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Perspective

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Revisiting the detection, fate, and health risks of microplastics in the environment through artificial intelligence

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Abstract

Against the backdrop of global change, the widespread presence of emerging contaminants (ECs) like microplastics (MPs), coupled with the escalating impacts of climate change, collectively poses a dual threat to global ecosystems and human health. The complexity, nonlinearity, and multi-scale nature of this 'triple planetary crisis' pose significant challenges to traditional environmental research methodologies. Artificial intelligence (AI), particularly deep learning technology, is leading a paradigm shift in environmental research due to its exceptional capabilities in processing high-dimensional data, recognizing complex patterns and performing causal inference. This article systematically elaborates on the transformative role of AI across the entire MPs research chain. At the detection stage, AI-driven high-throughput spectroscopy and microfluidic technologies enable rapid, precise identification and in-situ monitoring of low-concentration, small-sized MPs. In behavioral simulation, interpretable machine learning reveals the transport mechanisms of MPs in porous media, their shape-dependent settling behavior, and the vicious cycle of feedback with climate warming. In risk assessment, AI integrates multi-source data, showing great potential for elucidating the reproductive and neurotoxic mechanisms of MPs (e.g., ferroptosis), assessing their global distribution patterns and ecological risks, and quantifying human exposure (especially in pregnant women and children) via the food chain. We propose an "Pan-microplastic AI Framework" framework that extends beyond the scope of MPs. This framework uses AI to systematically address the combined crisis of emerging contaminants (ECs), climate change, and biodiversity loss. It employs methods such as multi-modal data fusion, causal discovery, and generative simulation to support "One Health" governance, enabling both macro-policy optimization and micro-precise interventions. Despite challenges such as data quality, model interpretability, and cross-scale integration, the deep integration of environmental science and AI is undoubtedly the necessary path to providing quantitative, systematic, and intelligent solutions for building a planetary health framework and achieving harmonious coexistence between humanity and nature.

Keywords: Microplastics, Artificial intelligence, Deep learning, Emerging contaminants, Health, One health

Introduction: Limitations of traditional research paradigms and the rise of AI

The world is facing a "triple planetary crisis" composed of biodiversity loss, climate change, and environmental pollution. These are not isolated challenges but interact deeply, collectively exacerbating the degradation of global ecosystems and the increase in human health risks. Over the past fifty years, global wildlife population sizes have declined by a staggering 73%, and approximately 1 million species face the threat of extinction, leading to an unprecedented collapse of

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ecosystem services[1]. Concurrently, since the late 19th century, the global temperature has risen by 1.2 °C, atmospheric CO_2 concentrations have surpassed the 410 ppm mark, and extreme climate events occur frequently[2,3]. Pollution, particularly plastic pollution, acts as a powerful accelerant in this crisis, severely deteriorating environmental quality. Over 8 million tons of plastic waste enter the ocean annually[4], fragmenting and degrading into ubiquitous microplastics (MPs) (particle size < 5 mm) and even nanoplastics, making them one of emerging contaminants (ECs).

The issue of MPs perfectly illustrates the interconnectedness of the "triple planetary crisis" (Fig. 1). MPs are themselves a form of pollution, posing risks of physical damage and chemical toxicity. MPs in soil can substantially increase greenhouse gas (GHG) emissions, though the magnitude varies by polymer type and soil conditions. Recent global meta-analyses indicate that MPs increase soil CO_2 emissions by an average of ~ 25%[5], while specific high-risk scenarios show much more drastic effects: biodegradable MPs (PBAT) can elevate CO_2 emissions by up to 3.13-fold[6], and certain polymers (phenol-formaldehyde) can cause a surge N_2O emissions by ~ 182%[7]. However, the above analysis is a data synthesis of laboratory studies, and field studies are urgently needed for a solid conclusion. A similar issue is also relevant to the toxicity of MPs. Through direct ingestion, indirect toxic effects (e.g., leachates), and habitat alteration, MPs disrupt community structures and ecosystem functions[8].

Confronted with the complexity and systemic nature of microplastic pollution, traditional environmental research methods appear inadequate. Environmental sample matrices are complex, MPs concentrations are low, sizes are small, and types are diverse. Traditional spectroscopic techniques (e.g., Fourier transform infrared spectroscopy and Raman) are often time-consuming and labor-intensive for large-scale screening. Furthermore, their identification efficiency can be compromised by environmental interferences such as biofilms and organic matter without extensive pretreatment[9]. The transport, transformation, and settling behaviors of MPs are influenced by the nonlinear interactions of multiple factors such as hydrodynamics, particle morphology, and aging degree, making accurate simulation with traditional models difficult. Risk assessment involves multi-scale processes from molecular toxicology to population effects, and from local exposure to global cycles. Existing data are fragmented, and there is a lack of in-depth revelation of causal relationships[10].

The current era provides an unprecedented abundance of environmental data. Real-time environmental monitoring networks, population health studies, global ocean observation systems, and biodiversity databases generate massive, multi-source, heterogeneous data, offering the potential to uncover complex environmental patterns. Artificial intelligence (AI), particularly its subfields of machine learning and deep learning, is the key to extracting deep insights from big data. AI offers revolutionary approaches to microplastic pollution research. Its unique advantages in handling high-dimensional data, recognizing complex patterns, and performing causal inference help address key challenges, including detection

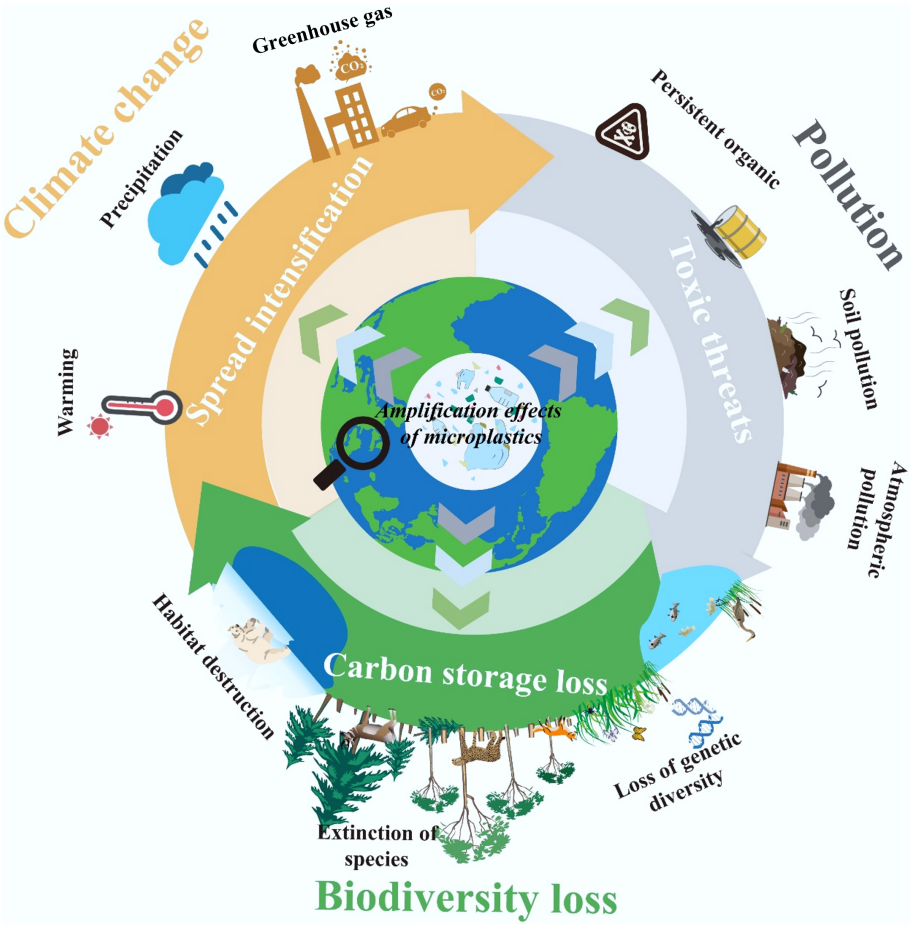

Fig. 1 The triple planetary crisis amplified by MPs. This figure illustrates the interconnected nature of climate change, biodiversity loss, and pollution, highlighting how MPs act as an amplifier by creating detrimental feedback loops.

bottlenecks, behavioral simulation dilemmas, and risk assessment uncertainties.

AI-enabled precise detection and intelligent identification of MPs

Traditional infrared and Raman spectroscopy rely on standard spectral library matching, suffering from inefficiency and limited accuracy with complex environmental samples. Researchers are now pushing the limits by fusing machine learning with spectroscopy-microfluidics, as well as large-scale drones or satellite remote sensing. A YOLO (You Only Look Once)-integrated droplet microfluidic system has been developed and achieves high linear quantification and accurate classification of MPs, outperforming traditional methods and demonstrating practical potential for handling complex environmental samples[11]. A convolutional neural network (CNN) combined with Raman spectroscopy and a tailored data interpolation strategy has been utilized to successfully classify individual microplastic particles in the 1–10 μm range rapidly, achieving approximately 85.47% confidence with only 0.4 seconds of exposure time[12]. This breakthrough greatly advances the screening capability for smaller, lower-concentration MPs, paving the way for studying the environmental behavior and health effects of MPs. Beyond the attention on the high-throughput, accurate classification and rapid detection of small-size particles, the complex and variable environmental matrix is the core challenge.

Transitioning from laboratory to field, in-situ identification and real-time monitoring networks utilizing portable detectors are of increasing interest to environmental stakeholders and researchers. Laboratory analysis struggles to capture the dynamic changes of MPs in real environments. In-situ and real-time detection technologies are crucial. A portable pyrolysis-point discharge spectrometer coupled with a support vector machine algorithm has been developed, enabling field in-situ identification of plastic polymers in the environment for rapid pollution source tracing, emergency monitoring, and large-scale surveys[13]. AI's pattern recognition and adaptive learning capabilities allow it to distinguish MPs from other similar particles coexisting in the environment and identify MPs whose spectra have changed due to aging or biofilm coverage, which is difficult for traditional methods.

Future microplastic detection will likely rely on a Space-Air-Ground-Sea Integrated Network (SAGSIN), as conceptualized in Fig. 2. This network would integrate data from multiple sources. Satellite remote sensing could identify large plastic accumulation zones, while unmanned aerial vehicles (UAVs) would perform fine-scale inspections of riverbanks and coastlines. Additionally, in-situ sensors deployed in water and soil would transmit data in real-time. Although soil detection remains challenging due to matrix complexity, recent advances in automatic correction algorithms for instrument imaging have shown promise in addressing aggregation and discontinuity issues, paving the way for more robust monitoring[14]. Coordinated by AI edge computing and cloud platforms, this system would enable broad-area, dynamic monitoring of microplastic pollution.

AI for uncovering mechanisms of microplastic fate

Investigating the sources and sinks of MPs in the environment is crucial for assessing exposure risks and developing control strategies. AI is revealing complex behavioral mechanisms of MPs that are difficult for traditional methods to capture. The vertical transport of MPs in porous media like soil and sediments is a key process for their entry into deeper environments. SHAP (SHapley Additive exPlanations)-interpretable Random Forest models have deeply revealed the transport mechanisms of aged MPs[15]. After aging, the increase in chlorine index and oxygen-to-carbon ratio in MPs promotes their

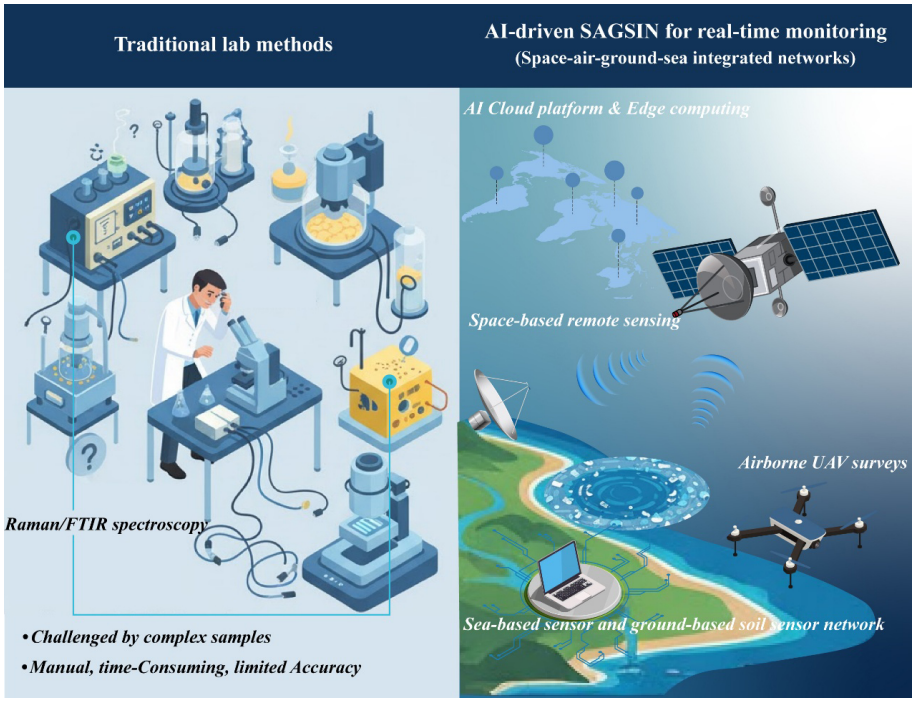

Fig. 2 AI-driven microplastic detection. In contrast to the traditional, labor-intensive laboratory analysis, the futuristic Space-Air-Ground-Sea Integrated Network (SAGSIN) leverages AI to fuse data from satellites, unmanned aerial vehicle (UAV), and in-situ sensors for comprehensive and real-time detection.

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vertical transport. Blocking and adsorption effects co-occur, and the multiple parameters of aged MPs enhance the nonlinear process of transport.

The settling velocity of MPs in water bodies directly affects their transport and ultimate sink. Due to their varied shapes, the traditional Stokes' law based on spherical assumptions has large deviations. Ensemble learning has been used to successfully predict the settling velocity of MPs with various shapes[16]. This approach can comprehensively consider particle morphology, density, and fluid properties, greatly improving the accuracy of predicting microplastic distribution in real, heterogeneous environmental media. MPs are typical Trojan horses[17]. A genetic algorithm-optimized support vector machine model has been developed to predict the sorption capacity of organic pollutants onto MPs[18]. This data-driven model can quickly assess the enrichment potential of different polymer types and aging states for various organic compounds, providing a new tool for combined pollution risk assessment.

Beyond the accurate prediction of settling and sorption behavior with influences from sizes and shapes, global cycle simulation and risk hotspot identification also deserve attention. On a large scale, integrating multi-source data (e.g., industrial emission inventories, land use, hydrogeology, and socio-economic indicators) using XGBoost, LightGBM, or Graph Neural Networks can predict microplastic concentrations in unmonitored areas (rivers, lakes, and coastal zones), mapping global or regional risk hotspots[19]. Combined with marine litter observation databases and ocean current data, microplastic accumulation zones (e.g., garbage patches) can be predicted, assessing exposure risks to pelagic and deep-sea ecosystems.

There are bidirectional feedback mechanisms between MPs and climate change, where MPs enhance the greenhouse effect and climate change amplifies microplastic toxicity. A meta-analysis indicated that soil microplastic pollution can increase CO_2 emissions by 140%, N_2O emissions by 195%, and global warming potential by 172%[7]. Rising water temperatures due to global warming amplify the biological toxicity effects of MPs. It was further found that biodegradable plastics (e.g., poly(butylene adipate-co-terephthalate)) may contribute more to CO_2 emissions, while traditional plastics (e.g., polyethylene) are more prone to promoting N_2O emissions[20]. Therefore, biodegradable plastics are not necessarily more environmentally friendly for climate change mitigation. Caution is warranted regarding potential confounding factors; exogenous substances may stimulate soil microbial metabolism, thereby increasing greenhouse gas emissions independent of the plastic itself. In other words, this may not be a unique phenomenon of microplastics, and most exogenous substances would produce the similar phenomena. Once microorganisms adapt to the exogenous substances, the enhancement effect on greenhouse gases probably is no longer significant.

Objective evaluation for health risk

Interpretable machine learning algorithms such as Random Forest, Support Vector Machine, K-nearest Neighbors, and Gradient Boosting Machine have been used to decode the global distribution of MPs in the surface ocean, with concentrations ranging from 0.176 to 27.055 particles/m^3, and to assess that current MPs in the 20–5,000 μm size range do not pose a potential ecological risk[19]. Such global-scale simulations are crucial for identifying pollution hotspots and evaluating the effectiveness of global plastic control policies. To complete the final stage of risk transmission assessment, AI can perform a sequence of complex tasks. It integrates a wide array of multi-source data, including global fish trophic level databases, pollutant biomonitoring data, food web models, global seafood production and trade data, and resident dietary surveys. Using the above synthesized information, AI then constructs pollutant biomagnification models (using Graph Neural Networks or Bayesian Networks to map trophic transfer) that trace contaminants from primary producers to top consumers[21]. These models make it possible to accurately assess the dietary intake levels of MPs for different countries, regions, and specific population groups, such as coastal residents, children, and pregnant women. Finally, the system calculates key health risk metrics, including the Hazard Quotient (the ratio of exposure dose to a reference dose that is without an appreciable risk of deleterious effects over a lifetime) and the Excess Cancer Risk (Chronic Daily Intake (CDI) multiplied by Cancer Slope Factor (CSF)).

AI not only helps us "see" and "track" MPs but also helps us "understand" their environmental and health consequences. A multi-level meta-analysis revealed that plastic leachates significantly negatively affect the survival, growth, development, and reproduction of aquatic animals, with marine species being more sensitive than freshwater species and primary consumers more vulnerable[22]. AI can integrate vast toxicological data via Natural Language Processing (NLP)-based data mining to identify sensitive species and key endpoints of effect, providing a basis for early warning of ecological risks[23]. The detection rate of microplastic contamination in human samples like placenta and meconium is as high as approximately 87%[24]. A study found that consuming food from plastic containers increased the chance of contamination in pregnant women by 5.39 times, and placental microplastic contamination significantly increased the risk of intrauterine growth restriction[24]. MPs have been detected in human semen, with studies suggesting an association with decreased sperm quality[25]. AI elucidates toxicity mechanisms and intrinsic links. Utilizing multi-omics integration algorithms (e.g., Network Toxicology and Interpretable Machine Learning), researchers have revealed that long-term exposure to polystyrene microplastics may disrupt gut microbiota, induce systemic inflammation, subsequently trigger ferroptosis in hippocampal neurons, and ultimately exacerbate seizure symptoms[26]. This work reveals a new mechanism of microplastic neurotoxicity involving crosstalk between inflammation and ferroptosis.

However, the detection of pollutants in organisms and their correlation with disease do not necessarily imply causation. This application of interpretable machine learning heralds a critical shift from traditional correlative models to AI-driven causal inference. By leveraging causal discovery algorithms (e.g., the Peter-Clark algorithm and the Non-combinatorial Optimization via Trace Exponential and Augmented Lagrangian for Structure learning) on observational data, researchers can construct causal networks that distinguish the true drivers of microplastic risks from mere confounding variables, moving beyond correlation to uncover mechanistic pathways.

Establishing a pan-microplastic AI framework for one health

Given the need for fine-scale exposure and disease burden assessment, AI is the key engine driving the "One Health" concept from theory to practice. From the perspective of air pollution and health, using high-resolution atmospheric chemistry transport models and population health data, combined with distributed lag non-linear models, allows for the fine quantification of the acute and chronic effects of microplastic exposure on mortality and hospitalization rates. For

waterborne pathogens and infectious diseases, integrating data on water quality, climate, and disease reports can be used to build spatio-temporal dynamic prediction and early warning systems. To establish the relationship between mixture exposure and chronic diseases, applying mixture exposure models like Bayesian Kernel Machine Regression allows for assessing the health risks of populations' simultaneous exposure to multiple pollutants (MPs, heavy metals, and other organic pollutants) through multiple media and pathways, and exploring mechanisms from the perspectives of epigenetics and metabolomics, with special attention to effects on neurodevelopment, the immune system, and metabolic syndrome in vulnerable populations. The explosive growth of microplastic researches requires effective data sharing platforms. Building platforms connecting environmental, agricultural, disease control, and hospital data, using blockchain for security, and cloud computing and AI for real-time integrated analysis, would enable joint surveillance and early warning for infectious diseases, antimicrobial resistance, and zoonotic diseases. To achieve precise risk intervention and move beyond "one-size-fits-all" approaches, a shift to "precision targeting" is necessary. This involves identifying high-risk communities or watersheds to prioritize environmental remediation, allocate public health resources, and implement targeted health screenings. It involves moving from actively participating in global agendas to deeply practicing local initiatives like "Zero-Waste Cities", "Healthy Cities" and "National Parks", translating scientific knowledge into concrete policies and actions. To achieve One Health, the current challenge is cross-scale integration, as integrating molecular toxicology, individual effects, population dynamics, and global cycles into a unified model remains a huge challenge.

Facing the "triple planetary crisis" within which microplastic pollution is embedded, a perspective beyond single pollutants is needed to build systematic solutions. Here, we establish the 'Pan-microplastic AI Framework' as a core structural approach, as conceptualized in Fig. 3. The Pan-microplastic AI Framework uses deep learning and other AI technologies to construct a relational network that can simulate and analyze the interactions among elements in high-dimensional ecological-environmental systems. Its goal is to reveal the hidden complexities that are difficult for traditional methods to capture, such as spatial connectivity and spillover effects, time lags and decadal oscillations, and trade-offs between system intervention and comprehensive benefits. The foundation of this framework is multi-modal data fusion. Deep learning models can integrate heterogeneous data streams—from satellite remote sensing and eco-acoustic recordings to genomic data and historical text logs—to create a holistic, dynamic representation of One Health, providing the rich informational context needed for advanced analysis.

The key roles of AI in the framework include three parts: (i) Causal discovery and mechanism analysis: combining interpretable AI to extract implicit mathematical relationships from data, discovering causal mechanisms between MPs, biodiversity loss, and climate change, beyond mere correlation; (ii) Multi-objective optimization and decision support: based on deep reinforcement learning, finding optimal intervention strategies among multiple, potentially conflicting objectives like pollution reduction, species protection, and carbon sink maintenance, aligning with the principle of system entropy reduction; (iii) Digital twin and policy sandbox: fusing

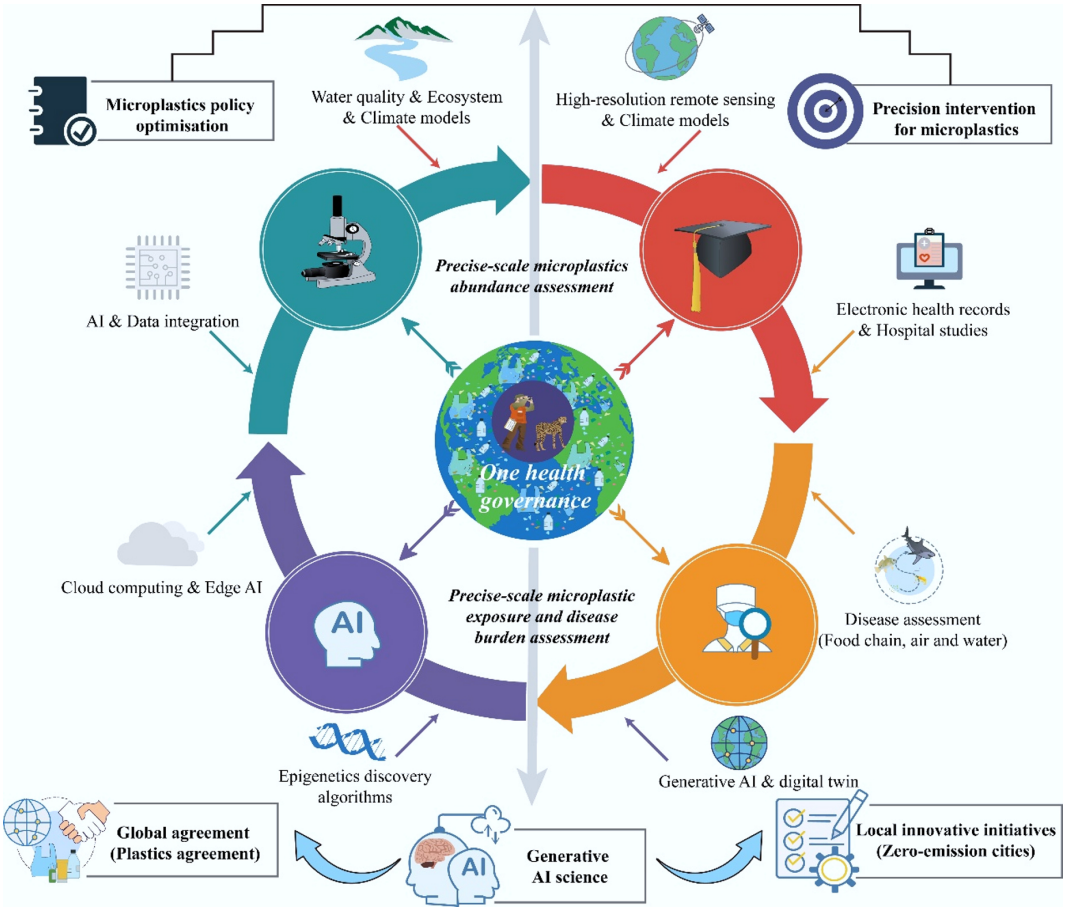

Fig. 3 Pan-microplastic AI Framework for One Health.

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generative AI with physical mechanisms to create digital twins of ecosystems, simulating the long-term consequences of different policy scenarios, enabling "pre-decision simulation". Generative AI, such as Generative Adversarial Networks (GANs) or Diffusion Models, can learn the underlying distribution of environmental data to generate realistic scenarios. To mitigate the risk of AI "hallucinations," these models must be coupled with Physics-Informed Machine Learning (PIML) constraints (e.g., Physics-informed GANs) and validated against observational subsets to ensure physical plausibility[27]. When fused with physical process models, they create high-fidelity "policy sandboxes" for testing the potential impacts of management actions before they are deployed in the real world.

Critical challenges and concluding remarks

The foundation of "AI for Science" is "Data for AI". Current challenges include scarcity of high-quality data, lack of standardization, and high model uncertainty. Furthermore, the sustainability of the AI related infrastructure itself must be considered; the high energy consumption of training large-scale models necessitates the adoption of "Green AI" principles—such as prioritizing efficiency-oriented metrics (e.g., floating point operations, carbon footprint reporting) and utilizing model compression techniques (e.g., pruning and quantization)—to minimize the carbon footprint of computational research[28]. Model performance depends on training data. Uneven geographical distribution and inconsistent methodologies may lead to model bias. AI-assisted screening (e.g., using LLMs) can standardize and accelerate data reliability assessment[29]. Current effective ways include building open and shared databases, and innovating funding and collaboration models for "Government-Enterprise-Scientist" consortia. The long-term fundamental solution is cultivating the next generation of interdisciplinary talent and shaping the new discipline of intelligent environmental science. Beyond the data itself, we must critically assess the inherent limitations of AI models to ensure their responsible application in scientific discovery. Key challenges include model interpretability, where the "black box" nature of deep learning can hinder mechanistic understanding; generalization, as models trained in one environment may not apply to others; and mistaking strong correlation for causation, which could lead to flawed scientific conclusions.

Microplastic pollution is a typical microcosm of the "triple planetary crisis." Its complexity, globality, and profound impacts call for a fundamental transformation in the paradigms of environmental research and management. AI, from micro-scale precise detection to macro-scale global simulation, from in-depth analysis of toxicity mechanisms to intelligent assessment of complex system risks, is comprehensively reshaping our ability to understand, predict, and respond to microplastic pollution. The proposed "Pan-microplastic AI Framework" can help break down research barriers between biodiversity loss, climate change, and pollution. It allows for the systematic and quantitative analysis of their intrinsic driving relationships and feedback mechanisms. Ultimately, AI-driven insights will empower One Health governance from global agreements to local practices, providing an actionable path towards the grand goal of planetary health.

Ethical statements

Not applicable.

Author contributions

The authors confirm their contributions to the paper as follows: Xiangang Hu designed the project; Xiangang Hu, Ruiqi Wang and Chunhui Liu contributed to the writing of the manuscript.

Data availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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Competing interests

The authors declare that they have no conflict of interest.

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