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Artificial Intelligence in Environmental Engineering: Scientific Production and Trends (1980-2024)

Inteligencia Artificial en Ingeniería Ambiental: Producción Científica y Tendencias (1980-2024)

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Abstract

Over the years, artificial intelligence has expanded its reach in various fields, including the environmental field. Considering the challenges that this field presents in the short, medium and long term, the objective of this article was to analyze the search trends applied to environmental engineering. To this end, research opportunities and the main challenges it faces were considered. Through an analysis of the literature in databases such as Google Scholar and Scopus, a growing interest in the use of artificial intelligence to address ecological and sustainability problems was identified. Although interest in this topic is documented since 1987, its application was oriented to military purposes. On the other hand, commercial and freely available tools applied to the object of study are described. After an analysis, it was concluded that predictive models have a great potential to prevent catastrophes and harmful impacts, and that the dissemination of information at national and international level is esential for data analysis in artificial intelligence.

Keywords: Databases, Artificial Intelligence, Environmental Engineering.

Resumen

A lo largo de los años, la inteligencia artificial ha expandido su alcance en diversos campos, incluyendo el ambiental. Considerando los desafíos que este campo presenta a corto, mediano y largo plazo, el objetivo de este artículo fue analizar las tendencias de búsqueda aplicadas a la ingeniería ambiental. Para ello, se consideraron las oportunidades de investigación y los principales desafíos que enfrenta. Mediante un análisis de la literatura en bases de datos como Google Scholar y Scopus, se identificó un creciente interés por el uso de la inteligencia artificial para abordar problemas ecológicos y de sostenibilidad. Si bien el interés en este tema se documenta desde 1987, su aplicación se orientó a fines militares. Por otro lado, se describen herramientas comerciales y de libre acceso aplicadas al objeto de estudio. Tras un análisis, se concluyó que los modelos predictivos tienen un gran potencial para prevenir catástrofes e impactos nocivos, y que la difusión de información a nivel nacional e internacional es esencial para el análisis de datos en inteligencia artificial.

Palabras Clave: Bases de datos, Ingeniería Ambiental, Inteligencia Artificial.

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1 Introduction

Environmental engineering is a discipline that combines the main principles of engineering to study, propose and solve problems focused on environmental sciences, so from this profession seeks to protect human beings from the adverse effects of pollution, considering the efficient management of solid waste, environmental legislation, health impacts, recycling strategies, protection of resources (water, soil and air), among others [1]. The literature review evidences how the successful fulfillment of the above elements requires a deep knowledge of the chemical and biological aspects of the potential pollutant [2]; as well as the understanding of the industrial sector and/or commercial processes that could lead to the release of such unwanted wastes [3][4].

Even though there are still great challenges in environmental issues, we cannot ignore the progress that includes water treatment and management, methods for soil conservation, sediment pollution control [5], strategies to improve air quality [6], techniques to degrade pollutants produced by available technical processes (industrial wastes) or by large population centers (municipal wastes). Reflecting scientific results and advanced applications in technologies, which involve an integrated vision of strategies and methods in the resolution of problems associated with sustainability. As a support to these technological processes, artificial intelligence has made inroads in several fields of knowledge, including engineering, where it has become a fundamental tool that allows: streamlining processes, generating optimization algorithms and automated design, performing predictive analysis, as well as handling large volumes of data [7]; transversal topics that contribute to the mission of civil, electrical and mechanical engineering, and, for our particular interest, environmental engineering. Based on the above, this research seeks to identify: research opportunities, projects and possible challenges or scenarios where artificial intelligence contributes to the development of the environmental field in a sustainable manner.

The methodology of this research is based on an exhaustive documentary review, where data were obtained from various academic databases, including Publish or Perish. For the search of supporting information, specialized web portals, bibliometric search software, relevant research articles and a detailed exploration of geo portals focused on the environmental field were used. This strategy made it possible to compile and analyze a broad spectrum of research and projects involving the application of artificial intelligence in the sustainable development of the environment.

The results of this research it will also contribute to environmental management organizations, technology companies and policy makers, who will be able to identify opportunities, innovative projects and emerging challenges at the intersection between AI and sustainability.

2 Methodology

The methodology of this article described in Figure 1 adopts a quantitative descriptive approach, as it seeks to analyze trends related to the application of artificial intelligence in environmental engineering, based on secondary sources such as academic databases like Publish or Perish[8]. The documentary type data were oriented to identify and analyze the relationship between artificial intelligence (AI) and environmental engineering. For the collection of information, a search was carried out using specialized web portals, bibliometric analysis software and the exploration of geo portals focused on the area of study. Tools such as Publish or Perish were used to access databases such as Scopus and Google Scholar, which allowed the collection of relevant scientific publications. Subsequently, the most relevant articles for the research topic were selected, taking into account the relevance of the publications. Likewise, research opportunities were identified, such as the challenges facing the use of AI in sustainable environmental development.

For the extraction of documents, a time interval was established from 1980 to 2024, seeking to obtain a broad review of the evolution of the subject, focusing more interest on the last 5 years. The query was performed on August 17 2024, using keywords such as "artificial intelligence, environmental, sustainability", obtaining a total of 497 documents relevant to the study. The Excel spreadsheet was used to systematize the information and the R-Studio software was used to calculate some bibliometric indicators such as: production of documents for 10-year periods, most productive authors, documents with the highest number of citations. These indicators made it possible to identify current research trends, as well as key actors and sources in the development of the field.

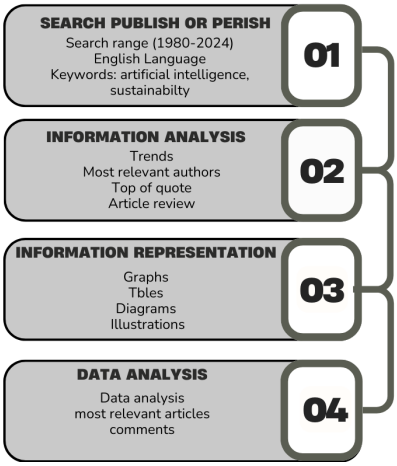

Figure 1: Diagram of the research methodology

3 Results

For the analysis of the results, a total of 497 documents were collected from the databases indicated in the flow chart. In this first section of results, bibliometric indicators are presented to identify the behavior of scientific production in the field, highlighting the trends, the main authors and the progress of study between artificial intelligence and environmental sustainability.
The second part details the relevant findings of the documentary analysis, in order to explore the thematic and methodological approaches that have generated a greater impact within the subject of this article.

3.1 Bibliometric approach. AI and Environmental Engineering.

In the analysis of the results extracted by means of the software shows a notable growth between 2021 and 2024 in artificial intelligence research in the environmental field, which may be associated with various factors, including: the increase in the availability of open data, the accelerated and accessible advancement of AI models, and even the interest in investigating the strengthening of global climate policies, as evidenced, among others, at COP26 in 2021 (United Nations Climate Change Conference).

The exponential fit of the number of publications (red dotted line) yields the equation seen within Figure 2, where the base coefficient of 0.2943 indicates that the scientific output in the subject under study was very low at the beginning of the 1980s. Additionally, the exponent coefficient of 1.4592 implies a very high effective annual growth rate, suggesting an extremely rapid and sustained growth in the scientific production on AI in environmental engineering, which is consistent with areas of knowledge that experience accelerated technological advances.

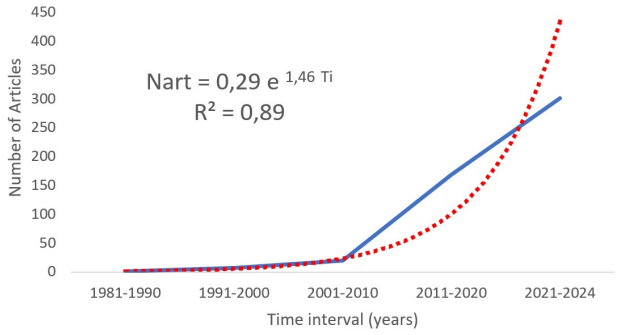

Figure 2: Publications by decade on AI in Environmental Engineering

In addition, other indicators are included that allow us to characterize the growth of scientific production in the area under study:
1. The average growth rate per period yields an approximate average value of 205% per period. This indicates systematic and accelerated growth in scientific production.
2. The number of articles published increased from 168 in the period 2011-2020 to 301 in the period 2021-2024, representing an increase of 79.2%.
3. The annual average production per period shows a progressive evolution in scientific production, as can be seen below
- Period 1 (1981-1990): 0.1 articles per year
- Period 2 (1991-2000): 0.7 articles per year
- Period 3 (2001-2010): 2.0 articles per year
- Period 4 (2011-2020): 16.8 articles per year
- Period 5 (2021-2024): 75.25 articles per year
These indicators show the notable increase in scientific production in recent periods of study.
The book entitled "Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control and Artificial Intelligence" by John H. Holland obtained the highest number of registered citations, reaching 83,049, and the highest number of citations per year, with 2595.28 (Table 1). As highlighted in the commemorative document to the author, this work has had a very significant impact on computer science, operations research, biology, ecology, psychology, economics, political science and philosophy of science, because it proposed using evolution as a metaphor to build an algorithm capable of solving complex problems, which gave rise to the field of evolutionary computation[9].

In the analysis of the first (oldest) article found, which combined the search criteria, the document entitled "Summary of the First Conference on Artificial Intelligence Research in Environmental Sciences (AIRIES)" was selected; this text summarizes the topics discussed at that conference held in the United States in 1986. It is worth mentioning that during that period, research was mainly oriented towards specific military applications, such as weather forecasting or the interpretation of situations on the battlefield. This considering the war context, either because of the Cold War or because of the confrontations with some Central American countries at that time [10].

On the other hand, in the analysis of the outstanding authors taking into account the number of publications (497 articles filtered from 1980-2024) where 2 authors stand out with 5 published articles related to the topic of study. Author Zhou Chen focuses his research interests on the application of artificial intelligence to medicine. However, 4 of the 5 articles focused on climate change, energy consumption and waste management supported by artificial intelligence. As for the author Vahid Nourani, his research interests are associated with the field of water and environmental engineering, with a strong emphasis on the application of Artificial Intelligence.

3.2 AI in Environmental Engineering

The review of the papers found in the methodological phase shows how AI has facilitated ecosystem monitoring, water resource management and prediction of environmental impacts, contributing to the implementation of more sustainable practices. The studies found evidence that the ability of AI to identify complex patterns and generate accurate models not only improves the efficiency of environmental processes, but also provides tools to address the challenges of climate change and environmental degradation [11].

Some authors point out that, with the development of computer science, information technologies and data mining, it is possible to extract previously unknown useful knowledge from large amounts of data stored in different formats. This makes it possible to perform prediction, classification, association, grouping and correlation tasks using statistical techniques such as artificial neural networks [12]. As exemplified by Geographic Information Systems and monitoring of weather conditions in cities. A sensory network in cities can visualize climate data, helping the planning and development of the city, resulting in a more efficient management of facilities and considerable savings [13].

Another tool that shows the articulation of AI with environmental engineering arises from data mining with query and

Table 1: Most highly cited published papers from 1980 to 2024

Citations	Description
83,049	Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence. (Book, Bradford Books Publishing House) by John Henry Holland-1992.
1,947	The role of artificial intelligence in achieving the Sustainable Development Goals. (Article, Nature communications) by Ricardo Vinuesa-2020.
880	Introduction to artificial intelligence (Book, Springer Publishing House) by Wolfgang Ertel-2018.

information extraction processes, with useful patterns and trends, where large amounts of existing data are involved [14]. In data mining, in particular, artificial intelligence (AI) techniques are used, for example: decision tree, artificial neural network, algorithms, support vector machine, case-based reasoning, which facilitates ecological and environmental reasoning. From another perspective, the statistics is a broad interscientific discipline, as it can help optimize data collection or preparation (sample size, sampling design, weighting, data set restriction, experimental design, etc.) for subsequent evaluation by means of Artificial Intelligence methods, in research among the most common uses found were environmental monitoring and prediction (air, water, biodiversity, among others), climate change, sustainable economic activities[15].

3.3 AI research opportunities in environmental sciences

This section describes the disciplinary areas supported by artificial intelligence and its opportunities in the field of environmental engineering, which are synthetically represented in Figure 3.

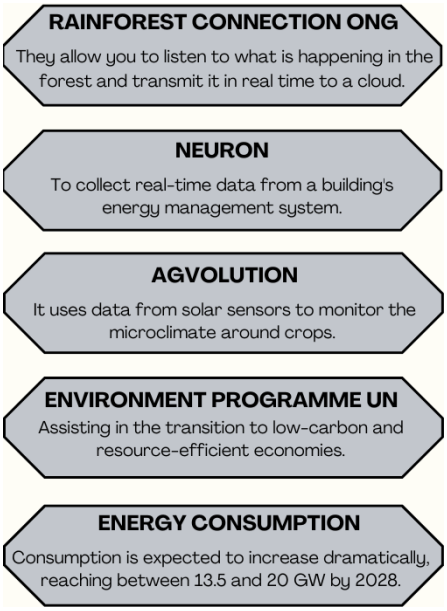

Figure 3: Diagram of opportunities and challenges of IA applied to environmental engineering.

Figure 3 illustrates technological tools that are a key opportunity in environmental engineering, including Rainforest, a company that developed warning and monitoring devices that can be applied in nature reserve or protection areas, as they are configured to recognize specific sounds (chainsaws, vehicles or other anthropogenic activities) that may threaten the well-being of the environment in which they are located. In another context related to energy consumption in Japan, an application was created that records data and generates recommendations for buildings to help reduce energy consumption and make their system more automated. In the field of agriculture, the company Agvolution offers crop monitoring sensors that generate recommendations for efficient care, allowing for excessive irrigation or spraying.

In addition, a reflection and analysis was made about one of the main challenges facing artificial intelligence, which is due to excessive energy consumption, taking into account the information found in an article published by the prestigious European company Schneider Electric, the energy consumption is 4.3 GW, which can be compared with the consumption of small countries [16].

Likewise, international governmental entities have evolved in relation to technology and environmental sciences. One example is the United Nations Environment Programme's Global Environment Situation Room, where partner countries freely share up-to-date data, reports, articles, and geoportals on various environmental issues [17].

Once this initial research exploration phase was completed, some potential lines of research to be explored and studied were identified, among which air quality prediction stands out, since it is possible to develop models based on large meteorological, industrial and traffic data sets, among others, to estimate pollutant levels. Similarly, the combination of AI and statistical methods makes it possible to optimize processes such as the management of natural resources, the mitigation of environmental impacts and improve the quality of decision making.

Figure 4 shows the United Nations Environment Programme (UNEP) geoportal, which presents real-time data on exposure to air pollution. This information is obtained from monitoring stations managed by various actors: governments, researchers, non-profit organizations, companies and individuals. When selecting a country, the geoportal also provides relevant data that facilitates the understanding of the situation, such as the age range of the most affected population (considering WHO interim targets), wind direction, location of monitoring stations and the presence of active fires that could alter air quality. The image illustrates how in India, a country known for its high population density, pollutant exposure levels are high at most stations.

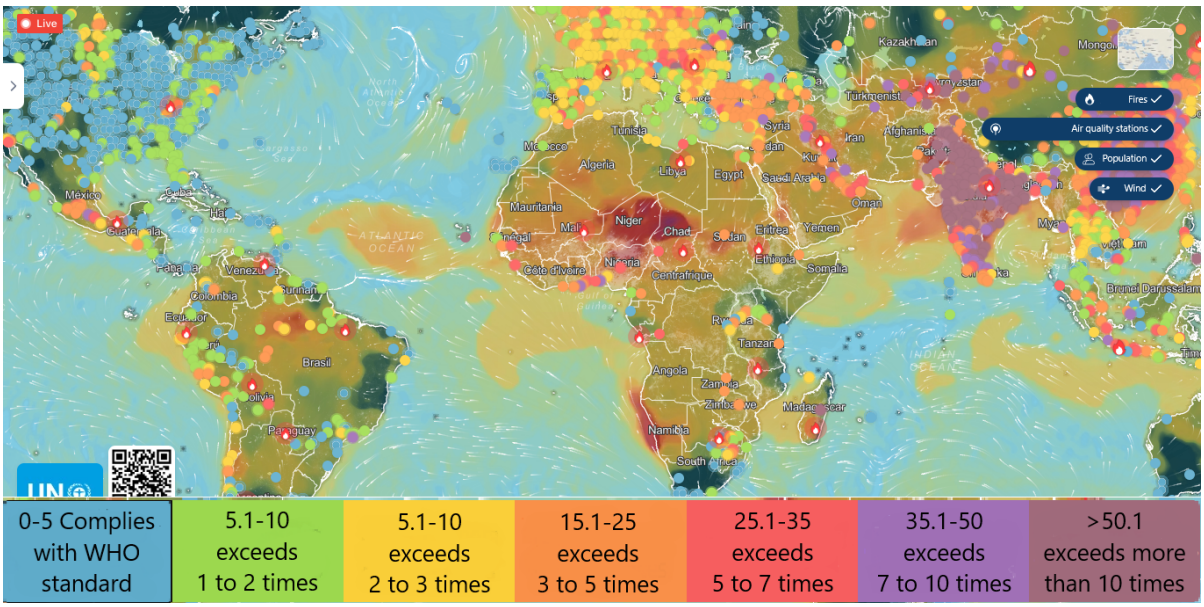

Figure 4: Global Environment Situation Room Interface - Air Quality Section [19].

4 Conclusions.

Bibliometric data evidences a significant increase in the number of publications, highlighting 2021 as the year with the highest, this reflects an interest in the application of AI in fields related to sustainability and the environment.

The oldest article describes the application of AI in military operations, this finding points to the historical evolution of AI, from strategic military applications to its integration in sectors such as environmental management. This analysis of scientific production made it possible to identify key areas of application, technological opportunities and specific challenges facing the field of study in its development towards sustainability. Innovative ideas proposed in the articles were reviewed and the research potential of each was evaluated, highlighting those studies that propose promising lines of research.

The study of emerging technologies used in the environmental field, as well as the current conflicts and challenges that limit their implementation, provide a comprehensive overview of the advances and future needs to promote sustainable development supported by artificial intelligence.

UNEP's activities help countries in transition to low-carbon and resource-efficient economies to strengthen environmental governance and legislation by providing and sharing evidence-based information contained in these UN digital platforms.

It is important to continue to deepen the study and application of artificial intelligence in environmental engineering, as it has great potential. Continued research in this area will allow the development of more robust and efficient technologies that can contribute directly to environmental protection and global welfare.

Some limitations of this research could be associated with the scope of the databases used, suggesting for future studies to expand to other sources that could provide greater coverage of the topic.

It should be noted that, while it is well known that artificial intelligence is a powerful tool for addressing environmental problems, it is important to critically consider the various challenges involved in its implementation. These include ethical risks related to data use and privacy, and the environmental impact associated with the high energy demand of AI systems, among others. Reflecting on these dimensions allows us to assess the potential of AI, but also to promote more equitable, responsible, and sustainable technological development.

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