Chapter 10

Rethinking homo economicus
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AI Applications for Environmental Monitoring and Pollution Control

Aplicaciones de IA para la monitorización ambiental y el control de la contaminación

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ABSTRACT

The chapter discusses the growing role of Artificial Intelligence (AI) in environmental monitoring and pollution control, and specifically how it can be used in the gas, oil, and chemical industries. As the ecological threats in the world are becoming more complicated, i.e. climate change, dangerous emissions, the degradation of resources, etc., the manual sampling and the use of periodic inspection as conventional methods of monitoring is becoming less efficient. Artificial intelligence offers a radical innovation in environmental management by offering real-time and data-driven predictive decision-making by means of the fusion of satellite images data, IoT sensor data, drones, and industrial devices data. The machine learning and deep learning techniques enhance the detection of pollutants, prediction of emission trends, optimization of industrial processes, and regulatory compliance. Additional aspects of AI and IoT, edge computing, use of AI in policy and decision making, and moral, societal and technical concerns of environmental AI devices are also explored in the chapter. Finally, it points out to new trends, such as digital twins, federated learning, autonomous robots, and climate-conscious AI models. All this demonstrates that AI is becoming one of the facilitators of sustainable, smart, and resilient environmental management.

Keywords: Artificial Intelligence (AI); Environmental Monitoring; Pollution Control; Machine Learning; Sustainability Systems.

RESUMEN

Este capítulo analiza el creciente papel de la Inteligencia Artificial (IA) en la monitorización ambiental y el control de la contaminación, y en particular su aplicación en las industrias del gas, el petróleo y la química. A medida que las amenazas ecológicas mundiales se complican, como el cambio climático, las emisiones peligrosas, la degradación de los recursos, etc., el muestreo manual y el uso de inspecciones periódicas como métodos convencionales de monitorización se vuelven menos eficientes. La IA ofrece una innovación radical en la gestión ambiental al ofrecer una toma de decisiones predictiva en tiempo real y basada en datos mediante la fusión de datos de imágenes satelitales, datos de sensores del IoT, drones y dispositivos industriales. Las técnicas de aprendizaje automático y aprendizaje profundo mejoran la detección de contaminantes, la predicción de tendencias de emisiones, la optimización de procesos

industriales y el cumplimiento normativo. También se exploran otros aspectos de la IA y el IoT, la computación de borde, el uso de la IA en la formulación de políticas y la toma de decisiones, y las preocupaciones morales, sociales y técnicas de los dispositivos de IA ambiental. Finalmente, se señalan nuevas tendencias, como los gemelos digitales, el aprendizaje federado, los robots autónomos y los modelos de IA con conciencia climática. Todo esto demuestra que la IA se está convirtiendo en uno de los facilitadores de una gestión ambiental sostenible, inteligente y resiliente.

Palabras clave: Inteligencia Artificial (IA); Monitoreo Ambiental; Control de la Contaminación; Aprendizaje Automático; Sistemas de Sostenibilidad.

INTRODUCTION

Overview of Global Environmental Challenges

The increased global concern on climate change, depletion of resources and polluting industries has exerted pressure on the oil, gas and chemicals industry which are energy consuming sectors forcing them to update their environmental management policies like never before. These technologies are at the core of the ongoing Triple Planetary Crisis: climate change, pollution of the environment, and the destruction of biodiversity.[1] Despite the international agreements on reducing emissions, the chemical pollution of the world, the destruction of water resources, and greenhouse gas emissions, the processes of industrial development continue to play a significant role in the world. One of the most pressing problems is the emission of methane (CH_4), and it remains very high. According to an International Energy Agency (IEA) assertion, the activities of the fossil fuels continue to generate over 120 million tonnes of methane annually which is one of the greatest short-term climate pollutants. Due to its Global Warming Potential (GWP) of more than 80 times that of CO_2 over a 20-year time period,[2] Methane mitigation has now become a global priority.

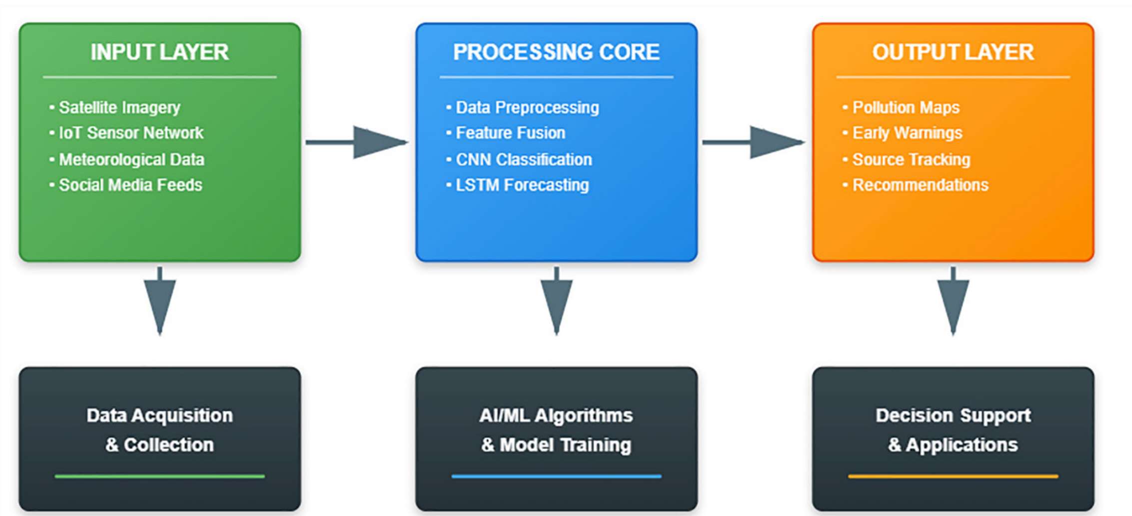

Figure 1. Three -Tier Archtitcture Integreting Multi-Source Data, AI Processing And Actionable Outputs

In the meantime, industries also face an increased pressure to treat generated water, toxic chemicals, and intractable organic pollutants (POPs) and remain safe and efficient at the same time. The international regulations such as the UNEP Global Framework on Chemicals and the Emissions Gap Report note that transformative, data-driven measures are important to minimize the effects and need to be taken in order to meet the Sustainable Development Goals. [3] Traditional Environmental Management Systems (EMS) that are currently operated manually through sampling, systems that are periodically inspected and the reactive-based systems are simply not responsive enough to keep pace with the magnitude and rapidity of the modern industrial operations. These methods are generally used to provide access to emissions, water quality, and ecosystem disruption late or incompletely. Artificial Intelligence (AI) is emerging as a facilitator in this respect at a great speed. The AI systems use sensor, satellite and drone data, as well as industrial data to transmit real-time, informative environmental data. Machine learning models are significantly superior to the conventional tools in detecting pollutants, anticipating equipment malfunctions, optimizing industrial processes, and facilitating compliance. This is the shift towards reactive monitoring and predictive and automated environmental intelligence as the industries keep aiming at achieving the net-zero targets and sustainability goals. In this chapter, the author explains how AI may be applied in enhancing environmental surveillance and reducing pollution. It brings out the best technologies that are most critical, practices, and uses that change the way industries measure, analyze, and reduce their ecological footprint. The opening part provides a foundation on the ways AI can be used to bridge the gap between industrial operations and global sustainability ambitions in the next centuries.[4,5]

Table 1. Summary of Key Environmental Challenges and the Enabling Role of AI in Energy-Intensive Industries

Theme	Problem / Context (from the text)	AI / EMS Implication
Triple Planetary Crisis	Oil, gas, and chemical industries are at the center of climate change, environmental pollution, and biodiversity loss.	These sectors are priority targets for transforming environmental management and decarbonization strategies.
Industrial contribution to environmental impacts	Global industrial activities continue to drive GHG emissions, chemical contamination, and water resource degradation despite international commitments to reduce emissions.	Strong need for more effective, data-driven monitoring and control tools that can capture the complete industrial footprint.
Methane (CH_4) emissions	Methane from fossil fuel operations exceeds 120 million tonnes annually; with a GWP > 80× CO_2 on a 20-year timescale, it is one of the most impactful short-lived climate pollutants.	Methane mitigation has become a top global priority, requiring precise detection and quantification, and rapid response across assets and facilities.
Other pollutants and water issues	Industries must manage produced water, hazardous chemicals, and persistent organic pollutants (POPs) while maintaining safe and efficient operations.	Integrated monitoring systems are needed to track water quality, toxic releases, and complex pollutant mixtures in real time.
Regulatory and policy pressure	International frameworks (e.g., UNEP's Global Framework on Chemicals and the Emissions Gap Report) call for transformative, data-driven solutions that support sustainable development targets.	Compliance is no longer just reporting; it requires robust, transparent, and auditable environmental intelligence platforms.

Limitations of traditional EMS	Traditional EMS relies on manual sampling, periodic inspections, and reactive responses, leading to delayed and incomplete visibility into emissions, water quality, and ecosystem disturbances.	Conventional methods cannot keep pace with the scale, complexity, and speed of modern industrial activities, creating a gap between operations and sustainability objectives.
Role of Artificial Intelligence (AI)	AI integrates data from sensors, satellites, drones, and industrial equipment to deliver real-time environmental insights. ML models can detect anomalies, predict equipment failures, optimize processes, and support compliance.	AI acts as a transformative enabler for environmental monitoring and pollution control, augmenting or replacing traditional EMS with intelligent, automated decision-support systems.
Shift to predictive environmental intelligence.	There is a transition from reactive monitoring to predictive, automated environmental intelligence as industries move toward net-zero and sustainability goals.	Predictive, AI-driven systems allow early intervention, emission mitigation, and continuous optimization, aligning industrial performance with climate and sustainability targets.
Aim of the chapter	The chapter examines how AI can enhance environmental monitoring and pollution control, highlighting key technologies, methods, and applications.	Provides a conceptual and practical foundation for using AI to bridge the gap between industrial operations and global sustainability objectives in the coming decades.

Why AI is Becoming Essential in Modern Environmental Systems

Traditional Environmental Management Systems (EMS) have been extensively founded on reactive, that is, manual sampling, routine checks and merely responding to alarm triggers when environmental thresholds have been hit.(6) In the context of Industry 4.0, such approaches have become even more inadequate as the amount of environmental data is increasing exponentially, industrial operations get more complicated and the processes of regulation are quickening down. As the trend is to shift towards real-time monitoring and data-driven decision-making in industries, Artificial Intelligence (AI) and Machine Learning (ML) are emerging as the intelligence layer of the modern environmental engineering because of the following three factors:(7)

Transition from Reactive to Predictive Management

The fundamental concept is that AI transforms the detection-and-fix paradigm to a prediction and prevention paradigm. Recent studies have shown that ML algorithms have the ability to use past data on the processes to foretell equipment failures, which may be valve fatigue, cases of corrosion, or seal leakage, several weeks before resulting in fugitive emissions or operational disruptions.(8) This predictive capability lowers the amount of releases of pollutants to the environment, enhances reliability and safety, as well as limiting unexpected downtime.(9)

Managing the Complexity of Big Environmental Data

Modern industrial plants receive vast quantities of environmental data every day with the help of the Industrial Internet of Things (IIoT) sensors, satellite surveillance, drone inspections, and weather networks. These data streams are too large, fast and of a kind that are not analyzable by humans. Multimodal data may include visual, infrared, thermal, and chemical data, and if analyzed by AI, powerful learning may occur. These models can be utilized to determine so-called super-emitters by determining the small fraction of the components that generate the majority of the leaks.[10] That would enable specific intervention and a more effective distribution of resources.

Ensuring Real-Time Compliance and Regulatory Transparency

Global environmental regulations are currently moving towards emissions reporting based on measurements. The frameworks such as the Oil and Gas Methane Partnership 2.0 (OGMP 2.0) demand that all information must be verified, accurate and verifiable and not a forecast derived out of the engineering computations. Even in the absence of physical analyzers or limited conditions, AI-driven soft sensors can be used to make real-time estimates of the concentrations of pollutants, including NOx, SOx, and methane. Such smart monitoring systems are beneficial in terms of increasing 24/7 auditability, improving the quality of compliance reporting and traceable records to regulatory agencies.[11]

Scope and Purpose

The chapter gives an overview of how the field of Artificial Intelligence (AI) can be used to improve environmental monitoring and pollution control in oil, gas, and chemical industries. It explains the way AI can help to collect environmental data, manage the industry effectively, and make sure that it complies with the regulations. The chapter presents the contribution of the modern AI tools by describing how it could be applied to the environmental science and data engineering to reduce emissions, create a sustainable environment, and enhance real-time ecological management. The aim of this chapter is to:

1. How do AI-based surveillance systems, such as computer vision, satellite imaging, and smart sensors, work in gathering the right data of the environment?
2. Show how AI can be used to run processes in a way that makes them sustainable, including less flaring, improved wastewater treatment, and energy consumption.
3. Provide new methods of digital governance, such as Digital Twins and automated reporting systems in improving their accountability and environmental regulations.

Data Sources for Environmental Monitoring

The idea of the environmental monitoring is based on the wide variety of the data resources that provide real time data about the air, waters, soil and industrial emissions. The present-day surveillance systems operate on chains of IoT devices which are used to measure the concentrations of gasses, temperature/humidity and water quality indicators, and the concentration of any particulate matter in real time.[12] One such satellite and remote-sensing platform is the NASA and Copernicus missions that provide high-resolution images to identify changes in land-use, vegetation stress, thermal change, and macro-scale pollution patterns. In addition, the visual, thermal, and gas-sensing payloads mounted on drones provide scalability and rapid data collection of areas that are inaccessible, e.g. pipelines, flare stacks, and water bodies. Environmental data can also be found in the government and international open data like EPA Air Quality Data, NASA Earth Observations and global climate databases. Although these sources are often abundant, noises, values missing, sensor drift, etc. may most likely be found, and thus pre-processing and AI-based data cleaning are the key to getting plausible and valid measurements of the environment.[13,14]

Machine Learning Techniques in Environmental Analysis

Machine learning will also play a significant role in the analysis of environmental data since it results in accurate prediction, classification, and identification of trends related to pollution. The popular examples of such models include the random Forest (RF), Support Vector, and

Artificial Neural Networks (ANN) and are used to predict and evaluate the environmental risks of pollutants based on the labeled data. Unsupervised learning is useful in identifying anomalies, as well as new pollution hotspots, and any latent patterns in large datasets, even in the absence of labels. The time-series forecasting deep learning techniques (Long Short-term Memory) networks, Gated Recurrent Unit (GRUs), and hybrid deep learning are required to forecast the future rates of pollution, as well as to analyze long-term trends. The main environmental analysis is also based on feature engineering where important environmental variables, including weather condition, chemical indicators, and other features will be chosen or developed to help improve accuracy and performance of the model.(15)

Deep Learning for Environmental Monitoring

The capability of deep learning to perform the tasks with the large, dense, and multidimensional data has helped to adopt it as an effective tool of environmental monitoring. CNNs have been widely used in satellite, drone, and thermal imagery to see the locations of oil spills, identify the changes in land usage, track the behavior of a wildfire, and map areas vulnerable to floods with a very impressive degree of accuracy.(16) Time-series data can be successfully employed to predict the long-term behavior of the environment, forecast the trends of pollutants, and recurrent neural network models such as LSTM and GRU can be successfully utilized in air quality forecasting. Unsupervised deep learning systems, such as Deep Autoencoders, may be employed to identify an abnormal emission or sensor failure or environmental anomaly that might be related to leakage or malfunction. Such neural learning algorithms can be applied in quicker, more precise, and automated scanning of the environment and are indispensable to the modern monitoring systems.(17)

AI-Enabled Pollution Control Systems

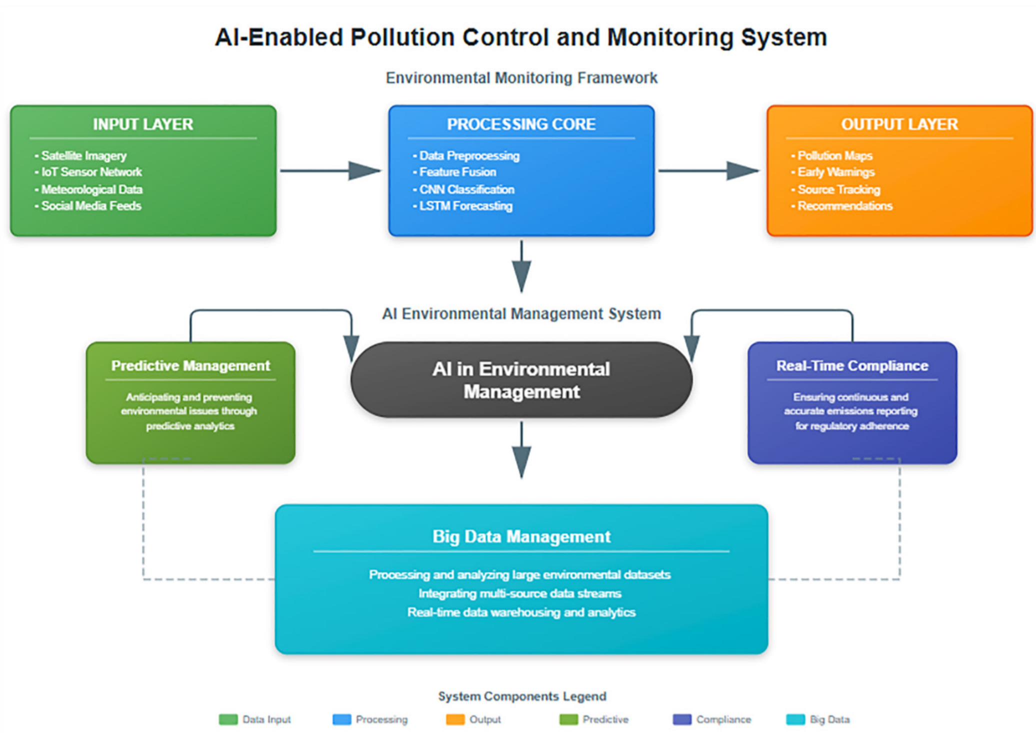

Figure 2. Integrated AI-Enabled Pollution Control and Environmental Monitoring System

Intelligent, AI-controlled pollution control systems enable real-time monitoring and minimization of emissions, enhancing environmental performance and system operation. These systems can automatically monitor air and water pollutants, detect abnormal emission events, and issue early alerts to operational systems before they reach critical levels. In factories, AI algorithms can detect leaks and optimize combustion cycles, as well as flare using predictive control based on sensor data. In cities, AI-based traffic management systems can be used to reduce vehicle emissions by adjusting signal timing based on congestion levels.(18) There is also the increased use of AI in wastewater treatment plants to streamline chemical dosage, aeration, and energy use, leading to cleaner effluents and lower operating expenses. On the whole, AI-based pollution management is more accurate and responsive than many other environmental management methods, making it more sustainable.(19)

AI in Environmental Policy and Decision Making

Artificial intelligence (AI) has become an issue in the context of environmental policy and decision-making, which can provide strong tools in the collection, monitoring, prediction, and analysis of data.(20) AI can track real-time environmental dynamics, such as the deforestation process, air and water pollutants, wildlife tracking, and climate changes with the implementation of satellite cameras, sensors, and robots. Its predictive models help governments and organizations to forecast results of climate change, determine the risk of disasters, and compare policy choices to find out which strategies are most effective in reducing and adapting to its impacts. The intelligent decision support systems assist the policymakers in cost benefit analysis, environmental impact analysis and optimum resource distribution in areas like energy planning, agriculture and urban development.(21) The benefits of such applications are high accuracy of results, faster insights and reduced costs as well as improved long term planning. Nevertheless, there are also obstacles associated with data quality, transparency, equity, privacy and overreliance on technology, they introduce. Nevertheless, AI is a continuous field of work that will result in the evidence-based environmental governance and assist in making more sustainable and informed decisions in climate policy, conservation, pollution management, and resource management.(22)

Integration of AI with IoT and Edge Computing

Integrating the AI and the Internet of Things (IoT) with the edge computing can establish an effective ecosystem where interconnected devices can acquire, process, and respond to information in real time, and centralized systems are minimally or not relied on. In this hybrid architecture, the IoT devices scan large amounts of data on the physical world and edge processing reduces response time, bandwidth usage and dependency on the cloud computing. This system will be enhanced by AI, which will allow the gadgets to comprehend the information, establish trends, predictions, and make decisions independently without sending information to remote servers.(23) When such components are combined with each other, the entire mechanism becomes quicker. There are faster reactions, operations proceed more efficiently, and information belonging to users remains more secure as much less data is to be passed through the network. Precisely, it is useful in tasks like smart cities, self-driving cars, automation in industries, environmental systems and health care, when the milliseconds count. This capability of the system to identify anomalies in real time, to provision predictive maintenance, maximize energy consumption and to propel the context aware automation is made possible by making AI more resilient and adaptive with an embedded predictive ability at the system edge. That contributes to considering AI, IoT, and edge computing as a fundamental technology stack of next-generation intelligent systems, which are scalable, efficient, and responsive.(24)

Ethical, Social, and Technical Challenges

Implementing the environmental AI systems is related to a number of ethical, social, and technical issues, which must be addressed to guarantee the responsible usage of the data privacy. One of the main concerns is also the privacy of information, since environmental sensors (such as drones, satellite imaging and distributed sensors) may mutually capture sensitive personal or geolocation data by accident, and the question of surveillance and data protection appears.[25] Uneven coverage of data, sensor noise, old data, and sampling bias also play their role in biased and uncertain predictions of AI that results in inaccurate or unfair predictions. Additionally, AI models are mostly applied as black boxes, which limits their reliability, interpretability, and transparency, which is imperative when these systems are applied to provide directions to the policies of the population, environmental risk analysis, or city layout. Finally, ecological justice aspects outline the fact that less-privileged or underserved communities may not be tracked or may be disproportionately affected by flawed AI-based decisions which can only widen presented disparities. To establish credible, equitable, and effective environmental AI systems, the concerns are all interrelated, which is crucial to address.[26]

Future Trends

In future simulation, prediction and scenario testing, the environmental AI is moving towards more intelligent, robust and integrated systems with digital twins of ecological systems. Simulation, prediction and testing Virtual replicas of ecosystems, watersheds, cities or climate processes will permit real-time simulation, prediction and testing and this will enhance improved decision-making and adaptive management.[27] The concept of federated learning is currently very popular in the analysis of distributed environmental data and achieving privacy, allowing models to be trained on sensors, institutions, regions without direct sharing of raw data. The autonomous environmental robots such as drones, underwater vehicles, and ground platforms will be more autonomous and competent, and will be able to monitor the environment in large scales, sample and respond to the environmental hazards more quickly. At the same time, climate-conscious AI will involve climate physics, long-term trends, and extreme events patterns into the algorithmic processes to make the predictions more precise and applicable to the rapidly evolving world. All these trends are heading towards the future as AI-controlled tools are becoming more interdependent, adaptable, and environmentally aware.[28]

CONCLUSIONS

AI-based environmental monitoring and pollution control is the future of the environmental monitoring and pollution management as it gives more precise, speedy insights than ever. The transformation of raw environmental data into useful intelligence to empower the identification of emissions, industrial optimization, and regulatory compliance, as well as a powerful policy and decision-making tool in ecological sustainability have been discussed in this chapter as AI is changing. Together with machine learning, deep learning, IoT-driven sensing, and edge computing, they have created a single ecosystem that has the potential to analyze, predict and autonomously act in the environment in real time. At the same time, ethical and social aspects including privacy, prejudice, transparency, and environmental equity show that the AI technology should be developed and implemented responsibly. Digital twins, federated learning, climate-conscious, and even autonomous environmental robots will all be part of AI in the future and will push the boundaries of AI. Lastly, the place of AI within the ecological systems will also change: it will become an unavoidable factor of cleaner operations, sustainable environment, and a more eco-friendly industrial future.

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