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Research on the Application of AI Technology in Environmental Monitoring and Protection

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Abstract

The rapid development of artificial intelligence (AI) technology has opened up a new theoretical paradigm and practical path for the field of environmental monitoring and protection. This article outlines the diversified applications of AI technology in environmental monitoring and protection, covering core areas such as air quality monitoring, water environment monitoring, pollution tracing, biodiversity conservation, and intelligent management of solid waste. Machine learning and deep learning algorithms have demonstrated strong advantages in real-time detection, precise traceability, and early warning response of pollutants by integrating heterogeneous environmental data from multiple sources. At the same time, AI technology also faces challenges such as data scarcity and uneven distribution, insufficient model generalization ability, lack of interpretability, and ethical governance. Based on this, this article proposes a development path for building a four-in-one intelligent environmental governance system of "data model standard governance", aiming to provide reference for strengthening the application of AI technology in environmental monitoring and protection, and further promoting the construction of digital ecological civilization.

Keywords

Artificial intelligence; environmental protection; environmental monitoring; environmental governance; deep learning

1. Introduction

Environmental issues are among the most severe challenges humanity faces in the 21st century. The unsustainable patterns of industrialization, urbanization, and resource consumption have triggered a series of cascading effects, including soil degradation, water pollution, and deteriorating air quality, posing profound threats to ecosystem stability and human health. While traditional environmental monitoring methods can provide high-precision data, their high costs, time-consuming nature, and limited spatial coverage make them ill-suited to address the complex characteristics of rapidly spreading modern pollution sources and spatiotemporal heterogeneity. Against this backdrop, the integration of artificial intelligence (AI) technology presents a paradigm-shifting opportunity for environmental monitoring and protection. As core branches of AI, machine learning (ML) and deep learning (DL) are rapidly expanding their application footprint in environmental research due to their powerful data processing capabilities, real-time monitoring advantages, and precise predictive functions. AI not only processes massive, multi-source, and heterogeneous environmental data but also identifies complex patterns and nonlinear relationships imperceptible to humans, thereby achieving a fundamental transformation from "passive recording" to "active early warning" and from "post-event remediation" to "prevention and control" [1].

Currently, a substantial body of global research has focused on the application of AI in the environmental field. However, existing reviews tend to emphasize technical enumeration while lacking systematic efficacy evaluations

and critical analysis. This paper aims to address this gap by systematically organizing AI technologies across key areas of environmental monitoring and protection, revealing their current applications, technical efficacy, and limitations. Building upon this, it further explores future development directions to provide theoretical foundations and practical references for constructing an intelligent environmental governance system.

2. The Application of AI in Various Fields of Environmental Monitoring

2.1 Air Quality Monitoring and Pollution Prediction

Air pollution monitoring is one of the most mature environmental fields in which AI technology is applied. In terms of pollution concentration prediction, deep learning models have achieved high-precision forecasting of key pollutants such as PM2.5 and PM10. The hybrid deep learning model significantly improves the prediction accuracy of the Air Quality Index (AQI) by integrating Long Short Term Memory (LSTM) networks for temporal prediction, CNN for extracting spatial features, and GNN for modeling spatial correlations between stations. In terms of pollution tracing, computer vision technology has improved the accuracy of pollution source identification to 92%. By integrating multiple sources of data, a pollutant traceability model is established. Convolutional neural networks are used to locate pollutants, followed by deep neural networks for pollution path tracking and diffusion prediction [2]. In addition, the combination of Physical Information Neural Network (PINN) and Interpretable AI (XAI) enables the model to not only accurately predict but also explain the physical mechanisms of pollution formation. It is worth noting that AI has moved from academic research to practical business applications in the field of atmospheric monitoring, indicating that AI is fundamentally reshaping the timeliness and coverage of atmospheric environmental monitoring.

2.2 Water Environment Monitoring and Pollution Traceability

Water environment monitoring is another important battlefield for the application of AI technology. In terms of water quality prediction, machine learning models have been widely applied to river water quality prediction. The hybrid deep learning and intelligent optimization algorithm model proposed by researchers, the Separable Attention Fusion Gated Bidirectional Long Short Term Memory Network (IDBO GBiLSTM) with improved beetle optimization, significantly improves the accuracy of water quality prediction. The water quality monitoring system based on LSTM-GRU realizes the real-time prediction of water quality trend by collecting data independently by unmanned craft and combining edge computing. Under data scarcity conditions, deep representation learning models can capture knowledge from the source watershed and transfer it to the target watershed, achieving cross-basin water quality prediction [3]. In terms of pollution tracing, AI technology has demonstrated advantages that traditional methods cannot match. Algorithms such as deep learning and transfer learning have demonstrated the ability to utilize multi-source data for multi-scale representation in complex environmental conditions; Time series models and physics-driven AI can dynamically analyze the migration paths of pollutants at multi-media interfaces. In terms of intelligent monitoring, a new method combining full-spectrum analysis and deep learning establishes a nonlinear mapping relationship between spectral features and water quality parameters by collecting continuous absorption spectra of water in the ultraviolet to near-infrared band (200~900nm), achieving rapid inversion of key water quality parameters such as chemical oxygen demand, total nitrogen, ammonia nitrogen, and total phosphorus.

2.3 Biodiversity Monitoring and Ecological Protection

Biodiversity conservation is an emerging frontier field of AI technology application. In terms of species identification and monitoring, the combination of AI and computer vision systems has achieved large-scale automated monitoring of wildlife. AI-driven camera traps can automatically capture and analyze wildlife images, helping researchers track and identify species in natural habitats. In the field of vegetation ecological protection, the integration of remote sensing, image recognition, and machine learning algorithms has been widely applied in vegetation health assessment, species classification, and spatiotemporal dynamic analysis. In terms of habitat protection, the combination of satellite imagery and AI is used to monitor deforestation, illegal logging, and habitat changes, providing the possibility for timely conservation interventions. The AI intelligent agent framework proposed by researchers automatically selects the optimal priority for protection and restoration by interpreting changes in species habitat connectivity and the synergistic benefits of climate and water resources.

2.4 Intelligent Management of Solid Waste

The intelligent management of solid waste is another important application direction of AI technology in the field of environmental protection. In terms of intelligent classification, the AI-driven garbage classification model combines IoT and blockchain technology to achieve real-time classification and traceable management of waste. The self-developed AI edge computing box and image recognition algorithm can analyze the garbage type and delivery behavior in the garbage can in real time, and the recognition accuracy rate is 95% [4]. The emergence of intelligent waste sorting robots such as Atron marks the transition of AI solid waste sorting from laboratory to commercial applications. In terms of system management, the "smart brain" for urban renewable resource management based on the Internet of Things and AI technology—a big data platform—can monitor the operation status of the recycling network in real time, analyze and predict through AI algorithms, and generate regional recycling "portraits". AI-driven end-to-end solid waste management solutions have been proven to effectively alleviate economic and environmental challenges.

2.5 Climate Change Prediction and Carbon Management

The application of AI in the field of climate change represents a qualitative leap in environmental prediction capabilities. In terms of climate simulation, the deep learning Earth system model DLESyM can complete a 1000-year climate simulation within 12 hours by coupling atmospheric and oceanic AI modules, with extremely low computational cost and energy consumption compared to traditional models. Aurora, the fundamental model of the Earth system, surpasses traditional operational forecasting systems in predicting air quality, waves, tropical cyclone paths, and high-resolution weather, reducing computational costs by several orders of magnitude. In terms of carbon management, AI has been systematically applied to the entire chain of monitoring, predicting, and reducing carbon emissions [5]. AI technology provides important technical support for achieving the "dual carbon" goal by analyzing multi-source data to optimize energy efficiency.

3. Decision Support and Governance Applications of AI in Environmental Protection

The value of AI technology beyond environmental monitoring lies in its ability to transform monitoring data into actionable governance decisions.

At the policy-making level, AI provides evidence support for environmental policy formulation through big data analysis and scenario simulation. Explainable AI (XAI) technology enables decision-makers to understand the logic behind model outputs - XAI is used to explain the complex relationships between pollution levels, meteorological conditions, human activity patterns, and geographic factors - thereby enhancing the transparency and credibility of AI-assisted decision-making.

At the level of intelligent supervision, AI technology has been embedded into the entire process of environmental law enforcement and management. The "Ecological Intelligent Assistant" deeply empowers scenarios such as environmental monitoring, pollution tracing, precise policy Q&A, and intelligent law enforcement assistance, achieving an intelligent governance model of "gradual iteration, multi-scenario adaptation, and independent exploration" [6]. In the "City Brain" environmental module in Shenzhen, the fusion of 800 IoT sites and 3 satellite remote sensing datasets has achieved minute-level warning of PM2.5 concentration with an accuracy rate of 92%.

At the policy framework level, China has clearly defined the strategic direction of AI empowering environmental protection at the top-level design level. In 2023, the National Ecological Environment Protection Conference pointed out the need to "deepen the application of digital technologies such as artificial intelligence, build a beautiful China digital governance system, and construct a green and intelligent digital ecological civilization". In 2025, the State Council issued the "Opinions on Deepening the Implementation of the 'Artificial Intelligence+' Action," providing policy guidance for the deep integration of AI and ecological environment protection. The "National Ecological Environment Monitoring Network Digital Transformation Plan" issued by the Ministry of Ecology and Environment further clarifies the specific path of intelligent transformation of the monitoring system driven by new technologies such as AI [7].

4. Future Development Prospects

In the future, the development of AI in the field of environmental monitoring and protection will mainly focus on the following directions:

One is to build high-quality multimodal environmental datasets. In fields such as biodiversity conservation,

constructing standardized datasets covering multiple sources of data such as satellite remote sensing, infrared cameras, and ground surveys is a fundamental prerequisite for promoting the development of large-scale models in the field. The second is to develop AI models that integrate interpretable and physical information. By embedding the physical mechanisms of environmental science into the AI model architecture, the interpretability and generalization ability of the model can be enhanced while maintaining prediction accuracy. The third is to promote edge computing and real-time intelligence. AI environmental monitoring system needs to sink to the edge to achieve real-time intelligent perception and response with low delay and low power consumption, which is particularly critical for rapid response to sudden pollution events [8]. The fourth is to establish an intelligent system that links perception, decision-making, and governance. The future development direction is to move from isolated analysis tools to intelligent cloud chain platforms that link perception, decision-making, and governance, and establish a technical standard system that covers model architecture, data interfaces, and evaluation protocols. This means that AI not only needs to "see" environmental issues, but also "know how to respond".

At the same time, the deep application of AI in the environmental field requires close collaboration between ecologists, computer scientists, and policymakers. It is necessary to establish a collaborative mechanism for algorithm ethics review and cross-border governance to ensure that the process of AI empowering the environment is fair, transparent, and sustainable. Therefore, strengthening interdisciplinary collaboration and ethical governance is also an important part of AI technology in environmental monitoring and protection, and must be given sufficient attention.

5. Conclusion

AI technology is profoundly changing the way and ability of humans to monitor, understand, and protect the natural environment. From precise prediction of air pollution to intelligent traceability of water environmental pollution, from large-scale monitoring of biodiversity to intelligent management of solid waste, from ultra-efficient simulation of climate change to full-chain control of carbon emissions, AI has penetrated almost all core areas of environmental monitoring and protection. This transformation is not only about improving efficiency at the technical level, but also a paradigm shift at the epistemological level - shifting environmental science from "data-driven inference" to "data-driven precision prediction". However, we should also be aware that AI is not the "master key" to solving all environmental problems. Challenges such as data scarcity, insufficient interpretability of models, limited generalization ability, and lack of ethical governance all require us to embrace technological dividends while maintaining prudence and criticism.

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