frontiers in Environmental Science

TYPE Systematic Review
PUBLISHED 24 March 2026
DOI 10.3389/fenvs.2026.1734506

OPEN ACCESS

EDITED BY
Nagai Shin,
Japan Agency for Marine-Earth Science and Technology, Japan

REVIEWED BY
Tetiana Kulinich,
Lviv Polytechnic National University, Ukraine
Kouqiang Zhang,
Yunnan University of Finance and Economics, China

*CORRESPONDENCE
Jairo Rojas Ángel,
rrangel2024@gmail.com
Siberman Carvajal Romero,
siberman.carvajal@correo.policia.gov.co
Mercedes Gaitan-Angulo,
mgaitanangulo@gamil.com

RECEIVED 29 October 2025
REVISED 24 January 2026
ACCEPTED 27 January 2026
PUBLISHED 24 March 2026

CITATION
Carvajal Romero S, Rojas Ángel J and Gaitan-Angulo M (2026) Technological innovation for environmental monitoring of strategic ecosystems: implications for sustainability.
Front. Environ. Sci. 14:1734506.
doi: 10.3389/fenvs.2026.1734506

Technological innovation for environmental monitoring of strategic ecosystems: implications for sustainability

Siberman Carvajal Romero [1]*, Jairo Rojas Ángel [2]* and Mercedes Gaitan-Angulo [1]*

[1]Dirección de Educación Policial, Escuela Nacional de Carabineros Alfonso López Pumarejo, Bogotá, Colombia, [2]Dirección de Educación policial, Escuela de Seguridad Vial, Bogotá, Colombia

One of the critical challenges in environmental, social, and economic terms is the progressive loss of strategic ecosystems, such as wetlands, moorlands, and mangroves. These natural systems provide water regulation, biodiversity conservation, climate change mitigation and the wellbeing and survival of living beings that directly and indirectly depend on them. The loss of strategic ecosystems like wetlands, moorlands, as well as mangroves, are representing the critical challenges that affect directly both environmental and social sustainability. Taking this into account, the technological innovation, where the AI, remote sensing and IoT, are emerging as key tools for strengthening the monitoring and sustainable management processes. Thus, the objective of this study is to analyze scientific developments which have had a great relevance in terms of technological innovation and their applicability on the environmental monitoring of strategic ecosystems and the consequences of it on the sustainability. For this end, 500 documents were analyzed for developing a bibliometric analysis indexed in Scopus (1993–2026), for processing the data were used VOS viewer and Bibliometrix. For instance, the results showed that there is an increased exponential growth of the academic production since 2016, which peaked in 2025; most of these studies were held by China, Germany and the United States, and the most studied technologies where the IoT Networks, AI, and satellite remote sensing. Although, Africa and Latin America had a lower participation in comparison, which is a clear proof of the gigantic gap in terms of accessing and implementing these technologies. This study provides evidence about regional gaps, research trends and key actors, while highlighting the constant need of strengthen the technological interoperability, the inclusion of local communities and the design of evidence-based public policies. These findings provide a solid basis for guiding future research and sustainability strategies in strategic ecosystems.

KEYWORDS
artificial intelligence, environmental monitoring, forest fires, police training, technological innovation

1 Introduction

With the advance of pollution in the 21st century, there has been substantial degradation of ecosystems, mainly due to human activities, which directly affect forests, wetlands, moors, and mangroves (Graizbord et al., 2024), an important source for human existence and living beings. The degradation and deterioration of

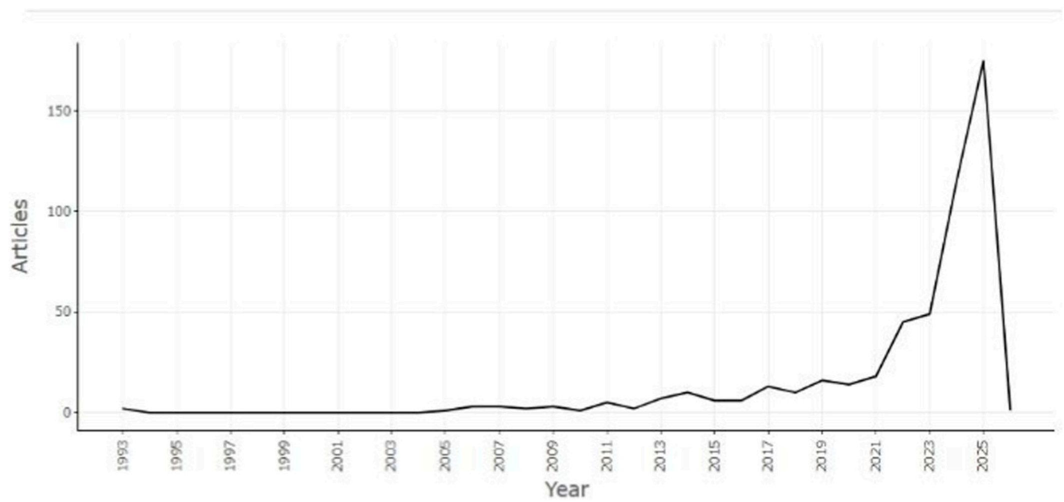

FIGURE 1
Annual scientific output. Source: Own elaboration using Bibliometrix (2025).

these ecosystems are a problem for the subsistence of living beings, given that they support and regulate the natural balance, according to how the water system and carbon capture are regulated, and their influence on diversity. These systems fulfil ecosystem functions, without them, life on Earth would be unsustainable (Kang et al., 2024). The progressive deterioration of strategic ecosystems such as forests, wetlands, moors, and mangroves constitute a major threat to environmental and social sustainability in the 21st century (Elías and Esper, 2021). These ecosystems play an essential role in water regulation, carbon sequestration and biodiversity preservation, which are fundamental to food security and the wellbeing of millions of individuals (Sietz et al., 2025). Nevertheless, there are factors like deforestations, pollution, urban expansion, and climate change, which have intensified their degradation, while increased the vulnerability of the communities, as well as jeopardizing the provision of the provision of the key ecosystem services.

Around the world, the technological innovation has increased widely, being considered as a strategic ally, useful for facing the emerging challenges; Artificial intelligence (AI), as pointed out by Ruiz and Martínez (2024), is a branch of computer science that focuses on the design and creation of systems based on mathematical models and algorithms that integrate large amounts of data to recognize patterns, adapt to new circumstances and optimize their performance autonomously or semi-autonomously through flexible languages. Where drones, IoT sensor networks, Artificial Intelligence (AI), satellite remote sensing and big data, led to have a real-time monitoring with constant information with a great coverage. This enables a greater management of environmental risk prevention (Kamyab et al., 2023). These applications are the proof that the use of technology is effective for predicting threats and measuring environmental variables, with these tools is possible to make conservation plans in order to design a sustainable ecosystem management.

Artificial intelligence, as a technological tool in environmental surveillance, through automation and satellite image remote sensing, makes it possible to process large volumes of data in order to accurately identify changes in forest cover and anticipate future deforestation hotspots, as applied in the Colombian Amazon (Tinoco et al., 2025). Likewise, unmanned vehicle systems have also emerged for the monitoring of aquatic ecosystems (Liu et al., 2025). In a similar vein, programs, networks, and databases aimed at environmental monitoring and assessment have been developed to support decision-making in ecosystem prevention and conservation efforts (Verma et al., 2025). Furthermore, the use of technologies such as machine learning (ML) holds significant potential for transforming applied data, as it provides tools that enable the effective prediction, monitoring, organization and recording of ecosystem biodiversity in any location (Khaskheli et al., 2025).

However, significant gaps still exist in access to and implementation of these technologies, especially in countries in the Southern Hemisphere. The main barriers are lack of interoperability standards, limited participation of local communities in monitoring processes, dependence on expensive digital infrastructure, and ethical challenges related to governance and data ownership (Mulatu et al., 2025). This technological disparity gives rise to disparities in knowledge creation and limits the transfer of innovation to particularly sensitive regions such as Latin America and Africa.

Figure 1 shows the annual evolution of scientific output during the period 1993–2026, revealing a non-linear pattern with three clearly differentiated phases. In the first stage (1993–2005), output remained marginal and showed little variability, suggesting an incipient phase for the field, characterised by low visibility and limited thematic consolidation.

A second phase (2006–2018) reflects gradual, albeit moderate, growth, indicating a process of progressive expansion of academic interest and greater incorporation of the topic into the research agenda.

The third phase (2019–2025) shows exponential growth, particularly marked from 2021 onwards, reaching its peak in 2025. This behaviour suggests a process of rapid expansion and growing research interest, possibly associated with contextual changes, technological advances or regulatory transformations that have revitalised the field.

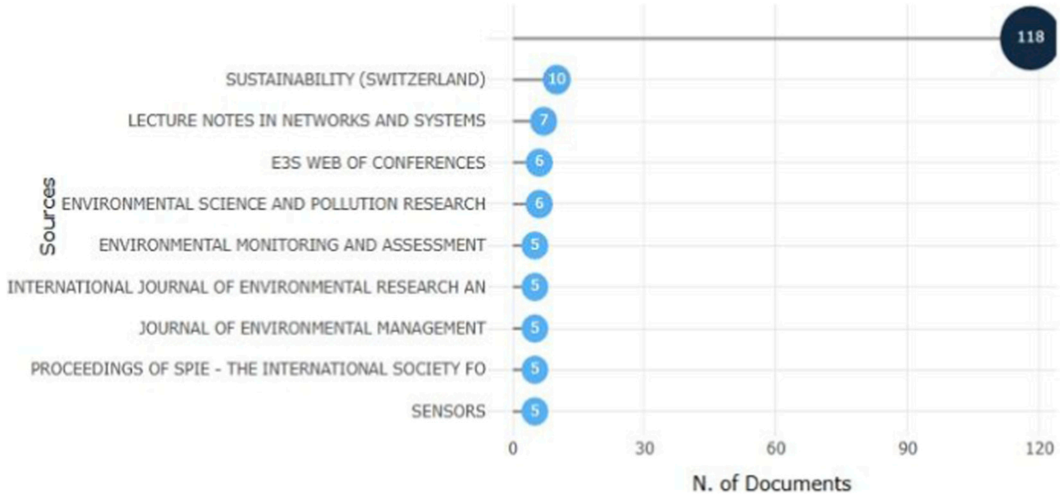

FIGURE 2
Most relevant sources. Source: Own elaboration using Bibliometrix (2025).

From a scientific maturity perspective, the observed trajectory indicates that the area is in a recent phase of accelerated growth, although it still shows signs of volatility. Overall, the dynamics suggest a field in transition towards consolidation, but still vulnerable to cyclical fluctuations and possible thematic expansion processes without sufficient theoretical articulation.

Figure 2 shows a marked editorial concentration in a small number of sources. Sustainability (Switzerland) stands out significantly with 118 documents, well above the rest of the journals, whose output ranges from 5 to 10 publications. This asymmetry reflects a high dependence of the field on a single publishing platform, which can be interpreted as an indicator of thematic specialisation, although it also suggests a structural concentration in scientific dissemination channels.

The second level of sources—which includes Lecture Notes in Networks and Systems, E3S Web of Conferences, Environmental Science and Pollution Research, Environmental Monitoring and Assessment, International Journal of Environmental Research and Public Health, Journal of Environmental Management, Proceedings of SPIE, and Sensors—presents a relatively homogeneous distribution, albeit with significantly lower volumes.

This limited dispersion suggests that, although the field is present in indexed impact journals, it does not yet show solid and balanced integration in multiple prestigious outlets. Overall, the evidence indicates that the field is editorially dynamic, but also structurally concentrated, which could limit its theoretical consolidation and institutional recognition if publication spaces are not diversified towards journals with greater disciplinary centrality.

In this context, it is necessary to pursue studies that analyze the role of technological innovations in environmental monitoring of strategic ecosystems, as underlined by Puig and Darbra (2024), research trends, regional knowledge gaps, and practical applications. Identify opportunities for the purpose of this study is to provide scientific evidence through a bibliographic analysis, which allows us to understand the development of the region, highlight its effects on sustainability, and design comprehensive public policies and conservation strategies based on evidence of clear environmental impacts Enables to guide (Vélez et al., 2024).

Thus, in the search for alternatives to prevent, control and safeguard ecosystem integrity and to maintain a natural balance within territories, researchers and governments, through public policies, have proposed significant and strategic measures for environmental sustainability supported by technology, such as strong environmental sustainability (SESI) and the SESPI progress index (Garcés et al., 2025). Similarly, other countries, such as China, have implemented pilot sustainable development plans to assess the effects of environmental quality in urban centers and to project adaptive strategies when policy objectives are not met (Chen et al., 2025). Meanwhile, research focused on public policies in South American countries such as Ecuador, Peru, Bolivia, and Colombia have produced a range of documents and tools aimed at achieving integrated fire management in the context of forest fires. These efforts have contributed to strengthening legislation and public policy responses to the phenomenon, with the support of the Andean Community (Correa et al., 2025).

- Similarly, through the articulation of public policies, case studies have been implemented across several regions of South America, including the Amazon, the Cerrado and the Chiquitania, in order to analyze how knowledge about fire and its impacts is produced, applied and circulated. These studies draw on diverse analytical approaches and descriptive models, encompassing ecological analysis, public policy assessment, science studies and the use of technology (Eloy et al., 2019).
- In addition, building on the strategic alliance between Colombia and Venezuela, and through bilateral cooperation and state-level policy agreements, joint initiatives have been established for the prevention of forest fires in the Colombian–Venezuelan plains. These initiatives make use of algorithmic modelling and moderate-resolution imaging spectroradiometer (MODIS) data, specifically the MCD64A1 product, integrating spatial information across four key dimensions: topography, human

 10.3389/fenvs.2026.1734506

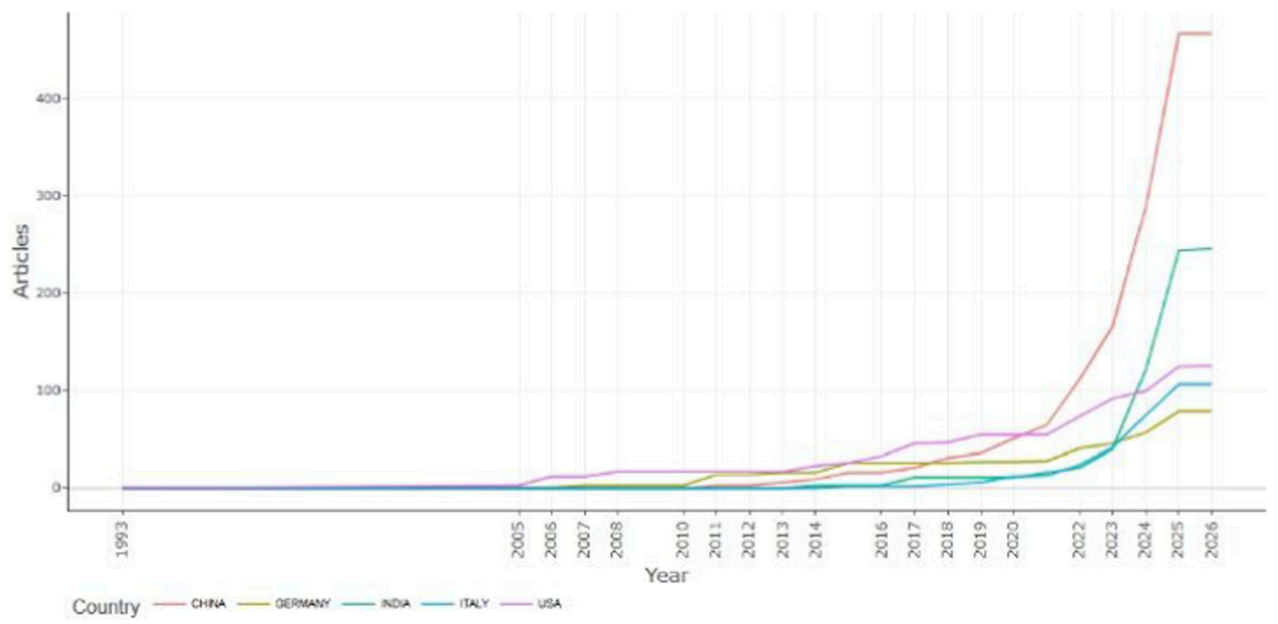

FIGURE 3
Production by country over time. Source: Own elaboration using Bibliometrix (2025).

presence, vegetation, and climatic variables (Barreto and Armentera, 2020).

This indicates that, both in Colombia and in other countries, there is an ongoing inter-institutional synergy aimed at the care and protection of ecosystems and the natural environment.

Nevertheless, although progress has been made, there are still significant gaps in the research and practical implementation of the technologies mentioned that contribute to the prevention of environmental disasters (Wu and Zhao, 2025). Among these, we can formally highlight the few interoperability standards between platforms, the limited inclusion of local communities in monitoring processes, access limitations in developing countries, and the risks associated with governance and data management ethics (Yeshiwas and Tiruneh, 2025; Hoffmann et al., 2025). In addition, there is greater interaction in the study for countries in the global north, leaving behind experiences applied to strategic ecosystems in regions such as Latin America and Africa (Poenaru and Manta, 2025).

Considering the above, this research aims to analyze technological innovation applied to the environmental monitoring of strategic ecosystems and its implications for sustainability. Therefore, it aims to answer the following research question: *What implications do these innovations have for environmental management and the formulation of public policies aimed at conservation?* In this way, the research will contribute significantly to the academic literature, offering technological solutions that support sustainability in local and global contexts.

2 Theoretical framework

When we talk about the environment, we are initially referring to strategic ecosystems that correspond to those categories where the protection and conservation of ecosystems important for the subsistence of living beings prevails (Sobhani et al., 2025). These include tropical forests, moorlands, wetlands, mangroves, and coral reefs, all of which have a major influence on the regulation of the water cycle, climate stabilization and the provision of food and raw materials (Biswas and Subramanian, 2025). In this regard, there has been substantial degradation which, rather than decreasing, is increasing over time, creating greater vulnerability to natural disasters and climate change (Zhao S. et al., 2023).

In addition, many studies call for a substantial response to the pollution of ecosystems, because if the serious and sudden impact continues as it has been, there will be significant consequences in terms of economic and social sustainability. Therefore, Poenaru et al. (2025) and Gaut et al. (2025) recognize that when there is a reduction in the carbon capture capacity of forests, pollution in wetlands or salinization of coastal soils due to the retreat of mangroves, this has direct consequences on ensuring food security and sustainability for local communities. Therefore, given the urgency of the situation, it is necessary to implement new and better strategies that enable more constant and advanced monitoring that goes beyond the limitations of traditional methods through the use of modern technology (Zhang et al., 2022).

Figure 3 shows the evolution over time of scientific output broken down by country, revealing different dynamics in the international consolidation of the field. During the initial period (1993–2005), output was practically non-existent in all the countries analysed, confirming an early phase with low global institutionalisation.

From 2006 onwards, a gradual activation can be observed, initially led by the United States and Germany, whose gradual increases suggest a process of early incorporation and thematic structuring. However, the most significant change occurs from 2021 onwards, when China registers exponential growth that far exceeds that of other countries, reaching a dominant position in terms of publication volume.

India also shows rapid growth in recent years, while Italy and Germany maintain more moderate and relatively stable growth trajectories. The United States, although showing sustained expansion, loses relative leadership in the face of growing Asian dynamism.

The growing participation of emerging economies suggests that the field is moving towards a phase of expanded internationalisation, albeit with marked asymmetry in scientific production. This pattern is characteristic of rapidly expanding areas, where global leadership is still in the process of being defined and traditional centres share the limelight with new hubs of scientific generation.

Overall, the evidence points to a transition from development initially concentrated in Western economies to a more multipolar configuration, with recent Asian predominance. The sustainability of this dynamic will depend, to a large extent, on the ability of these countries to transform quantitative growth into intellectual influence and conceptual leadership within the field.

In this vein, multiple authors have agreed that strategic ecosystems should be understood as natural infrastructures with the capacity to provide services that are equivalent to and as valuable as high-cost engineering works. This is illustrated by the case of Andean moorlands, identified as one of the most megadiverse habitats on the planet, where a variety of ecosystems emerge as a source and conservation of natural balance (Rodríguez Caguana and Morales Naranjo, 2020). These play a role similar to that of natural sponges, regulating water flow for cities with large populations such as Bogotá or Quito, which reduces the high costs of building artificial infrastructure to store this resource (Mora et al., 2021). Similarly, there is another natural method for absorbing the energy of storms and hurricanes: mangroves, which prevent significant material losses to coastal communities, further demonstrating their economic and social value beyond the environmental dimension.

Another example is the case of coral reefs, whose deterioration threatens marine biodiversity and, in the same way, the economy of entire communities that are directly dependent on artisanal fishing and tourism would also be affected. Some of the most recent studies have shown that if the trend of deterioration persists, more than 70% of all reefs in the Caribbean could be lost in the next 20 years, which would compromise regional biodiversity and food security (Hoffmann et al., 2025). Given this outlook, there is a global call to develop and implement monitoring systems that integrate these emerging technologies in order to anticipate any risks that may arise and, in the same way, design public policies that protect the reefs.

However, it is vitally important to recognize that strategic ecosystems contain more than just economic and social value; they transcend this to become cultural and spiritual, in relation to indigenous and local populations, as a source of wisdom and ancestral knowledge for the survival of their communities (Pedersen Zari et al., 2025), in which everyone is part of a group that works to protect and sustainably manage the ecosystem and its resources through the implementation of community monitoring systems (Reddy et al., 2024). However, with globalization and constant industrial development, this knowledge has historically been marginalized. In this situation, various researchers have stated that official conservation programs should integrate emerging technologies for ecosystem conservation with traditional knowledge, generating hybrid management models to enhance long-term sustainability (Yeshiwas and Tiruneh, 2025).

On the other hand, emerging technologies applied to environmental monitoring are also an important part of the literature review, as remote sensing and remote sensors are shown to be tools capable of mapping land cover, measuring changes in forest biomass, and detecting desertification processes in short time frames (Xu B. et al., 2024). Furthermore, the integration of hyperspectral and multispectral sensors expands the capacity for analysis, improving the detection of subtle changes in water quality or vegetation health (Hoffmann et al., 2025).

As an example, Asian countries are taken as benchmarks in technological innovation, as they use fixed-wing drones, specially equipped with thermal cameras that are used to measure how soil temperature varies, thereby mitigating the potential risk of forest fires and enabling measures to be taken in response (Zhu et al., 2025).

Secondly, research related to technological programs such as that of Ju et al. (2025) allows large-scale monitoring of the earth to identify the most significant changes. On the other hand, the observation programs known as *Copernicus* and *Landsat* have generated large, freely accessible databases that are an essential input for global and regional research (Fernández et al., 2024). However, limitations associated with temporal and spatial resolution, as well as technological dependence on industrialized nations, persist, further hindering access to new and better measures for environmental protection.

Likewise, satellite remote sensing has effectively led to the generation of predictive models of deforestation and loss of vegetation cover at the global level. Some of the most notable examples are the monitoring of the Amazon using Landsat and Sentinel images, which have shown that there is a sustained increase in deforested areas of agroforests and forests, mainly in the Amazon (Yang et al., 2025). This has been used to generate international campaigns related to the conservation of these areas and the ecosystem, which in turn has enabled public policy decisions to be made to preserve fauna and flora (Malik et al., 2026). The application of remote sensing not only describes the state of ecosystems in real time, but also allows future scenarios to be generated based on the information provided and possible risks to be anticipated.

Similarly, remote sensors designed using AI algorithms have improved classification in relation to land use and coverage. Through techniques such as machine learning, it has been possible to differentiate between crops, pastures, water bodies and deforested areas with greater precision, which has transcended traditional methods (Xu Y. et al., 2024). These advances, which are particularly important for strategic ecosystems, maintain constant monitoring of vegetation cover, where even minor changes can bring significant changes in the dynamics of ecosystems.

In addition, one of the most important aspects of studies is the development and implementation of collaborative remote sensing. This happens due to the freely accessible satellite images that are complemented by citizen participation and low-cost drones (so-called civilian sensing), allowing local communities to cooperate in the collection and verification of environmental data. As a result, more inclusive processes have begun to emerge, democratizing access to environmental information (Poenaru and Manta, 2025).

In short, remote sensing has become a crucial tool for coastal and marine monitoring. Specific sensors have made it possible to measure water turbidity, identifying the presence of oil spills and harmful algal blooms in real time (Gaur et al., 2025). Now, for coral reefs, there are multispectral sensors that can detect bleaching processes, providing early information for the prompt implementation of risk mitigation measures. Thanks to the uses of remote sensing, it is clear that it has great versatility for conserving strategic terrestrial and aquatic ecosystems.

Furthermore, environmental IoT and sensors used as networks have been extremely useful in terms of real-time data collection relating to the environment. These sensors are known as WSNs and are strategically located at the most sensitive points so that access to information is clear and concise. In this way, data such as soil moisture, solar radiation levels, and the set of pollutants in the atmosphere can be obtained, along with flow levels in water bodies (Petrillo et al., 2025).

In agricultural areas, for example, these tools are used to develop intelligent systems that detect risk through soil management analysis. Since, considering the crops to be grown and also for livestock purposes, it is necessary to maintain strict care levels for proper harvesting and feeding, respectively, which not only guarantees quality and wellbeing, but also ensures the use of water resources and reduces pressure on strategic ecosystems (Yeshiwas and Tiruneh, 2025).

Additionally, environmental IoT is integrated with cloud platforms that process and visualize data in interfaces accessible to researchers and decision-makers. Experiences such as those developed in India and China have shown that these technologies can be scalable and replicable, although they require considerable investment in digital infrastructure and connectivity (Gaur et al., 2025).

Also, IoT networks have been shown in myriad studies to be capable of creating diverse systems for early warning, making them extremely useful tools for natural phenomena such as landslides, forest fires and floods. Thanks to these systems, which constantly collect data through their sensors, optimal risk management is possible by having all the information available in real time on digital platforms. This is a particularly important aspect in strategic ecosystems, where devastating changes can occur without warning, so these tools allow environmental authorities to react more effectively (Poenaru and Manta, 2025).

Similarly, IoT networks have begun to be used in urban ecosystems, where these sensors allow for the monitoring of the interaction between areas undergoing urban expansion and natural areas. Due to the constant growth of cities, this type of technology is especially useful for identifying the impact that human settlements have on the ecosystem, its forests, wetlands, and riverbanks. In this way, methods for the conservation of strategic ecosystems are established, leading to sustainable territorial planning (Zhao Y. et al., 2023).

Then, the IoT makes a significant contribution to the environment through Blockchain technologies, which ensure data traceability and transparency, guaranteeing that, when these aspects are combined, the information will be completely accurate and will not be manipulated, which increases confidence in political decision-making and in the studies of the scientific community (Yeshiwas and Tiruneh, 2025). In turn, environmental markets have become trusted tools, with transparent information on emissions, deforestation, water consumption, among other aspects that are useful for generating a database and thereby creating compensation schemes or carbon credits.

However, there is still much to be done for IoT networks, given their applicability and integration in remote locations where the installation of sensors is complex due to difficult access, such as mangroves or moors. This is an issue that the literature has not yet been able to address, there is a clear need to develop energy-efficient devices that can operate for prolonged periods of time and, above all, do not require regular maintenance or human intervention. While it is true that advances in renewable energies, such as solar panels and ambient energy collection systems, have been able to improve the outlook and provide a solution to the current challenge, technological improvements are needed to ensure access and sustainability in those areas that are difficult to access (Malik et al., 2026).

Nevertheless, the role of AI and tools such as machine learning has been revolutionary in environmental analysis, as algorithms are trained to identify complex patterns in time series and classify land cover from satellite images (Malik et al., 2026). One of the notable benefits is the ability to predict future scenarios of environmental degradation by considering climatic and socio-economic variables.

For example, the use of convolutional neural networks has shown remarkable performance in identifying tree species from aerial images, which is vital in reforestation and conservation programs (Xu B. et al., 2024). Similarly, AI has been used in the early detection of microplastics in water bodies and their dispersion analysis (Gaur et al., 2025), demonstrating cross-cutting applications that transcend traditional monitoring.

The capacity for mass analysis has made it possible to expand and improve the conditions of manual methods, which has led to more accurate and continuous monitoring of different strategic ecosystems, as postulated by Kuppusamy et al. (2024), who highlight the importance of using AI as an effective manager of large amounts of environmental information, as it produces learning algorithms based on satellite images of different resolutions, thus allowing a comparison between the current situation and historical data, so that automatic alerts can be generated on biodiversity loss, deforestation, coastal erosion and other risks (Poenaru and Manta, 2025).

With the constant advancement of AI, it has begun to be used for modelling future scenarios in contexts related to climate change. To this end, three types of variables have been integrated: climatic, geographical, and socio-economic. Thus, through predictive models designed with AI, it is possible to estimate the possible changes that strategic ecosystems will undergo in the next two or three decades (Yeshiwas and Tiruneh, 2025). This information is vitally important for planning adaptation and mitigation strategies, which must be aligned with the SDGs and national conservation policies.

Machine learning has also been used for ecosystem analysis, giving rise to a new field known as Eco acoustics. Microphones installed in forests and wetlands can be used to collect different sounds, mainly related to animals such as birds, insects and amphibians. These sounds are then processed by AI algorithms that identify each species present in the environment, making it possible to measure the state of biodiversity and thus non-invasive and low-cost monitoring of wildlife compared to traditional methods (Hoffmann et al., 2025).

AI has also begun to be used in marine ecosystems, such as seagrass beds and coral reefs, where underwater images have advanced the study of these environments. To this end, complex algorithms have been implemented to directly classify species and coverage levels automatically, which has streamlined research processes and improved the accuracy of biological inventories, as they are conducted automatically (Zhao S. et al., 2023).

However, studies have pointed out major limitations in the use of AI, including a direct dependence on large training databases, which, in particular contexts such as Latin America and Africa, are not always available. Furthermore, according to Floridi and Cowls (2019), the increasing use of artificial intelligence has led to ethical debates about the control and ownership of this data, as most of this data is processed by global corporations, creating disparities in access to the benefits of innovation occur.

On the other hand, due to the rise of data science applied to the environment, the development of systems has intensified in order to integrate large volumes of information generated by satellites, sensors, and environmental institutions. Thus, Poeneru and Munt (2025) affirm that Geographic Information Systems (GIS) and big data have emerged as essential platforms for planning biological corridors, monitoring protected areas, and mapping ecosystem dynamics.

By combining Big Data and GIS, it is possible to perform more efficient and simpler multi-level analyses and integration of local, regional, and global information on a single platform (Zhao Y. et al., 2023). Additionally, free science initiatives have taken a huge relevance in recent years to facilitate access to environmental databases. It contributes significantly to transparency and collaboration between both sides researchers and the communities been affected. However, previous research warns that data availability does not always equate to optimal management, as it also depends on the technical and financial capabilities of each country (Hoffmann et al., 2025).

In addition, one of the most significant contributions of Big Data is its ability to integrate and manage diverse sources of heterogeneous information, such as socio-economic statistics, climate data, and satellite images, while also maintaining data from multiple sensors in real time and generating constant comparisons with historical records. Thanks to this combination, new models with a greater degree of complexity can be developed to understand more accurately the factors and impact that exist between humans and nature, leading to a more holistic scenario for decision-making regarding ecosystem conservation (Petrillo et al., 2025).

For their part, GIS have been transformed into dynamic analysis platforms that are loaded in the cloud, so that both researchers and environmental managers are able to access the various interactive maps, which are frequently updated, where hundreds of data related to biodiversity, water quality, deforestation and fires occurring in the environment are constantly being superimposed (Yeshiwas and Tiruneh, 2025). While it is true that GIS are essential tools, it is imperative to use them correctly to design land use plans that take ecological sustainability into account and, in turn, enable the generation and definition of public policies.

On the other hand, studies highlight that there is a growing use of Big Data in risk management, which is mainly done through the analysis of historical and real-time data. Thanks to the combination and use of these two aspects, it is possible to anticipate possible risks related to phenomena such as floods or droughts that can be prolonged and negatively affect strategic ecosystems. As a result, these types of approaches have led to the improved development of vulnerability maps and early warning systems in both Asian and European countries, but in the near future they could be applied in different contexts, such as Latin America, with adaptations made in line with the economic reality of each case (Zhu et al., 2025).

Furthermore, GIS, like Big Data, has proven to have great comprehensive applicability in various areas, becoming useful for monitoring the marine environment, such as fishing and protected reserves. To this end, digital platforms have been implemented that are capable of identifying patterns related to overexploitation and maritime traffic, which are extremely useful for designing control and conservation strategies (Gaur et al., 2025).

However, there is a problem related to access to technologies that drive the development of GIS and Big Data, given that there is great inequality between developed and developing countries, which shows that there is a large gap in technical capabilities, knowledge and innovation, limiting the use that a country can make of these tools (Poenaru and Manta, 2025). In addition, there is considerable dependence on private platforms for environmental data management, which increasingly exposes the generation of digital sovereignty, mainly where natural resources are strategic. These limitations therefore lead to cooperation and promote the creation of infrastructures that can be shared between different contexts, being open in order to increase their applicability.

In terms of literature, there is a large gap between developed and developing countries, resulting in a stark contrast between them. For example, in Europe, programs involving satellite technologies, climate modelling and IoT sensors have been developed for the purpose of monitoring air quality and marine ecosystems (Petrillo et al., 2025). In Asia, there are other advances with a focus on the protection of coastal ecosystems, which, through underwater sensors and drones, have the ability to track changes in marine biodiversity (Zhao S. et al., 2023).

Similarly, in Latin America, monitoring programs have been developed for Amazonian forests and Andean moorlands. However, the integration of technologies is still in its preliminary stages, which is why most programs are funded through international cooperation (Poenaru and Manta, 2025). In Africa, savannahs and deserts are monitored, but this has been limited to academic studies, as there are not many resources available to develop comprehensive platforms that can be implemented. These examples highlight the stark contrasts in global technological asymmetry, which conditions countries' ability to protect their strategic ecosystems.

However, despite the many advances related to the study of the applicability of artificial intelligence, IoT and Big Data in traffic management in Latin America, certain gaps in the academic and technical literature are still noticeable. The first gap is part of the problem mentioned above, where the available studies come mainly from developed countries such as the United States, Europe and Asia. In the case of Latin America, there is still a significant shortage of research related to and applied to a Latin American context. Due to this major limitation, it is impossible to consider models that can be adapted to the social, economic, and infrastructural characteristics and particularities of each context (Crawford, 2021; Zheng et al., 2020).

Similarly, there is a considerable deficit in comparative studies, contrasting with the progress made by different Latin American countries. Although there is literature on documented cases related to cities such as Sao Paulo, Santiago de Chile, and Mexico City, these are isolated cases that demonstrate the limited research that exists, which prevents the identification of common patterns, shared challenges, and transferable strategies between different contexts. Therefore, the lack of a solid comparative framework limits the possibility of designing evidence-based regional public policies (Gómez et al., 2024).

Another gap is the scarcity of longitudinal studies, which are needed to measure the long-term effects of implementing different smart technologies in urban mobility. According to Hluszko et al. (2024), it is true that there is already a wealth of literature on the subject, but most of it is limited to pilot projects or projects with a very short scope, lacking in-depth analysis of the sustainability and scalability of the solutions offered to Latin American cities. For this reason, it is difficult to evaluate technological innovations and their impact on reducing management, decreasing pollutant emissions, and saving energy in a sustainable manner over time (Mora et al., 2021).

Finally, there is a gap in the analysis of the social and ethical impact of using innovative technologies to improve traffic management. However, although there are many studies that focus on highlighting the technical benefits of Big Data, AI and the IoT, there are very few that examine in depth the risks related to the privacy of this data and equity of access to different technologies, which has become, in a way, a form of digital exclusion that only some can apply. Due to the absence of this critical perspective, there is limited comprehensive understanding of the cultural and social implications that accompany the modernization of different urban mobility systems (Floridi and Cowls, 2019).

3 Methodology

In this study, research documents on technological innovation for the environmental monitoring of strategic ecosystems were analyzed.

First, it is important to understand that the term bibliometric refers to the application of statistical methods to identify research trends, prominent authors, prominent affiliations, prominent documents, and other elements in order to provide an overview of current research work in specific fields (Ellegaard and Wallin, 2015).

This study adopts a bibliometric analysis complemented by a structured literature review, aiming to map global scientific production, identify research trends, and analyze thematic and regional patterns related to technological innovation for environmental monitoring of strategic ecosystems.

Although systematic elements were applied during document selection—such as predefined search equations, inclusion and exclusion criteria, and a transparent screening process—the primary methodological focus of this research is bibliometric, rather than a conventional systematic review of intervention effectiveness or outcomes.

Consequently, the study does not strictly adhere to PRISMA, Cochrane, or Campbell guidelines, which are primarily designed for systematic reviews assessing causal relationships, interventions, or clinical and policy effectiveness. Instead, transparency and reproducibility were ensured through a stepwise bibliometric workflow, explicitly reported in Figure 4, which details the numerical filtering and selection of documents at each stage of the analysis.

This approach is consistent with previous bibliometric studies in environmental and technological research, where adapted flow diagrams are commonly used to reflect database-driven screening processes and metadata-based selection.

This research is designed as a bibliometric analysis complemented by a scoping review, following an exploratory logic aimed at mapping the extent, nature, and distribution of scientific evidence rather than evaluating the effectiveness of specific interventions.

While elements of systematic screening were applied, the study does not claim full adherence to PRISMA guidelines, as its primary objective is not to synthesize causal evidence but to explore research patterns, thematic structures, and regional participation. The document selection process is therefore reported using a bibliometric flow adapted to database-driven analysis (Figure 4), consistent with established practices in bibliometric research.

Based on this, a systematic search strategy was used in the Scopus and ScienceDirect databases, given their recognition for their broad and multidisciplinary coverage in environmental and technological sciences. Boolean expressions were used to search for information using the following search equation: [(“technological innovation” OR “technology innovation” OR “digital innovation”) AND (“environmental monitoring” OR “environmental surveillance”) AND (“strategic ecosystem*” OR “protected area*” OR “ecosystem services”) AND (sustainab* OR “sustainability”)].

The period considered ranged from 1993 to 2026, yielding a total of 507 documents published in 288 scientific sources and produced by 3,309 authors who contributed 5,191 keywords related to the topic.

Subsequently, considering inclusion and exclusion criteria, it was recognized that, among the published documents, there was a wide variety of articles, chapters and books, conferences, and reviews. In addition, there were publications related to technological innovation applied to the environmental monitoring of strategic ecosystems and sustainability, both in English and Spanish.

Duplicate documents, publications without complete metadata, such as unreported authors, and works outside the thematic scope, for example, technological innovation in non-environmental sectors, were then identified and excluded due to the inferior quality of the information. Thus, after an initial review, duplicate records and documents that did not contain sufficient information on authorship or affiliation were eliminated, reducing the set to approximately 480 documents.

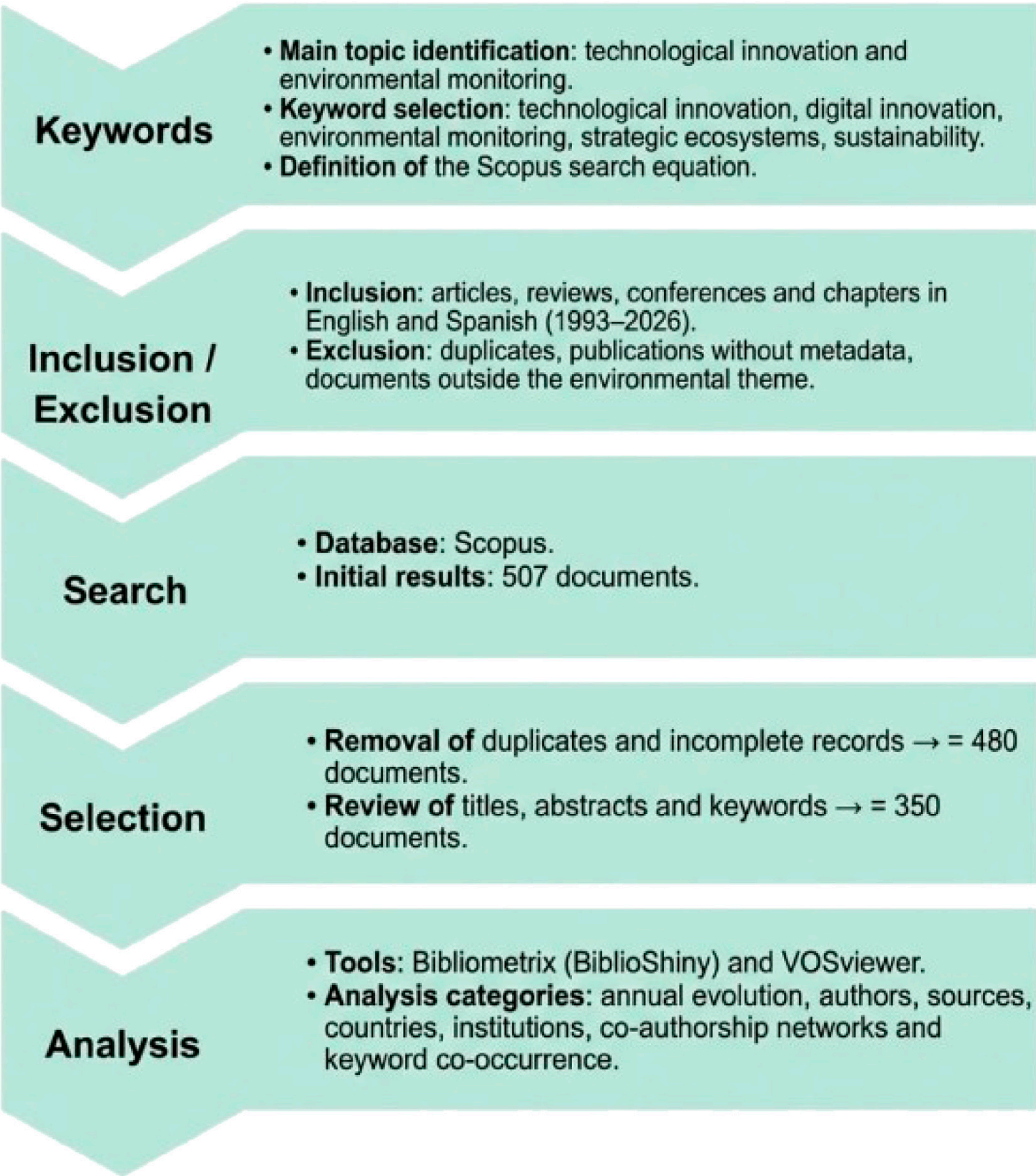

FIGURE 4
Stages of the bibliometric analysis and document selection process. Note: The flow diagram is adapted for bibliometric analysis and does not represent a PRISMA flowchart. Source: syntactic definition of bibliometric analysis, own elaboration (2025).

Also, after reading the titles, abstracts, and keywords, those that did not directly address technological innovation applied to environmental monitoring and sustainability were excluded. At this stage, approximately 350 relevant publications were retained.

However, after applying the criteria of thematic and methodological relevance, the 500 documents were included in the bibliometric analysis, which were processed using Bibliometrix (BiblioShiny) and VOS viewer to identify trends in production, collaboration and keyword co-occurrence. This was due to the quality of the bibliometrics to be published. For this reason, Bibliometrix (BiblioShiny) was used to extract basic indicators (annual production, sources, authors, institutions, countries, and keywords).

3.1 Document selection criteria and relevance assessment

The selection of documents followed a structured, multi-stage process designed to ensure both thematic and methodological relevance. In the first stage, titles, abstracts, and keywords were screened to confirm an explicit focus on technological innovation applied to environmental monitoring, strategic ecosystems, and sustainability. Publications addressing technological innovation exclusively in non-environmental sectors—such as industrial production, finance, healthcare, or urban systems without an environmental monitoring component—were excluded.

Ensure thematic and methodological relevance, a multi-stage screening process was applied. First, documents were filtered based

FIGURE 5
Key information. Source: Own elaboration using Bibliometrix (2025).

on titles, abstracts, and keywords to verify their explicit focus on technological innovation applied to environmental monitoring, strategic ecosystems, and sustainability. Publications addressing technological innovation exclusively in non-environmental sectors (e.g., industrial manufacturing, finance, healthcare, or purely urban infrastructure without environmental linkage) were excluded at this stage.

Second, methodological relevance was assessed by identifying whether the study involved empirical applications, methodological developments, or analytical discussions related to environmental monitoring technologies (e.g., remote sensing, IoT, artificial intelligence, big data, or decision-support systems). Studies that mentioned sustainability or technology only tangentially, without a clear environmental monitoring component, were excluded.

Finally, duplicate records, documents with incomplete metadata, and publications lacking sufficient information on authorship or institutional affiliation were removed. This stepwise process ensured that the final dataset reflected both conceptual alignment with the research objectives and methodological consistency with bibliometric analysis.

3.2 Limitations related to database coverage

While the use of Scopus and ScienceDirect ensures high-quality, peer-reviewed, and internationally visible literature, this choice also entails certain limitations. Restricting the search to these databases may introduce a selection bias by underrepresenting regional and locally produced research, particularly studies published in languages other than English and indexed in national or regional databases.

This limitation is especially relevant for regions such as Latin America and Africa, where a massive portion of applied research on environmental monitoring and ecosystem management is disseminated through local journals, institutional reports, or non-indexed outlets. Consequently, the observed regional disparities in scientific production should be interpreted not only as differences in research activity but also as an effect of structural asymmetries in global knowledge indexing systems.

Nevertheless, given that the primary objective of this study is to analyze the international academic landscape and global research trends, the selection of Scopus and ScienceDirect was considered methodologically consistent. Future studies could address this limitation by incorporating regional databases (e.g., SciELO, RedALyC, African Journals Online) and multilingual search strategies to deepen the understanding of contextual drivers behind regional research gaps.

4 Results

Figure 5 shows the main information on the database of 500 documents covering an analysis period between 1993 and 2026, with a total of 507 documents published in 288 scientific sources. A total of 3,309 authors participated in this set, collectively contributing 5,191 keywords related to the field.

The analysis reflects an average of 11.5 co-authors per document, which shows a prominent level of scientific collaboration, complemented by 20.32% international co-authorship, an indicator of transnational research networks. However, the annual growth rate of publications is negative (−2.08%), suggesting a recent decline in the pace of production, despite the contemporary relevance of the topic.

In terms of impact, the documents have an average of 10.39 citations per publication, indicating moderate visibility in the academic community. Finally, the average age of the documents is 2.87 years, indicating that much of the literature analyzed corresponds to recent research associated with the rise of emerging technologies applied to the monitoring and sustainability of strategic ecosystems.

The evolution of scientific production on technological innovation applied to the environmental monitoring of strategic ecosystems shows irregular behavior between 1993 and 2015, with a

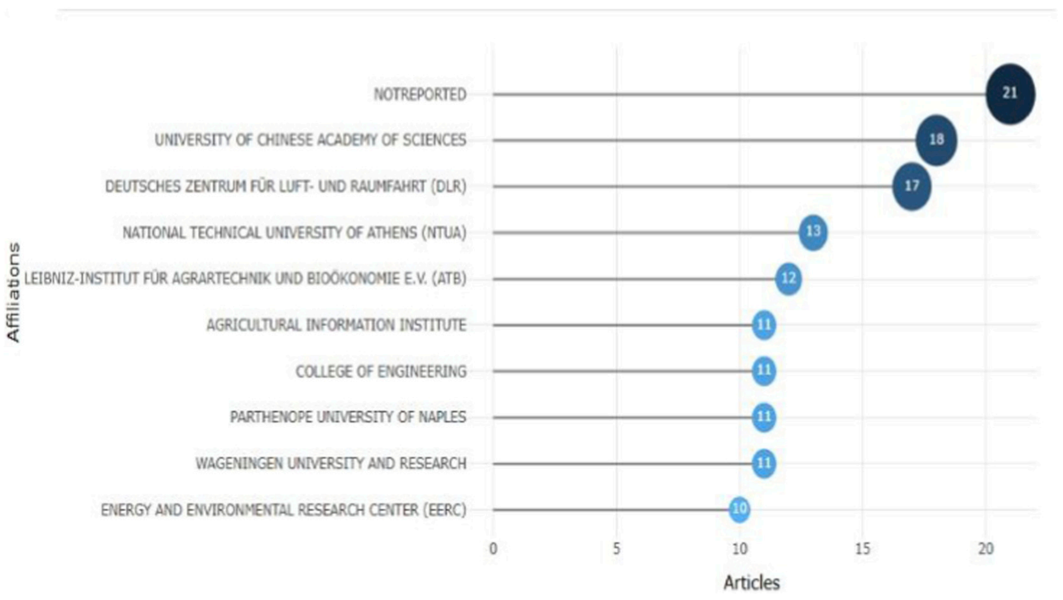

FIGURE 6
Most important affiliations. Source: Own elaboration using Bibliometrix (2025).

sparse number of annual publications and little consolidation of the field in its early decades.

From 2016 onwards, there has been a progressive increase in the number of articles, which has intensified significantly since 2020, reaching its peak in 2025, with more than 170 publications in a single year. This peak reflects a growing interest from the academic community, possibly associated with advances in emerging technologies such as remote sensing, artificial intelligence, the Internet of Things (IoT) and big data, applied to environmental sustainability.

The sharp drop in 2026 is due to the inherent bias of incomplete records for the current year, and not necessarily to an actual decline in research. In summary, the trend shows that over the last decade, the topic has positioned itself as a field of high scientific relevance, intricately linked to global challenges of sustainability, conservation of strategic ecosystems, and real-time monitoring.

Analysis of publication sources shows that studies on technological innovation for environmental monitoring of strategic ecosystems and sustainability are mainly concentrated in high-impact journals and conferences in the environmental and technological sciences.

The journal Sustainability (Switzerland) leads with 10 documents, consolidating its position as a key channel for academic dissemination in this field. It is followed by Lecture Notes in Networks and Systems with 7 publications, and both E3S Web of Conferences and Environmental Science and Pollution Research with 6 articles each. Other notable sources include Environmental Monitoring and Assessment, International Journal of Environmental Research and Public Health, Journal of Environmental Management, Proceedings of SPIE–The International Society for Optics and Photonics, and Sensors, all with 5 documents.

Figure 6 shows that the category "NOTREPORTED" tops the list with 21 articles, suggesting publications with no clearly registered affiliation. It is followed by prominent institutions such as the University of Chinese Academy of Sciences with 18 articles, the Deutschers Zentrum für Luft- und Raumfahrt (DLR) with 17, and the National Technical University of Athens (NTUA) with 13. Four institutions share the same number of publications (11 articles): the Leibniz-Institut für Agrartechnik und Bioökonomie e.V. (ATB), the Agricultural Information Institute, the College of Engineering, and the Parthenope University of Naples. Lastly, the prestigious Wageningen University and Research, as well as the Energy and Environmental Research Centre (EERC), each of them contributed with 10 articles. In this matter of ideas, the distribution highlights the international participation in scientific production, to which Europe, Asia and America have had significant contributions, something that suggests that the field of study may be related to certain topics like environmental engineering, sustainability, or even agricultural technology.

Artificial intelligence as a technological tool in environmental surveillance based on its automation and remote sensing. On the other hand, in Latin America and Africa, studies have shown that technology integrating artificial intelligence (AI), and satellites has made a significant impact on environmental protection, particularly in the fight against forest fires and deforestation (Alkhatib et al., 2023). For instance, in Argentina, the Satellites on Fire platform uses AI to detect smoke within the first three minutes and hotspots every 10 minutes. Thanks to this, it has intervened in over 400 incidents, saving thousands of hectares by combining meteorological and deforestation data (Rodríguez, 2025). In the Amazon, where platforms such as Pantera operate, AI can identify fires in remote areas in under three minutes, helping to prevent CO_2 emissions and reduce damage across 13.5 million hectares (BID-Invest, 2024). In Kenya, M-Situ employs AI-enabled devices to issue early warnings of deforestation and fires through sound and gas detection, successfully reducing

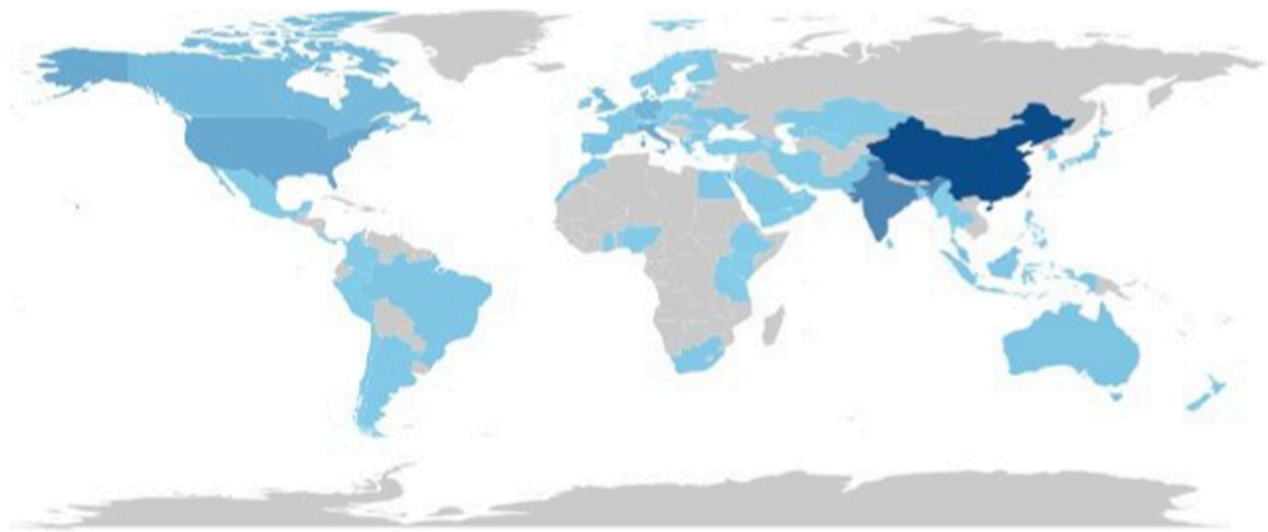

FIGURE 7
Scientific production by country. Source: Own elaboration using Bibliometrix (2025).

illegal logging by 47% and protecting 1,500 ha (El, 2024; Meliani and Basti, 2024).

In Canada, researchers have developed a modelling system based on deep reinforcement learning (DRL) for the strategic placement of firebreaks, using Deep Q-Learning, Double Deep Q-Learning and Dueling Double Deep Q-Learning as decision-making strategies for wildfire management. These approaches have already been implemented in countries such as Spain and Chile (Murray et al., 2025).

Regarding pilot projects, notable initiatives include the *Programa Amazônia Sem Fogo* (PASF-Br), carried out in partnership with the Italian Government, Brazil and Bolivia between 1999 and 2008 (Steil et al., 2020). Another pilot program involved collaboration among Brazil, Japan, Germany, and Australia, focusing on fire management inspired by the Australian model and using remote sensing technologies to prevent prescribed burns and large-scale wildfires (Mistry et al., 2019; Eloy et al., 2019). In addition, a real-time monitoring system for wildfire prevention and suppression has been developed through an integrated platform combining IoT sensors, satellite imagery and meteorological data, as demonstrated in a case study conducted in the semi-arid region of Brazil (Araújo et al., 2025).

In relation to pilot projects and collaborative initiatives in Africa, Tung et al. (2023) highlight a project conducted in twelve protected forests in Burkina Faso, which utilized remote sensing data on wildfires alongside community awareness campaigns addressing the impacts of fire. This initiative also involved the implementation of a synthetic control program to support wildfire prevention efforts. Similarly, studies indicate that emerging technologies such as the Internet of Things (IoT), artificial intelligence and 5G networks are being deployed in Africa as tools for wildfire management with support from European partner countries (Pandey et al., 2023). Consequently, Carta et al. (2023) highlights research conducted in Portugal, Russia and Italy analyzing a range of technologies with strong potential for integration into early warning systems for wildfires across African territories.

Figure 7 shows a world map with various shades of blue, with the darkest shade of blue showing the countries with the most influence on the subject under these investigations. China places at the forefront with 467 published documents and is the only country with the highest participation and influence. Nevertheless, India is also one of the most participant countries in this matter with 246 documents and the United States with 126 documents.

It is also clear that there are countries on each continent that contribute outstandingly and remain in constant contact with the research subject, creating relevance in the sense of noteworthy progress.

On the other hand, in Latin America, Brazil is the most participant country with 23 documents published. In second place, Argentina takes the place with 10 papers. Although not among the main players, Colombia with 6 published documents has established itself as an important player in this kind of studies.

Although the overall annual growth rate of publications is negative (−2.08%), this indicator reflects an average calculated across the entire study period (1993–2026), which includes prolonged phases of low scientific production during the early years of the field. This aggregated metric therefore masks the accelerated growth observed after 2016, when technological advances and sustainability agendas significantly increased research output. Additionally, the apparent decline in 2026 is influenced by incomplete indexing of publications for the ongoing year, rather than by a genuine reduction in scientific activity.

The development of scientific production over time reflects the clear concentration of publications in recent years, with China leading. The country has experienced exponential growth since 2020, and has reached more than 400 articles by 2025, thus strengthening its position as a leading country in research on technological innovations for environmental monitoring of strategic ecosystems.

In second place is Germany, which has been showing steady growth since 2020 and is expected to publish more than

 10.3389/fenvs.2026.1734506

Source: Own elaboration using Bibliometrix (2025)

FIGURE 8
Word cloud. Source: Own elaboration using Bibliometrix (2025).

200 publications by 2025, demonstrating its leading role related to the development of applied engineering and the environmental technologies. The United States maintains a steady upward trajectory, reaching around 120 publications in 2025, followed by India and Italy, with figures close to 100 publications each.

Figure 8 shows a word cloud in which the concept "environmental monitoring," which is used more than 100 times in the database, is the most representative in terms of keywords. Next is "sustainable development," with 84 occurrences, which is another of the key concepts for recognizing the work under study.

After these, words such as "innovation," "artificial intelligence," and "internet of things" also appear with considerable frequency.

5 Discussion

The results obtained confirm findings from previous research that highlight the relevance of remote sensing, IoT, and artificial intelligence in ecosystem monitoring (Zhu et al., 2025; Poenaru and Manta, 2025) but broaden their scope by contextualizing them in strategic Latin American ecosystems. By this, the study aims to propose an integrative methodological approach, which is the result between the combination of a bibliometric analysis and a systematic review, by relying in a conceptual framework.

According to Xu Y. et al. (2024) and Malik et al. (2026), the dynamism is linked with the global expansion of the digital technologies, including in this AI, IoT and big data. Due to this, the bibliometric results propose an exponential growth for the scientific production, mainly since 2016. Then, what affirms Zhao Y. et al. (2023), is related with the capabilities in the global north, and with the leadership of China, United States and Germany, due to the high concentration of scientific production.

The identified regional gap should therefore be interpreted with caution, as it reflects not only differences in technological capacity and research investment, but also the unequal visibility of local knowledge within dominant international indexing systems. This highlights the need to complement global bibliometric analyses with regionally grounded and multilingual approaches.

Nevertheless, despite the advances made, there are gaps specially in the South, where publication numbers are lower. It could be caused, mainly, due to poor access to digital infrastructure and research investment (Uddin et al., 2024). Furthermore, there exists an inferior quality on identifying risks of the technological dependence and, those inequalities could not achieve success standards (Poenaru and Manta, 2025; Hoffmann et al., 2025).

For instance, in Colombia, the key findings are not having a good integration and implications on scientific revolution, mostly in the prevention of forest fires, mainly in the Amazon region and the Orinoquía. When adapting AI for those understanding, it is recognized a benefit for strengthen warning capabilities and integrate in a better way, strategies for adapting an intuitional presence (Buchelt et al., 2024).

The dominance of countries such as China, Germany, and the United States in scientific production can be attributed to a combination of structural and institutional factors. These include sustained investment in research and development, advanced digital and satellite infrastructure, strong linkages between academia, industry, and government, and long-standing national strategies prioritizing environmental innovation and technological sovereignty.

In China, large-scale public investment and centralized research agendas have accelerated the deployment of remote sensing, artificial intelligence, and IoT-based monitoring systems. Germany's leadership is intricately linked to its applied engineering tradition, strong environmental governance frameworks, and participation in European research programs. Similarly, the United States benefits from diversified funding sources, mature research ecosystems, and early adoption of data-intensive environmental technologies.

In contrast, many countries in Latin America and Africa face constraints related to limited research funding, fragmented infrastructure, dependence on external technologies, and reduced access to high-cost data platforms. These disparities contribute to an uneven global research landscape and partially explain the observed regional asymmetries in scientific production.

Similarly, the National Police of Colombia has implemented artificial intelligence (AI) training programs for its officers, focusing on predictive tools and data analysis that enable rapid responses to environmental threats. This includes the early detection of fire risks through machine learning models and geographic alerts (Facuy, 2024), complemented by training and environmental management initiatives that strengthen officers' skills in ecosystem protection, promote active prevention of environmental crimes, and foster community education in vulnerable areas. Additionally, the institution has sent teams to international training in India, where the focus is on using AI to enhance environmental security, optimize resources, and detect threats such as forest fires (Policia Nacional de Colombia, 2024). Furthermore, partnerships have been established with universities, such as the University of Caldas, to train patrol officers in data processing and big data, applying these skills to environmental security (Universidad de Caldas, 2025).

Artificial intelligence (AI) has become a powerful technological tool for environmental monitoring. Through automation and satellite image remote sensing, it is possible to process large volumes of data to accurately identify changes in forest cover and anticipate future deforestation hotspots, as demonstrated in the Colombian Amazon (Tinoco et al., 2025). Similarly, unmanned vehicle systems have emerged for monitoring aquatic ecosystems (Liu et al., 2025). In addition, programs, networks, and databases have been developed to support environmental monitoring and assessment, aiding decision-making in ecosystem conservation and management (Verma et al., 2025). Moreover, technologies such as machine learning (ML) hold significant potential for transforming applied data, providing tools that enable the effective prediction, monitoring, organization, and recording of ecosystem biodiversity anywhere in the world (Khaskheli et al., 2025).

From a methodological perspective, this study prioritizes bibliometric mapping over systematic synthesis, which allows for the identification of global patterns and structural research gaps, while acknowledging the need for future PRISMA-compliant systematic reviews focusing on regional or intervention-based evidence.

Therefore, considering Asia as an influent continent, contribute to the study made, where they use drones and machine learning for identifying fire outbreaks and produce a real-time risk map (Zhu et al., 2025). Aligned with it, it is proved that technological sustainability depends the most, on the social and political legitimacy (Buchelt et al., 2024).

Although Scopus and ScienceDirect provide extensive coverage of high-impact and peer-reviewed literature, their use may entail certain limitations. Research outputs disseminated through regional journals, institutional repositories, or publications in languages other than English may be underrepresented. As a result, some locally grounded or context-specific studies—particularly from regions in the Global South—may not be fully captured in the present analysis.

Moreover, the limitations presented are related with the lack of sources that could not be integrated then, in future investigations. As there is unregistered local literature, there is not the possibility to enrich analysis. But this discussion opens a debate about effectiveness in the reduction of global asymmetries, and how can it be articulated with local knowledge and the design of public policies.

From a methodological perspective, the observed regional disparities should be interpreted cautiously. The exclusive reliance on highly indexed databases may have contributed to a systematic underrepresentation of regional research and non-English publications, reinforcing the visibility of research from the Global North. This limitation highlights the need for future bibliometric and scoping studies to incorporate regional databases and multilingual search strategies to achieve a more inclusive representation of global knowledge.

6 Conclusion

This study revealed a significant increase in scientific production linked to technological innovation aimed at environmental monitoring of strategic ecosystems, especially since 2016. Tools such as satellite remote sensing, IoT-based smart sensor networks, and artificial intelligence systems have positioned themselves as the principal areas of research development, with China, Germany, and the United States leading the way. Even so, the low participation of regions such as Latin America and Africa reflects the persistence of wide gaps in terms of access to resources, investment in science, and technological infrastructure.

The results emphasize the importance of moving toward greater technological integration and the creation of participatory monitoring models, where local knowledge is articulated with digital advances. In particular, the application of artificial intelligence-driven predictive systems in police training and community environmental education programs is presented as a key strategy for preventing forest fires in particularly fragile areas such as the Amazon, the Orinoquía, and the center of the country. However, the success of these initiatives will depend on overcoming structural obstacles related to connectivity, institutional capacity, and responsible data management.

On the other hand, studies conducted in Colombia and the Neotropical region by the Humboldt Institute between 2023 and 2024, on the use of AI as a tool for conservation and the sustainable use of natural resources (Cañas et al., 2025), highlight the importance of technology as a local alternative resource. Similarly, in the same region, Ecuador has been applying AI to analyze ecosystem dynamics and variations in Argentina, Brazil, Chile, Colombia, and Uruguay, promoting government co-responsibility through the development of public policies aimed at their protection (Martínez, 2023).

The analysis also highlights the lack of attention to the ethical and social aspects of new technologies applied to environmental management. Issues such as privacy protection, equal access, and digital sovereignty are essential factors in ensuring that technological processes maintain legitimacy and sustainability. Consequently, both governments and communities need to direct their efforts toward creating technological projects that promote fair and responsible environmental management in the near future. In particular, the application of predictive systems based on artificial intelligence in police training and community environmental education programs is presented as a key strategy for the prevention of forest fires in particularly fragile areas such as the Amazon, the Orinoquía and the center of the country.

Similarly, the study presents an innovative conceptual model that integrates climate and socio-environmental indicators in order to anticipate areas at greatest risk of forest fires. This approach reinforces prevention and can be adapted to other tropical ecosystems. In turn, the findings provide valuable tools for the design of public policies focused on ecological restoration, territorial planning, and disaster risk reduction, thus promoting long-term environmental sustainability.

7 Ethical, privacy, and accessibility considerations in vulnerable regions

The increasing adoption of advanced technologies for environmental monitoring—such as remote sensing, artificial intelligence, Internet of Things (IoT), and large-scale data analytics—raises important ethical, privacy, and accessibility concerns, particularly in vulnerable and marginalized regions. While these tools offer significant potential for improving environmental governance and ecosystem protection, their deployment is not ethically neutral.

From an ethical perspective, the use of high-resolution monitoring technologies may exacerbate existing power asymmetries if data collection, processing, and interpretation remain controlled by external actors or institutions from the Global North. This can lead to forms of technological dependency and data extractivism, where local communities contribute data but have limited access to its benefits or decision-making processes.

Privacy concerns are also relevant, especially in contexts were environmental monitoring overlaps with inhabited territories, indigenous lands, or informal settlements. The collection of geospatial and sensor-based data may unintentionally expose sensitive information related to livelihoods, land use, or community practices, underscoring the need for context-sensitive data governance frameworks.

Accessibility represents an additional challenge. High costs associated with advanced monitoring infrastructure, limited digital connectivity, and insufficient technical capacity may restrict the adoption and long-term sustainability of these technologies in low-resource settings. Without targeted capacity-building initiatives and inclusive policy design, technological innovation risks reinforcing existing inequalities rather than reducing them.

Addressing these challenges requires the integration of ethical guidelines, participatory approaches, and capacity-strengthening strategies that ensure local ownership of data, respect for community rights, and equitable access to technological benefits. Future research and policy initiatives should therefore prioritize not only technological efficiency, but also social justice, inclusiveness, and ethical responsibility.

7.1 Policy implications for low-resource contexts

The results of this research carry important implications for policy actors aiming to encourage the uptake of artificial intelligence (AI) and remote sensing technologies in environmental monitoring, particularly in settings marked by financial, technical, and institutional constraints. The bibliometric analysis reveals a dual trend: a rapid growth in the use of these technologies alongside enduring regional inequalities that limit their diffusion across the Global South.

From a policy perspective, greater emphasis on open-access satellite data and open-source analytical tools can serve as an effective entry point. The availability of platforms such as Landsat, Sentinel and cloud-based geospatial environments helps reduce initial investment requirements and enables public institutions to establish monitoring and early warning capabilities without dependence on costly proprietary systems.

Moreover, evidence suggests that AI- and remote sensing–based monitoring initiatives are more effective when implemented through gradual and scalable pathways. Pilot projects targeting high-risk or strategically relevant ecosystems can support institutional learning and adaptation, facilitating subsequent expansion as governance structures and technical expertise develop. Such incremental approaches are particularly appropriate in contexts characterized by uncertainty regarding long-term financing and digital infrastructure.

The long-term viability of these technologies is also strongly associated with institutional capacity-building. Policy frameworks that prioritize skills development in data interpretation, AI-supported decision-making and ethical data governance enhance the ability of environmental authorities and enforcement bodies to sustain technological use. In this regard, collaboration with academic institutions and international partners plays a key role in knowledge exchange while helping to minimize technological dependency.

In addition, the involvement of local communities represents a significant enabling condition for effective monitoring systems. Integrative approaches that combine AI-based analysis with community-led observation and local knowledge can improve data reliability, lower operational costs, and strengthen social acceptance. Such participatory models contribute to more adaptive and locally grounded forms of environmental governance.

Taken together, these considerations indicate that the successful adoption of AI and remote sensing in low-resource contexts is shaped less by technological complexity than by coherent policy design, institutional integration and inclusive implementation strategies aligned with broader sustainability goals.

7.2 Future lines of research

In recent years, the use of innovative technologies for environmental monitoring has become an area of growing scientific and social importance. This advance has been made possible by the progress of tools such as artificial intelligence, the Internet of Things (IoT), and big data analysis. The dynamism of this field has driven a notable increase in international research and publications; however, significant inequalities persist between countries in the global North and South. In this scenario, challenges remain in relation to adapting technologies to regional realities, integrating local knowledge, managing data ethically and transparently, and creating public policies based on scientific evidence. The lines of research proposed in this study seek to address these gaps by exploring inclusive, scalable, and ethically responsible models of environmental innovation, with a particular focus on regions of high ecological vulnerability such as Latin America and Africa.

7.2.1 Ethical and governance considerations

The adoption of artificial intelligence (AI) and remote sensing technologies for environmental monitoring raises significant ethical and governance challenges, particularly in resource-constrained contexts. Among these, data sovereignty is of particular importance, as the collection, storage and processing of environmental information often rely on external platforms, potentially limiting local control over strategic data. In this regard, strengthening governance frameworks that clearly define data ownership, access rights and responsible data use is essential.

In addition, the expansion of AI-based monitoring systems introduces challenges related to privacy and the ethical use of information. Although environmental data are not always considered sensitive, their integration with geospatial and socio-environmental information may generate indirect risks for local communities. This underscores the need for principles of transparency, data minimization and safeguards against unintended or secondary uses of collected data.

Finally, the inclusion of local and marginalized communities represents a central ethical dimension of AI-enabled environmental monitoring. In the absence of effective participatory mechanisms, these technologies risk reproducing existing inequalities. Integrating local knowledge and participatory monitoring approaches contributes to more inclusive, legitimate, and socially robust forms of environmental governance.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SC: Formal Analysis, Methodology, Investigation, Writing – review and editing. JR: Conceptualization, Writing – original draft, Formal Analysis, Investigation. MG-A: Writing – review and editing, Methodology, Writing – original draft, Conceptualization.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Alkhatib, R., Sahwan, W., Alkhatieb, A., and Schütt, B. (2023). A brief review of machine learning algorithms in forest fires science. *Appl. Sci.* 13 (14), 8275. doi:10.3390/app13148275

Araújo, T., Ribeiro, D., Silva, I., Ferreira, H., Pequeno, E., Gomes, A. B., et al. (2025). Real-time monitoring system for forest fire prevention and combat: a case study in the Brazilian semi-arid region. *An. do Simpósio Bras. Sist. Informação (SBSI) XXI Simpósio*, 1–10. doi:10.5753/sbsi.2025.246473

Barreto, J. S., and Armentera, D. (2020). Open data and machine learning to model the occurrence of fire in the ecoregion of "Llanos Colombo–Venezolanos". *Remote Sens.* 12, 2–18. doi:10.3390/rs12233921

BID-Invest (2024). IA, datos y algoritmos para proteger la Amazonía. Available online at: https://idbinvest.org/es/blog/economia-digital/ia-datos-y-algoritmos-para-proteger-la-amazonia.

Bilbao, B. A., Mistry, J., Millán, A., and Berardi, A. (2019). Sharing multiple perspectives on burning: towards a participatory and intercultural fire management policy in Venezuela, Brazil, and Guyana. *Fire* 2 (3), 39. doi:10.3390/fire2030039

Biswas, T., and Subramanian, S. (2025). "Conservation challenges and adaptation strategies in fragile ecosystems," in *Environmental science and engineering* (Springer), 179–195. doi:10.1007/978-3-031-77149-1_8

Buchelt, A., Adrowitzer, A., Kieseberg, P., Gollob, C., Nothdurft, A., Eresheim, S., et al. (2024). Exploring artificial intelligence for applications of drones in forest ecology and management. *For. Ecol. Manag.* 551. 121530. doi:10.1016/j.foreco.2023.121530

Cañas, J. S., Parra-Guevara, C., Montoya Castrillón, M., Ramírez-Mejía, J. M., Perilla, G.-A., Marentes, E., et al. (2025). Inteligencia artificial para la conservación y uso sostenible de la biodiversidad: una visión desde Colombia. *arXiv*. doi:10.48550/arXiv.2503.14543

Carta, F., Zidda, C., Putzu, M., Loru, D., Anedda, M., and Giusto, D. (2023). Advancements in forest fire prevention: a comprehensive survey. *Sensors* 23 (14), 6635. doi:10.3390/s23146635

Chen, Y., Tan, Z., Chen, S., and Zhao, W. (2025). Environmental effects of China's sustainable development pilot policy: evidence from the national innovation demonstration zone for sustainable development agenda. *Chin. J. Popul. Resour. Environ.* 23 (4), 431–440. doi:10.1016/j.cjpre.2025.10.001

Correa, L., Carrión, V., López, C., Segura, D., and Carrión, V. (2025). Towards integrated fire management: strengthening forest fire legislation and policies in the andean community of nations. *Policies Andean Community Nations. Fire* 8 (7), 266. doi:10.3390/fire8070266

Crawford, K. (2021). *Atlas of AI: power, politics, and the planetary costs of artificial intelligence*. Yale University Press. doi:10.2307/j.ctv1ghv45t

El, pais. (2024). ¿Puede la Inteligencia Artificial 'made in Africa' ayudar a Kenia a combatir la deforestación? *Planeta Futuro*. Available online at: https://elpais.com/planeta-futuro/2024-12-20/puede-la-inteligencia-artificial-made-in-africa-ayudar-a-kenia-a-combatir-la-deforestacion.html.

Elías, Y., and Esper, L. (2021). The importance of preserving paramo areas or water factories (english, trans.). *Diálogos saberes* 52, 111–126. doi:10.18041/0124-0021/diálogos.52.2020.8651

Ellegaard, O., and Wallin, J. A. (2015). The bibliometric analysis of scholarly production: how great is the impact? *Scientometrics* 105 (3), 1809–1831. doi:10.1007/s11192-015-1645-z

Eloy, L., Bilbao, B., Mistry, J., and Schmidt, I. (2019). From fire suppression to fire management: advances and resistances to changes in fire policy in the savannas of Brazil and Venezuela. *Geogr. J.* 185 (1), 10–22. doi:10.1111/geoj.12245

Facuy, D. P. (2024). Aplicación de visión por computadora e inteligencia artificial para la prevención de incendios forestales en áreas protegidas del litoral ecuatoriano. *Rev. Int. De. Investig. Y Desarro. Glob.* 3 (3), 1–16. doi:10.64041/riidg.v3i3.24

Fernández, J., Peter, H., Fernández, C., Berzosa, J., Fernández, M., Bao, L., et al. (2024). The copernicus POD service. *Adv. Space Res.* 74 (6), 2615–2648. doi:10.1016/j.asr.2024.02.056

Floridi, L., and Cowls, J. (2019). A unified framework of five principles for AI in society. *Harv. Data Sci. Rev.* 1 (1). doi:10.1162/99608f92.8cd550d1

Garcés, E., Franco, C. J., Liaño, A. U., Ruiz, C. A., and Fairbrass, A. (2025). Assessing environmental sustainability in Colombia: metrics and policy recommendations. *Environ. Sustain. Indic.*, 100812. doi:10.1016/j.indic.2025.100812

Garzón, J. L., Ruiz, J. H., Castro, J. G., and Pérez, J. J. (2025). The importance of artificial intelligence in police forces: a bibliometric analysis. *Logos Sci. and Technol. Mag.* 17 (1), 119–134. doi:10.22335/rlct.v17i1.2009

Gaur, P., Raheja, Y., Regar, R. K., Singh, A., Kumari, K., Kumari, A., et al. (2025). Tiny plastics, massive consequences: the environmental threat of microplastics. *Water, Air, Soil Pollut.* 236 (11), 705. doi:10.1007/s11270-025-08363-7

Gaut, A., Singh, R., and Kumar, V. (2025). Ecosystem services under threat: monitoring tools and policy implications. *Sustainability* 17 (6), 4872–4890. Available online at: https://www.mdpi.com/2071-1050/17/11.

Gómez, J., Díaz, J., and García, C. (2024). Artificial intelligence and the environment. *RMd-revistamultidisciplinar* 6 (4), 83–97. doi:10.23882/cdig.24270

Graizbord, B., Granillo, J. L. G., and López Ibarra, O. (2024). Vulnerability and climate risk. The challenges of Mexico City towards the first third of the 21st century. *Investig. Geogr.* 114. doi:10.14350/rig.60844

Hluszko, C., Barros, M. V., Souza, A. M. de, Ramos Huarachi, D. A., Castillo Ulloa, M. I., Moretti, V., et al. (2024). Sustainability in practice: analyzing environmental, social and governance practices in leading Latin American organizations' reports. *Clean. Prod. Lett.* 7. 100069. doi:10.1016/j.clpl.2024.100069

Hoffmann, T. G., de Souza, C. K., Sonawane, A. D., Praeger, U., Büchele, F., Neuwald, D. A., et al. (2025). Challenges and future perspectives in postharvest monitoring of perishable goods. *Food Res. Int.* 221, 117406. doi:10.1016/j.foodres.2025.117406

Ju, J., Zhou, Q., Freitag, B., Roy, D. P., Zhang, H. K., Sridhar, M., et al. (2025). The harmonized landsat and Sentinel-2 version 2.0 surface reflectance dataset. *Remote Sens. Environ.* 324, 114723. doi:10.1016/j.rse.2025.114723

Kamyab, H., Khademi, T., Chelliapan, S., SaberiKamarposhti, M., Rezania, S., Yusuf, M., et al. (2023). The latest innovative avenues for the utilization of artificial intelligence and big data analytics in water resource management. *Results Eng.* 20, 101566. doi:10.1016/j.rineng.2023.101566

Kang, J., Dong, W., Liu, T., and Fang, L. (2024). Exploring ecosystem sensitivity patterns in China: a quantitative analysis using the importance-vulnerability-sensitivity framework and neighborhood effects method. *Ecol. Indic.* 167, 112623. doi:10.1016/j.ecolind.2024.112623

Khaskheli, M. A., Nizamani, M. M., Laghari, U. A., Laghari, A. H., Khanzada, A., Sundas, F., et al. (2025). Chapter 5. Application of geographic information system and remote sensing technology in ecosystem services and biodiversity conservation. *Deep Learn. Earth Observation Clim. Monit.*, 97–122. doi:10.1016/B978-0-443-24712-5.00006-3

Kuppusamy, S., Meivelu, M., Praburaman, L., Mujahid Alam, M., Al-Sehemi, A. G., and K, A. (2024). Integrating AI in food contaminant analysis: enhancing quality and environmental protection. *J. Hazard. Mater. Adv.* 16, 100509. doi:10.1016/j.hazadv.2024.100509

Liu, X., Ho, L., Bruneel, S., and Goethals, P. (2025). Applications of unmanned vehicle systems for multi-spatial scale monitoring and management of aquatic ecosystems: a review. *El Servier, Ecol. Inf.* 85, 02926. doi:10.1016/j.ecoinf.2024.102926

Malik, S., Singh, J. P., Kumar, A., Ibrahim, A. A., and Baskoutas, S. (2026). Smartphone-integrated paper sensor strips for environmental monitoring. *J. Photochem. Photobiol. A Chem.* 471, 116675. doi:10.1016/j.jphotochem.2025.116675

Martínez, X. B. (2023). Situation of artificial intelligence in Ecuador in elation to the leading countries of the southern cone region. *FIGEMPA Res. Dev.* 16 (2), 23–38. doi:10.29166/revfig.v16i2.4498

Meliani, L., and Basti, H. (2024). The contribution of artificial intelligence to improve the success and sustainability of STARTUPS, practical models. *Int. J. Innovative Technol. Soc. Sci.* 4 (44), 1–13. doi:10.31435/ijitss.4(44).2024.4539

Mistry, J., Belloni, I., Eloy, L., and Bilbao, B. (2019). New perspectives in fire management in South American savannas: the importance of intercultural governance. *Journal of Environment and Society* 48, 172–179. doi:10.1111/geoj.12245

Mora, L., Deakin, M., and Reid, A. (2021). Smart city development and sustainability: a longitudinal perspective. *Cities* 114, 103193. doi:10.1016/j.cities.2021.103193

Mulatu, T., Larsen, L., and Yeshitella, K. (2025). The impact of land governance and ownership regimes on public green spaces in East African cities: the case of addis Ababa (ethiopia) and kampala (uganda). *Cities* 156, 105539. doi:10.1016/j.cities.2024.105539

Murray, L., Castillo, T., Martín, I., Weber, R., González, J. R., García, J., et al. (2025). Deep reinforcement learning for optimal firebreak placement in forest fire prevention. *Appl. Soft Comput.* 175, 113043. doi:10.1016/j.asoc.2025.113043

Pandey, S., Singh, R., Kathuria, S., Prafful, N., Chhabra, G., and Joshi, K. (2023). Emerging technologies for prevention and monitoring of forest fire. *International Conference on Innovative Data Communication Technologies and their Application.*

Pedersen Zari, M., Abbott, M., Chenery, I., Smith, H., Kiddle, R., Tone, L., et al. (2025). Indigenous knowledge driven nature-based solutions: findings from an international design competition. *Nature-Based Solutions* 8, 100252. doi:10.1016/j.nbsj.2025.100252

Petrillo, A., Rehman, M., and Khan, F. (2025). Optimizing coffee supply chain transparency and sustainability through digital innovation. *Eur. J. Innovation Manag.* 28 (11), 267–289. doi:10.1108/EJIM-01-2025-0088

Poenaru, M. M., Manta, F. L., Gherțescu, C., and Manta, A. G. (2025). Shaping the future of horticulture: innovative monitoring technologies for sustainable production. *Horticulturae* 11 (5), 449. doi:10.3390/horticulturae11050449

Poeneru, A. A., and Munt, B. B. (2025). Integrating geospatial data systems for environmental sustainability management. *Environ. Model. and Softw.* 178, 105765.

Policia Nacional de Colombia (2024). *The Colombian national police receives training in artificial intelligence in India*. Policia Nacional de Colombia. Available online at: https://www.policia.gov.co/noticia/policia-nacional-colombia-se-capacita-en-inteligencia-artificial-en-india.

Puig, M., and Darbra, R. M. (2024). Innovations and insights in environmental monitoring and assessment in port areas. *Curr. Opin. Environ. Sustain.* 70. 101472. doi:10.1016/j.cosust.2024.101472

Reddy, A. A., Maraseni, T., Lahiri, S., Karki, S., Koju, U., Shrestha, A., et al. (2024). Perspectives on forest governance among the Indigenous communities of India's eastern Ghats. *For. Policy Econ.* 169, 103350. doi:10.1016/j.forpol.2024.103350

Rodríguez, F. (2025). Satellites on Fire, la startup que detecta incendios en minutos. *Detección aumentada con IA.* Available online at: https://www.innovaciondigital360.com/entrevistas/satellites-on-fire-prevencionincendios/.

Rodríguez Caguana, A., and Morales Naranjo, V. (2020). The rights of nature in intercultural dialogue: a look at case law on Andean páramos and Indian glaciers. *Deusto J. Hum. Rights* 6, 99–123. doi:10.18543/djhr.1909

Ruiz, J. P., and Martínez, A. (2024). Educational transformation: artificial intelligence in quality improvement and electronic tutoring. *Mag. Edetania* 65, 167–190. doi:10.46583/edetania_2024.65.1137

Sietz, D., Niamir, A., Müller, D., Hickler, T., Kanemoto, K., Moran, D. D., et al. (2025). Mapping human-nature archetypes to guide global biodiversity, food security, and land-use policy. *One Earth* 8 (8). doi:10.1016/j.oneear.2025.101416

Sobhani, P., Danehkar, A., Deljouei, A., Marcu, M. V., and Sadeghi, S. M. M. (2025). Assessing cultural ecosystem services in the hara mangrove forests: indicators for sustainable management in a Middle Eastern coastal marine protected area. *Ecol. Indic.* 178, 113834. doi:10.1016/j.ecolind.2025.113834

Steil, L., Bianchi, R., and Pereira, A. L. (2020). Program amazon without fire Brazil. *Braz. Biodivers. Mag.* 10, (1), 105. doi:10.37002/biobrasil.v10i1.1598

Tinoco, L. E., Galindres, D., Cifuentes, D., Hernández, J. M., López, G. D., Domínguez, G., et al. (2025). Leveraging artificial intelligence for deforestation monitoring and conservation in the Colombian amazon. *El Servier, Adv. Comput.* 139, 632. doi:10.1016/bs.adcom.2025.11.002

Tung, A. A., Mensah, K., and Ouédraogo, P. (2023). Integrating remote sensing and community-based monitoring for wildfire management in protected forests of Burkina Faso. *Environ. Monit. Assess.* 195 (4), 1–18.

Uddin, M., Siddik, A. B., Yuhuan, Z., and Naeem, M. A. (2024). Fintech and environmental efficiency: the dual role of foreign direct investment in G20 nations. *J. Environ. Manag.* 360, 121211. doi:10.1016/j.jenvman.2024.121211

Universidad de Caldas (2025). 170 students training to become police patrol officers will receive training in artificial intelligence with the university of Caldas. *Univ. Caldas*. Available online at: https://www.ucaldas.edu.co/portal/170-estudiantes-para-patrulleros-de-policia-se-formaran-en-inteligencia-artificial-con-la-universidad-de-caldas/.

Vélez, A. A., Ramírez, L., and Torres, M. (2024). Environmental impacts and sustainability-oriented public policy design. *Sustain. Sci.* 19 (2), 455–472.

Vélez-Macías, K. A., Sánchez-Cortez, J. L., and Macas-Espinosa, V. X. (2024). Characterization and evaluation of environmental units as a management and conservation strategy of the palmira desert (ecuador). *Int. J. Geoheritage Parks* 12 (3), 446–464. doi:10.1016/j.ijgeop.2024.07.009

Vélez, A. A., Ramírez, L., and Torres, M. (2024). Environmental impacts and sustainability-oriented public policy design. *Sustain. Sci.* 19 (2), 455–472.

Verma, S., Vij, S., Mir, N. R., Kumar, S., and Kapoor, N. (2025). Ecosystem monitoring, modeling and assessment. *Encycl. Bioinforma. Comput. Biol.* 4, 102–130. doi:10.1016/B978-0-323-95502-7.00150-0

Wu, W., and Zhao, Y. (2025). Big data grace: implementations of the feature engineering and data science algorithms for environmental protection law. *Alexandria Eng. J.* 125, 256–264. doi:10.1016/j.aej.2025.03.121

Xu, B., Zhang, H., and Xue, L. (2024). Method of tree leaf recognition based on Cross-CBAM lightweight neural network. *J. For. Eng.* 9 (6), 161–170. doi:10.13360/j.issn.2096-1359.202308025

Xu, Y., Zhang, J., and Xue, H. (2024). Remote sensing and AI for biodiversity monitoring. *Remote Sens. Environ.* 297, 113815. doi:10.1016/j.rse.2023.113815

Yang, W., Ortiz-Gonzalo, D., Tong, X., Gominski, D., and Fensholt, R. (2025). Mapping forest-agroforest frontiers in the Peruvian amazon with deep learning and PlanetScope satellite data. *Ecol. Inf.* 86, 103034. doi:10.1016/j.ecoinf.2025.103034

Yeshiwas, T. A., Tiruneh, A. B., and Sisay, M. A. (2025). A review article on the assessment of additive manufacturing in sustainable development. *J. Mater. Sci. Mater. Eng.* 20 (1), 85. doi:10.1186/s40712-025-00306-8

Zhang, X., Li, S., and Yu, H. (2022). Analysis on the ecosystem service protection effect of national nature reserve in Qinghai-Tibetan Plateau from weight perspective. *Ecol. Indic.* 142, 109225. doi:10.1016/j.ecolind.2022.109225

Zhao S., S., Wang, X., and Dai, Y. (2023). Practice and planning of marine conservation in China. *World Reg. Stud.* 32 (8), 37–45. doi:10.3969/j.issn.1004-9479.2023.08.20220099

Zhao Y., Y., Wang, Q., and Dai, X. (2023). Technological frontiers in environmental monitoring: a cross-continental analysis. *Environ. Sci. and Policy* 145, 112–124. doi:10.1016/j.envsci.2023.05.013

Zheng, Y., Capra, L., Wolfson, O., and Yang, H. (2020). Urban computing: concepts, methodologies, and applications. *ACM Trans. Intelligent Syst. Technol.* 5 (3), 1–55. doi:10.1145/2632230

Zhu, Z., Zhao, S., and Li, Q. (2025). Spatiotemporal evolution and prediction of land ecological quality in China. *Ecol. Indic.* 164, 113983. doi:10.1016/j.ecolind.2025.113983