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Artificial Intelligence for Sustainable Monitoring of Soil Microplastic Pollution

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Microplastic (MP) pollution is an emerging threat to soil health, agricultural productivity and environmental sustainability. Agricultural soils receive microplastics from plastic mulches, sewage sludge, compost, irrigation water and atmospheric deposition. Conventional analytical methods, including microscopy, Fourier-transform infrared and Raman spectroscopy, provide accurate identification but are labor-intensive and unsuitable for large-scale monitoring. Artificial intelligence (AI), incorporating machine learning, deep learning and computer vision, enables rapid detection, classification, mapping and ecological risk assessment of soil microplastics. The integration of AI with geographical information system, remote sensing, unmanned aerial vehicles and internet of things technologies further enhance real-time monitoring and precision soil management. This article highlights recent advances, current challenges and future opportunities for AI-based soil microplastic monitoring to support sustainable agriculture and environmental protection.

Keywords: Artificial intelligence, Microplastics, Machine learning, Deep learning, Precision agriculture, Environmental sustainability.

Introduction

Microplastics (MPs), plastic particles smaller than 5 mm, have emerged as important contaminants of agricultural soils due to the widespread use of plastic mulches, sewage sludge, compost, wastewater irrigation and atmospheric deposition. Their persistence in soils can alter soil physical, chemical and biological properties, disrupt nutrient cycling and microbial communities and ultimately affect crop productivity, ecosystem functioning and food safety (Wang *et al*., 2021). Accurate monitoring of soil microplastics is essential for understanding their occurrence, transport and ecological impacts. However, conventional analytical techniques, including microscopy, Fourier-transform infrared (FTIR) spectroscopy, Raman spectroscopy and pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS), are often labor-intensive, time-consuming and require specialized expertise, limiting their application for large-scale environmental monitoring (Cowger *et al*., 2021). Artificial intelligence (AI) has emerged as a promising approach for automated detection, classification and mapping of microplastics using machine learning, deep learning, computer vision and spectroscopic data. Integration of AI with remote sensing, geographic information systems (GIS), unmanned aerial vehicles (UAVs) and Internet of Things (IoT) technologies offers new opportunities for rapid, accurate and real-time monitoring of soil microplastic pollution. This article summarizes recent advances in AI-assisted monitoring of soil microplastics, discusses current challenges and identifies future research directions for sustainable soil management.

Sources and Fate of Microplastics in Agricultural Soils

1. **Plastic mulch:** Plastic mulching is a major source of microplastics (MPs) in agricultural soils. Weathering, UV radiation and tillage fragment polyethylene mulch films into MPs, which persist in soil and affect soil structure, aggregation, microbial activity and nutrient cycling (de Souza Machado *et al*., 2018).
2. **Sewage sludge and biosolids:** Wastewater treatment plants retain most microplastics in sewage sludge. Land application of biosolids introduces these particles into agricultural soils, where they accumulate and may transport heavy metals and organic contaminants.
3. **Compost and organic amendments:** Compost derived from municipal and organic wastes may contain plastic residues that fragment into microplastics during composting. Repeated application of contaminated compost contributes to MP accumulation and may alter soil biological processes.
4. **Irrigation water:** Treated wastewater and reclaimed water contain residual microplastics that are deposited in agricultural soils during irrigation, making irrigation an important pathway for long-term MP accumulation.
5. **Atmospheric deposition:** Microplastic fibers and fragments released from urban and industrial activities are transported by wind and deposited onto agricultural lands through dry and wet deposition, contributing to widespread soil contamination.
6. **Transport and degradation:** The movement of microplastics in soil depends on particle size, soil properties, rainfall, tillage and soil organisms. Weathering processes gradually fragment plastics into smaller particles and nano plastics, increasing their mobility and ecological risks.

Conventional Methods for Soil Microplastic Analysis

Soil microplastic (MP) analysis involves sampling, extraction, identification and polymer characterization. Representative sampling is followed by density separation using saturated salt solutions (NaCl, $ZnCl_2$, or NaI) to isolate MPs, while chemical digestion with hydrogen peroxide (H_2O_2), Fenton's reagent or enzymes removes organic matter without damaging plastic particles (Cowger *et al*., 2021). Microscopy is commonly used for preliminary identification based on particle size, shape and color but cannot accurately identify polymer types. Therefore, Fourier-transform infrared (FTIR) and Raman spectroscopy are widely used to identify polymer composition through their characteristic spectral fingerprints. Pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS) provides highly accurate qualitative and quantitative analysis of plastic polymers. Although these methods provide reliable results, they are labor-intensive, time-consuming, costly and require specialized equipment and expertise. In addition, the lack of standardized protocols limits data comparability across studies, emphasizing the need for automated and high-throughput approaches such as artificial intelligence for soil microplastic monitoring.

Artificial Intelligence Techniques

Artificial intelligence (AI) has emerged as a powerful tool for the rapid detection, classification and monitoring of soil microplastics. Machine learning (ML) algorithms, including Random Forest (RF), Support Vector Machine (SVM), Extreme Gradient Boosting (XGBoost) and Artificial Neural Networks (ANNs), are widely used to classify microplastic particles, analyze spectroscopic data and predict contamination levels with high accuracy (Cowger *et al*., 2021). Among deep learning approaches, Convolutional Neural Networks (CNNs) enable automated extraction of image features for accurate identification and classification of microplastics from microscopic and spectroscopic images, reducing manual interpretation. More recently, Vision Transformers (ViTs) have demonstrated improved performance in image recognition by capturing long-range spatial relationships, offering promising applications for automated microplastic detection. In addition, computer vision techniques integrated with microscopy, FTIR and Raman spectroscopy facilitate rapid particle segmentation, polymer classification and automated counting, supporting high-throughput environmental monitoring.

Artificial intelligence Applications in Soil Microplastic Monitoring

The integration of AI with remote sensing, unmanned aerial vehicles (UAVs) and geographic information systems (GIS) facilitates spatial mapping of microplastic contamination and identification of pollution hotspots. Machine learning models can predict contamination patterns by integrating environmental, land-use and soil datasets, while time-series analysis enables monitoring of temporal changes in microplastic accumulation. Furthermore, AI-based decision support systems assist researchers and policymakers in risk assessment, pollution management and the development of sustainable strategies for mitigating soil microplastic contamination (Wang *et al*., 2023).

Artificial intelligence for Ecological Risk Assessment

Artificial intelligence (AI) is increasingly used to assess the ecological risks of microplastics by predicting their transport, accumulation and distribution under different soil and environmental conditions. AI also supports the evaluation of microplastic impacts on soil physical and chemical properties, soil microbial communities, nutrient cycling and crop productivity by analyzing large environmental datasets. Furthermore, AI-based risk assessment models help predict the transfer of microplastics and associated contaminants through the soil–plant–food chain, providing valuable information for human health risk assessment and sustainable soil management (Wang *et al*., 2021).

Current Challenges

Despite its potential, the application of artificial intelligence (AI) in soil microplastic monitoring faces several challenges. Limited labeled datasets and the lack of standardized sampling and analytical protocols restrict the development and validation of robust AI models. Differences in soil properties, polymer types and environmental conditions also reduce model transferability across regions. In addition, data quality and uncertainty, high computational requirements for training deep learning models and the limited explainability and transparency of AI predictions hinder their widespread adoption.

Future Perspectives

Future advances in AI-based soil microplastic monitoring will rely on the development of digital twins for real-time simulation of microplastic transport and ecological risks. Foundation AI models trained on large environmental datasets could improve the accuracy and transferability of predictions across different soil types. Integrating AI with IoT sensor networks, remote sensing and UAVs will enable continuous, real-time field monitoring of microplastic contamination. Furthermore, federated learning can facilitate collaborative model development while preserving data privacy and open-access databases with standardized benchmarking protocols will enhance model validation and reproducibility.

Conclusion

Microplastic pollution poses a growing threat to soil health and sustainable agriculture. While conventional methods are accurate, they are labor-intensive and unsuitable for large-scale monitoring. Artificial intelligence (AI) offers rapid and automated detection, classification, mapping and risk assessment of soil microplastics by integrating machine learning, deep learning, spectroscopy, GIS, remote sensing and IoT. Addressing challenges such as limited datasets, lack of standardized protocols and model interpretability will be essential for developing reliable AI-based monitoring systems that support precision soil management and environmental sustainability.

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