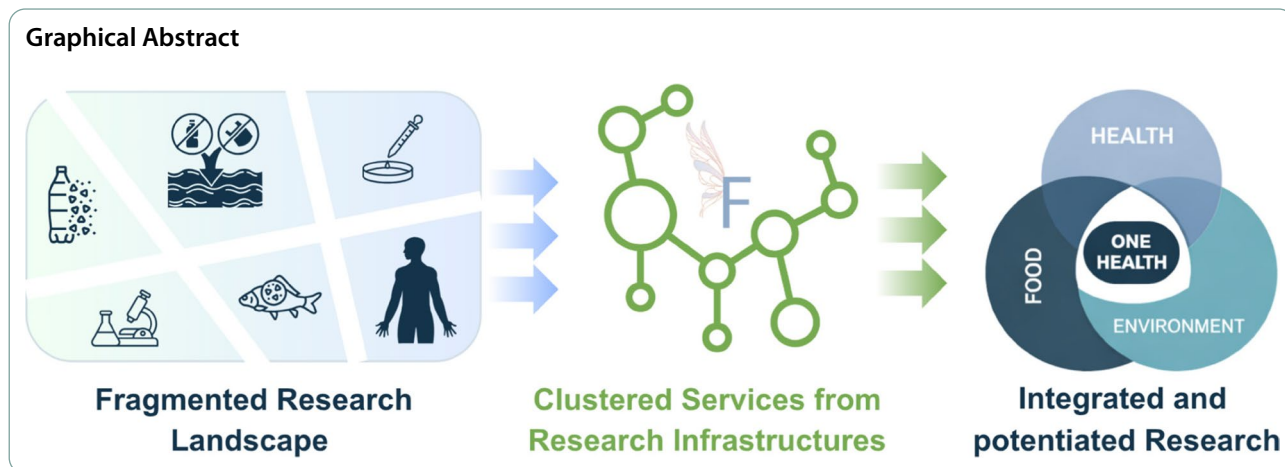
The One Health framework offers an integrative perspective that links the environment, food and health, but its implementation is hindered by disciplinary silos and a lack of standardization. Analytical challenges, especially regarding nanoplastics, include difficulties in detection

*Correspondence:
Antonio Rosato
antonio.rosato@unifi.it

Full list of author information is available at the end of the article



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and quantification, alongside underdeveloped modelling tools and unequal access to advanced technologies.

As emphasized by FHERITALE, Research Infrastructures offer a way to address these limitations by enabling coordination, standardization, and shared services. Integrating them can support a transition towards solution-oriented research, including mechanistic understanding, mitigation and policy-relevant strategies, thereby strengthening Europe's capacity to respond to micro- and nanomaterial challenges.

Introduction

Artificial materials at the micro- and nanoscale—microplastics, nanoplastics, bioplastics, metal oxides, and plastic additives—have become ubiquitous in modern life. Their presence in water, soil, air, food, and biological tissues has triggered widespread concern about their potential impacts on human health, environmental integrity, and food safety. Regarding plastics, in 2024 the European Union produced 54.6 million tons, of which 43.3 million tons came from fossil-based production, 10.7 million tons from recycling, and 0.6 million tons as bio-based plastics (PLASTIC 2026). The amount of packaging plastics waste was 15.8 million tons in 2023 (Eurostat 2025). Conventional plastics are petroleum-derived polymers designed for durability that are not biodegradable under natural conditions. Bio-based and bio-attributed plastics are chemically similar polymers produced partly or entirely from renewable biomass, yet they may behave like conventional plastics in the environment. From an environmental point of view, their main advantage is a smaller carbon footprint. Biodegradable plastics are defined by their end-of-life behavior, namely microbial degradation into CO₂, water, and biomass under specified conditions, which are not necessarily met in the natural ecosystem. Bioplastics is an umbrella term loosely covering plastics that are bio-based, biodegradable, or both (European Commission 2022).

In contrast to engineered nanomaterials, such as metal nanoparticles, which benefit from decades of research and regulatory guidance (Shahalaei et al. 2024), micro- and nanoplastics lack methodological maturity (Huang et al. 2024). Analytical methods vary widely, terminology is inconsistent, and research efforts are distributed unevenly across domains. A recent controversy highlighted the need for the scientific community to devote substantial efforts to refining, standardizing, and harmonizing analytical methods for detecting microplastics in tissue samples (The Guardian 2026). These improvements are needed not only to enhance the reliability and reproducibility of research in the field but also to provide a solid basis for government decision-making. Cross-domain collaborations would be relevant for providing researchers in the field with guidelines to improve their work, including the development of better method documentation and checklists to support publication in scientific journals (Xu et al. 2025). A further aspect to consider is that, while detection and characterization have provided a wealth of data (albeit sometimes controversial), the understanding of biological interactions, exposure pathways and long-term risks lags (Landrigan et al. 2025). For example, some studies are available on animals (in-vivo) and animal models (in-vitro), typically from an ecotoxicological perspective (Qualhato et al. 2023, Augustus de Araújo et al. 2025). Basic questions, such as how micro- and nano-plastics are taken up by cells, have been addressed to some extent (Khan and Jia 2023, Hua et al. 2022), but fundamental limitations remain, making it so far impossible to accurately compare data from a set of diverse studies (Hernández et al. 2025).

The FHERITALE project aims to develop strategies to address this fragmentation by bringing together European Research Infrastructures (RIs) across the food, health, and environmental domains. Through bibliometric analysis, expert consultation, and service mapping, FHERITALE provides a cross-cutting view of the

scientific landscape and identifies strategic priorities for future research and policy. This manuscript leverages such work to articulate a broader vision for how Europe can build an integrated, One Health-oriented research ecosystem capable of addressing the complex challenges posed by artificial micro- and nanomaterials.

The one health imperative - a conceptual foundation for integration

The One Health framework was defined by the One Health High-Level Expert Panel (OHHLEP) (One Health High Level Expert Panel 2026) as an approach that “*aims to sustainably balance and optimize the health of people, animals, and ecosystems*”. The One Health framework is the only lens capable of capturing the full lifecycle and consequences of artificial materials, including:

- Environmental pathways (soil, water, air)
- Food chain transfer
- Human exposure and toxicology
- Animal health impacts
- Socio-economic and regulatory dimensions

It is a crucial context for the investigation of micro- and nanoparticles because they can traverse environmental compartments, food chains, and physiological barriers in biological systems. Therefore, their impacts cannot be thoroughly understood within disciplinary boundaries.

Despite broad recognition of its importance, One Health remains difficult to put into practice. We have highlighted how the artificial materials field suffers from a pressing need for shared terminology and vocabulary. Researchers from different domains often use similar

terms which mean different things or describe similar phenomena through different terminologies. This terminological fragmentation undermines data comparability and complicates regulatory interpretation.

A direct effect of the above is that it encourages research efforts to remain siloed within scientific domains. Environmental studies tend to focus on distribution, degradation, and environmental fate, toxicological studies examine cellular and organismal effects, and food scientists investigate contamination pathways and exposure through diet. Furthermore, social scientists are rarely integrated into technical discussions. A cross-domain perspective is needed to remove the structural barriers that hinder the development of a comprehensive understanding. Although such barriers frequently arise in the challenging process of bridging disciplines, clearly identifying them through concrete initiatives such as the FHERITALE project is an essential step towards overcoming them.

Mapping the current research landscape

The landscape exercise that we carried out made it possible to identify the main criticalities, detailed below and summarized in Fig. 1.

Technological asymmetries

A bibliometric analysis of more than 800 papers carried out as part of FHERITALE’s tasks (Murgioni et al. 2025) has highlighted a research landscape that is both active and uneven. A notable issue is that while there is an EU regulatory definition of nanomaterial (European Commission Recommendation 2022/C 229/01), there is no such definition for micro- or nanoplastics. In practice,

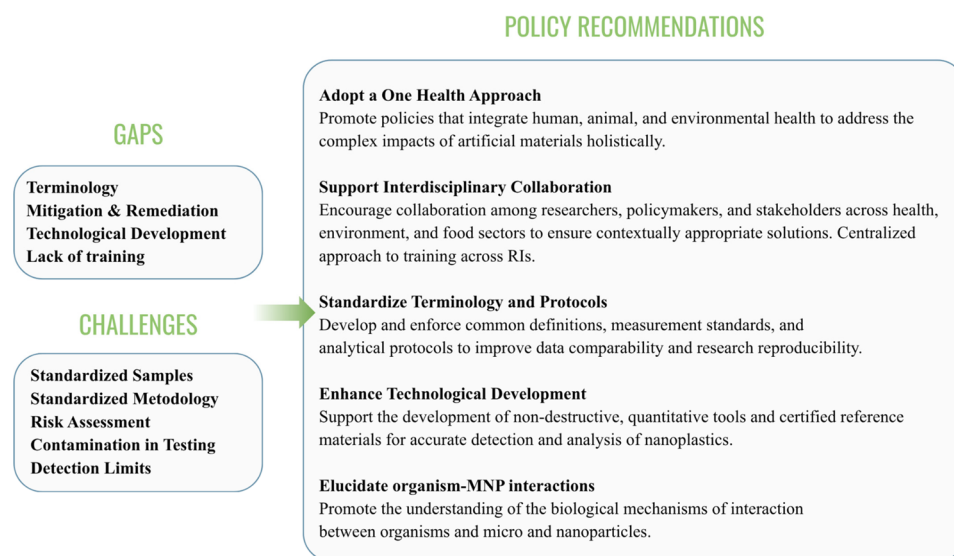


Fig. 1 Summary of the gaps and challenges identified by FHERITALE through its landscaping activities and interactions with experts, along with some of the corresponding policy recommendations

solid, synthetic polymer particles smaller than 5 mm in their longest dimension are dubbed microplastics, a definition proposed in a 2008 workshop of the US National Oceanic and Atmospheric Administration (Arthur et al. 2009). For nanoplastics, two competing conventions exist: $< 1 \mu\text{m}$ (1000 nm), which is commonly used in environmental science, since it matches the practical detection limit for many analytical methods; $< 100 \text{ nm}$, which aligns with the above-mentioned EU definition of nanomaterial, as well as with the definition of nanomaterial available from ISO (ISO/TS 80004-1), in which nanoscale is described as roughly 1–100 nm and nanomaterial as a material with any external dimension, internal structure, or surface structure in that range. The scientific debate persists regarding the exact size boundaries distinguishing micro- and nanoplastics (Gigault et al. 2018, Frias et al. 2019, Rani-Borges and Ando 2024), but such distinction is beyond our scope, as the outcomes of the European FHERITALE project focus on mapping and providing infrastructure services whose operational range depends directly on the detection limits and spatial resolution of available analytical technologies. For this reason, in our bibliometric work, we adopted the particle size as defined by the authors for each article.

Microscopy dominates the methodological toolkit, reflecting its accessibility and versatility, along with optical spectroscopy methods. At the micro-scale, these two groups of techniques cover 58% of the studies analyzed, whereas this figure is 39% at the nano-scale. These figures were derived according to the particle-size classifications defined by the authors of the original studies (Murgioni et al. 2025). This difference may be due to possible practical difficulties/limitations of microscopy methods at the smaller scale. Consequently, the technologies for the detection and characterization of the smallest and most complex particles must be developed further to provide viable additional approaches, focusing on non-optical microscopy or mass-based methods. Nanoplastics remain significantly understudied with respect to microplastics, also in terms of the relative number of available articles, despite growing evidence that their small size and high surface-to-volume ratio may make them more biologically active.

Biodegradable plastics have been receiving comparatively little attention, even though they are increasingly prevalent in consumer products and may degrade into particles with distinct toxicological profiles. Plastic additives are also worthy of greater investigation as they are an integral part of particles and further enhance their impact. Mitigation and remediation research is scarce, suggesting that the field remains primarily descriptive rather than solutions oriented. Cross-domain studies—those integrating environmental, food, and health perspectives—are still the exception rather than the rule.

As mentioned above, while microscopy is widely used, other advanced techniques, such as high-resolution nuclear magnetic resonance, non-destructive imaging, and computational modeling, are underutilized (Murgioni et al. 2025). This imbalance can be the result of multiple factors, including the steep cost and difficulty of maintaining the specialized instruments. As a result, research capacity varies widely across laboratories and countries, creating inequities that hinder the development of harmonized protocols and shared standards.

Gaps in mechanistic understanding of biological and environmental impact

Our understanding of how artificial materials interact biologically at the micro- and nanoscale is less developed than our ability to characterize them. The project outcomes highlighted the lack of robust analytical and technological tools for studying micro- and nanoplastics, particularly in complex matrices such as tissues, soils, and food (Vankoningsloo et al. 2026). It is worth highlighting also the existence of an Environmental-Human Testing Gap. Notably, the smallest and most bioactive particles are the least studied. Risk assessment, especially in the food sector, remains insufficient, and real-world exposure studies are rare (Vankoningsloo et al. 2026). These gaps prevent the development of evidence-based policies and risk management strategies.

Analytical and technological challenges

Standardization deficits

A widely acknowledged issue is the absence of standardized sampling protocols, extraction and purification methods, analytical workflows, reference materials, and reporting formats. Without standardization, reproducibility suffers, and cross-study comparisons become unreliable. This lack of harmonization also impedes regulatory uptake, as policymakers require consistent and validated data to support decision-making (Murgioni et al. 2025, Vankoningsloo et al. 2026). In this context, a key milestone was the publication of ISO 24187:2023, which describes the principles to be followed in the analysis of microplastics in various environmental matrices, including particle size classification, sampling apparatus, sample preparation, and determination of representative sample quantities. Rather than prescribing a single method, this standard compiles several analytical approaches and provides general guidelines for sampling, sample preparation, and data processing, applicable not only to environmental matrices but also to drinking water and food. Building on this foundation, ISO has since developed matrix- and technique-specific standards: ISO 16094-2, published in September 2025, provides guidelines for microplastic analysis of water samples using vibrational spectroscopy methods (Raman and FTIR), while Parts 3

and 4, covering thermoanalytical methods and sample preparation for complex water matrices respectively, remain under development. Despite this progress, different laboratories continue to use different sampling protocols, sample preparation procedures, and instrumental setups, resulting in poorly comparable results and underscoring the ongoing need for harmonized methodology and quality-assurance procedures.

In parallel with addressing the above issues more comprehensively, it is important to recognize the existence of a significant need for training on the proper use of analytical methods and the interpretation of data. This need is expected to become even more pressing with the desired implementation of novel standards and standardized methods taking off. With training opportunities being unevenly distributed across Europe, many laboratories are at risk of falling behind in their development of expertise in advanced techniques (Murgioni et al. 2025, Vankoningsloo et al. 2026).

The nanoplastics and modeling frontiers

Nanoplastics represents the most analytically challenging class of materials. Their small size, heterogeneity, and tendency to aggregate complicate detection and quantification. Distinguishing nanoplastics from natural colloids, quantifying low concentrations in complex matrices, tracking transformations during digestion or weathering, and assessing biological uptake all remaining significant challenges, further complicated by the aforementioned lack of standards (Murgioni et al. 2025, Vankoningsloo et al. 2026).

A further need is for computational tools able to simulate exposure scenarios and predict particle behavior. Modeling is essential for estimating environmental fate, predicting bioaccumulation, supporting risk assessment, and designing mitigation strategies. Nevertheless, computational approaches remain underdeveloped and underutilized, partly due to the lack of standardized input data and partly due to limited cross-domain collaboration (Murgioni et al. 2025, Vankoningsloo et al. 2026).

The discussion in Section "Mapping the Current Research Landscape" and "Analytical and Technological Challenges" is visually summarized in Fig. 1 (Vankoningsloo et al. 2026, Boer et al. 2025, Murgioni et al. 2025).

The strategic role of research infrastructures

RIs as integrators of expertise and technology

One of FHERITALE's major contributions is the mapping of services across European RIs. The resulting landscape includes dozens of services spanning physical and chemical characterization, structural analysis, toxicology, biological activity, exposure assessment, and environmental monitoring. A report describing the map in its version of July 2025 is available (Mandemaker et al. 2025).

The current map of the relevant services (Fig. 2) offered by European RIs is available on the FHERITALE website, at <https://fheritale.eu/survey-outcomes>.

The diversity of services represented on the map is a strength, but only when effectively coordinated. Without integration, the field risks duplicating efforts, missing opportunities for synergy, and failing to develop the comprehensive workflows needed for One Health research. One way to address this challenge could be addressed through the implementation of a cluster of the services offered by the various RIs (as well as other large-scale facilities). A service cluster is a specific collection of services offered by the various RIs adhering to a defined set of standards, oriented to the interaction with the micro- and nanoplastics community (or, generally speaking, with any defined research community). Such a cluster model would enable multi-modal analytical workflows, shared quality standards, joint technology development, coordinated training programs, and cross-domain research projects. By pooling expertise and resources, RIs can overcome the limitations of individual laboratories while creating a more equitable and efficient research ecosystem. However, service clusters alone do not address the aspects that require technological development, particularly in the investigation of nanoplastics. Although the definition of nanoplastics remains under active debate (Gigault et al. 2018, Frias et al. 2019, Rani-Borges and Ando 2024), a pragmatic consideration in organizing clusters of services is that the spatial resolution and detection limits of available instrumentation determine which materials can be meaningfully analyzed. Bridging such gaps is a longer-term goal, again to be tackled collaboratively by RIs. One of the final aims of FHERITALE is to address specific development actions that can be addressed as follow-up activities of the project.

The development of a cluster of services could leverage the Service Readiness Classification (SRC) offered by FHERITALE, which provides a strategic framework for assessing the maturity of analytical methods. The SRC methodology is derived from the Technology Readiness Level (TRL) framework, which is widely used to assess the maturity of a particular technology during its development lifecycle. The TRL scale ranges from TRL 1 to TRL 9, where each level represents a distinct stage in the development process from basic research and conceptual exploration to full system deployment in an operational environment. In our SRC approach, we focus on the categorization of the maturity of the technologies analyzed and specifically on their usability as services provided by research infrastructure. This is determined by their operational maturity, their accessibility, and the alignment of the services with the scientific priorities of FHERITALE. To this end, we defined the three classes (A, B, C), namely: A, Fully Operational Services/Technologies; B, Existing

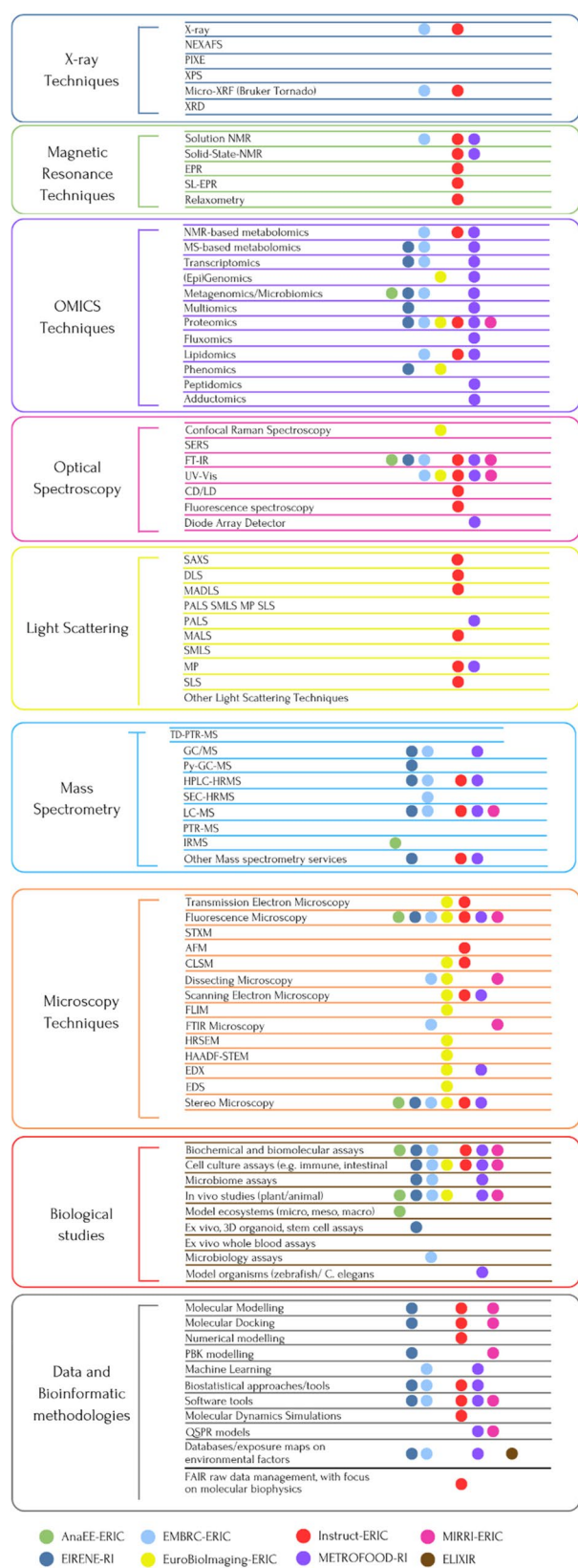


Fig. 2 The current map of services offered by European research infrastructures. The methodology by which the map has been prepared is described in the corresponding project document (Mandemaker 2025)

Services/Technologies but Partially Aligned or Restricted; C, Technologies Not Ready for Service (Mustatea et al. 2025). By prioritizing the availability to users and the alignment with defined scientific priorities, the SRC supports long-term planning and investment. This approach recognizes that technological development is not linear and that emerging methods may require sustained support before they can be offered as reliable services.

Beyond the provision of access to high-end instrumentation, RIs are uniquely positioned to foster the development of new analytical technologies, create certified reference materials, validate protocols, and support interdisciplinary research teams. Their role extends beyond service provision to shaping the future of the field. By fostering collaboration across domains, RIs can accelerate innovation and ensure that technological advances are aligned with the needs of researchers, policymakers, and society.

Regulatory and policy dimensions

The need for harmonized definitions and standards

Regulatory progress is hindered by inconsistent terminology and by heterogeneous definitions and reporting of data. These elements, together with the factors outlined in Section "Standardization deficits" (such as lack of reference materials and of standard protocols), are crucial enablers for harmonization of risk assessments across sectors and countries, as well as tackling the fragmentation of regulatory frameworks.

The food sector faces specific challenges. Food contact materials, packaging, and agricultural plastics all contribute to potential exposure to both plastic particles and their associated chemical additives. Yet the lack of standardized methods for detecting and quantifying micro- and nanoplastics in food matrices complicates regulatory oversight. The existing differences between national/EU regulations and those of other countries complicate trade and create competitive imbalances. Europe has an opportunity to lead globally by establishing robust, science-based standards that can serve as a model for international regulation.

Regulation must also consider public awareness, socio-economic impacts, equity in access to technologies, and potential unintended consequences of new materials. FHERITALE's long-term recommendations call for integrating social sciences to address these dimensions, recognizing that technological solutions alone are insufficient to address the complex challenges posed by artificial micro- and nanomaterials.

From characterization to solutions: a new research agenda

Considering the gaps identified across the environmental, food, and health domains, the future of micro- and nanomaterial research must evolve from

a descriptive enterprise into one that actively develops and tests solutions. Although significant progress has been made in characterizing particles and understanding their distribution, far less attention has been devoted to developing mitigation and remediation strategies. Also, the mechanisms by which micro- and nanoparticles enter cells or cross organ barriers remain to be elucidated. Without this information, exposure pathways cannot be properly understood, nor managed. Addressing these research aspects pertains to the scientific community, leveraging state-of-the-art RI services.

In practice, reducing human exposure demands a clearer understanding of the pathways that allow micro- and nanoparticles to enter the body, whether through food, water, air, or consumer products, and the development of interventions that can effectively interrupt these routes. This transition toward solutions cannot succeed without integrating socio-economic and behavioral research, since public

perception, consumer habits, and economic incentives all shape the production, use, and disposal of materials. Equally important is the need to combine computational and experimental approaches, using models to predict environmental fate, exposure levels, and toxicological outcomes, and validating these predictions through empirical studies. Such integration will enable the creation of robust, predictive frameworks that support both scientific inquiry and policy development. A solutions-oriented research agenda must be interdisciplinary by design, technologically ambitious, and closely aligned with regulatory and societal needs, ensuring that scientific advances translate into actions to control and counter environmental contamination as well as human health risks.

Addressing this imbalance requires a shift toward strategies that reduce emissions at the source, redesign materials to minimize fragmentation, and explore bio-remediation or other innovative approaches capable of removing particles from ecosystems.



Fig. 3 Clusters of integrated service solutions proposed by the FHERITALE project to enhance the accessibility and interoperability of research infrastructures focused on micro- and nanomaterials

A vision for a pan-European one health RI ecosystem

Drawing on FHERITALE's insights, we propose a vision for a coordinated European ecosystem with several key pillars. First, a harmonized analytical infrastructure is essential. This includes common terminology (ontology), shared protocols, certified reference materials, and interoperable data systems, enabling researchers across Europe and beyond to generate comparable and reliable data (Zoani et al. 2026). Second, integrated service clusters can facilitate multi-modal workflows, cross-RI training programs, and joint technology development (Zoani et al. 2026). By pooling expertise and resources, RIs can create a more efficient and equitable research ecosystem through clusters of services (Fig. 3). Third, a One Health knowledge hub can serve as a central platform for data integration, exposure modeling, and RI coordination. This hub would enable researchers to synthesize findings across domains and provide policymakers with evidence-based insights (Zoani et al. 2026). Fourth, a solutions-oriented research agenda is needed to shift the field from characterization to mitigation. This includes research on bioremediation, material redesign, socio-economic impacts, and policy interventions (Zoani et al. 2026). Finally, Europe can assume global leadership by establishing harmonized standards, coordinating RI capabilities, advancing cutting-edge analytical technologies, and supporting international regulatory alignment (Zoani et al. 2026).

Conclusion

The FHERITALE Policy Brief and White Paper provide a comprehensive and cross-domain assessment of the challenges and opportunities in micro- and nanomaterial research. They reveal a field rich in scientific activity but hampered by fragmentation, inconsistent terminology, and uneven technological capacity. Research Infrastructures offer a powerful mechanism to overcome these barriers, provided they are strategically coordinated and aligned with a One Health vision.

This perspective argues that Europe stands at a pivotal moment. By integrating RI capabilities, harmonizing standards, and shifting toward solutions-oriented research, Europe can build a world-leading ecosystem capable of addressing the complex challenges posed by artificial micro- and nanomaterials. The path forward requires investment, coordination, and sustained commitment, but offers great potential benefits for environmental integrity, food safety, and human health.

Abbreviations

FHERITALE	Food, Health and Environment Research Infrastructures to Tackle Emerging Priorities
RI / RIs	Research Infrastructure(s)
SRC	Service Readiness Classification
TRL	Technology Readiness Level
OHHLEP	One Health High-Level Expert Panel

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Authors' contributions

E.M. Figure preparation; E.M., F.M., A.R. Writing - Original Draft; all authors, Writing - Review & Editing; N.B., M.B., J.M.C., H.S., J.V.L., R.C.H.V., C.Z., A.R., Funding acquisition.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Ethical approval and consent were not required for this study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

¹Consorzio Interuniversitario Risonanze Magnetiche di Metallo Proteine, Via Luigi Sacconi 6, Sesto Fiorentino 50019, Italy

²Faculty of Science, Masaryk University, Kamenice 753/5, Brno 625 00, Czech Republic

³National Research and Development Institute for Food Bioresources, 5 Ancuta Baneasa Street, Bucharest 020323, Romania

⁴AnaEE-ERIC, 1 Avenue de la Terrasse, Gif-sur-Yvette 91190, France

⁵Spanish National Center for Biotechnology, CNB-CSIC, Calle Darwin 3, Madrid 28049, Spain

⁶Institute for Risk Assessment Sciences (IRAS), Utrecht University, Universiteitsweg 99, Utrecht 3584 CG, The Netherlands

⁷Department for Sustainability, Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Via Anguillarese 301, Roma 00123, Italy

⁸Institute for Organic Chemistry, Center for Biomolecular Magnetic Resonance (BMRZ), Max-von-Laue-Str. 7, Frankfurt/M. 60438, Germany

⁹Instruct-ERIC, Oxford House, Parkway Court, John Smith Drive, Oxford OX4 2JY, United Kingdom

¹⁰Sciensano, Rue Juliette Wytsmanstraat 14, Brussels 1050, Belgium

¹¹Department of Chemistry, University of Florence, Via della Lastruccia 3, Sesto Fiorentino 50019, Italy

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