



A review of quantum sensors applied to environmental monitoring: bibliometrics, integration, challenges, and future trends

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Abstract: This paper presents a critical review of the application of quantum sensors in environmental monitoring. The methodology involved the collection and processing of scientific data, the characterization of production by year, country, and study area, as well as the analysis of keyword co-occurrence to identify thematic clusters. These technologies show a significant innovation, offering non-invasive solutions for monitoring climate change, for managing water resources, and for supporting public policies aimed at environmental sustainability. The main thematic axes and trends in scientific collaboration in this rapidly expanding interdisciplinary field were identified. The results reveal the predominance of Science, Technology, Engineering, and Mathematics (STEM) areas, representing approximately 60% of all publications. The thematic analysis identified relevant groups associated with environmental data collection and analysis, including climate change, wireless sensors, and data acquisition. The study highlights emerging technologies such as Optical Pumped Magnetometers (OPMs) and sensors based on quantum vacuum fluctuations for CO₂ detection, demonstrating extraordinary sensitivities that surpass classical methods. The evolution toward distributed quantum sensor networks, using quantum entanglement, promises to revolutionize global environmental monitoring. The study aims to consolidate existing knowledge, point out trends, and reinforce the strategic role of quantum sensors in achieving SDGs such as 6, 9, and 13.

Keywords: *quantum sensing; environmental monitoring; climate change; sustainable development; quantum technologies.*

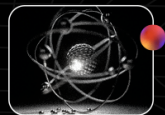
1. INTRODUÇÃO

Advances in quantum theory have enabled the development of extremely accurate sensors, including quantum gravimeters, atomic interferometers, and quantum gradiometers, capable of detecting extremely subtle variations in the gravitational field, movements of water and ice masses, and ground deformations [1-2]. This tech is a big deal for environmental monitoring, offering non-invasive ways to track climate change, manage water resources, and support public policies focused on sustainability [3-5]. Recently, the application of quantum principles such as particle entanglement and cold atom interference to measuring instruments has expanded the frontiers of Earth science and environmental observation, establishing a rapidly expanding interdisciplinary field of research [3].

The use of quantum sensors for environmental purposes has become increasingly relevant, both for

the scientific community and for public managers and productive sectors. Recent studies highlight their potential for monitoring the hydrological cycle, detecting greenhouse gases, and accurately mapping the Earth's gravitational field, contributing to the Sustainable Development Goals (SDGs), such as clean water and sanitation (SDG 6), industry, innovation, and infrastructure (SDG 9), and action against global climate change (SDG 13). [6].

In this context, in contrast to the growing volume of technical publications, there are few studies that adopt a bibliometric approach to map trends, identify collaboration networks, and describe the temporal evolution of research on quantum sensors applied to environmental monitoring. The absence of a comprehensive overview makes it difficult to identify global patterns, emerging themes, and collaborative



gaps that could guide future efforts and foster more efficient scientific policies.

This study aims to address this gap by performing a bibliometric and scientometric analysis of scholarly publications regarding quantum sensors for environmental monitoring and sustainability purposes. The application of this approach aims to consolidate existing knowledge, assess the dynamics of scientific networks, and highlight emerging trends in the field. The following questions are focus of this work: (i) how has scientific production on quantum sensors applied to environmental monitoring evolved over time? (ii) which countries and institutions lead research in this area? and (iii) what are the most recurrent emerging topics and themes in recent literature?

2. METODOLOGY

2.1. Data Collection and Processing

The bibliometric and scientometric analysis was carried out in the Scopus database (Elsevier). A combination of following descriptors in English were used: “quantum sensors” OR “quantum sensing” OR “quantum technology” and “environmental monitoring” OR “environmental sustainability” OR “sustainability.” English-language documents such as scientific articles and conference papers published between 2015 and July 2025 were considered.

2.2. Bibliometric and scientometric analysis

Descriptive analyses and scientific mapping were conducted using VOSviewer 1.6.18 software to generate maps of co-authorship, co-citation, and co-occurrence networks.

Initially, a general characterization of scientific production was performed as follows: number of

articles published per year, number of articles published by country, and number of articles published by field of study. Time series graphs were generated to illustrate the evolution of publication volume over the years.

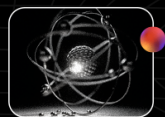
2.3. Thematic Analysis

Co-occurrence analyses of keywords extracted from bibliographic records were performed to identify the main topics and emerging themes in the literature. This step was conducted in VOSviewer, generating density maps and thematic clusters based on the most frequent terms in the field. The clusters were interpreted based on their semantic proximity and relative frequency, enabling the categorization of predominant lines of research—such as technological development of sensors, specific environmental applications, and integration with sustainability policies. In addition, total strength metrics were used to assess the strength of associations between terms and the centrality of key concepts in the thematic network. The temporal behavior of the most frequent terms was also analyzed, identifying upward or downward trends over the period studied.

3. RESULTS AND DISCUSSIONS

3.1. Bibliometric Analysis

A total of 39 publications related to quantum technology, sustainability, and monitoring sensors were obtained in the search. Figure 1 shows the evolution of scientific production on the topic over the years. The search covered a period of ten years, but the first scientific publication on the topic appeared in 2020,



meaning that the results presented refer only to the last six years.

Figure 1. Graphic representation of paper published by year

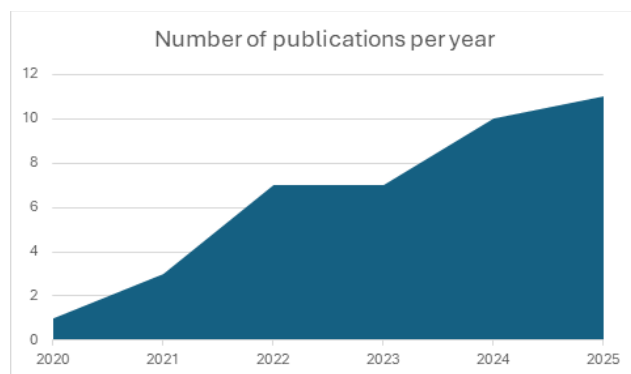
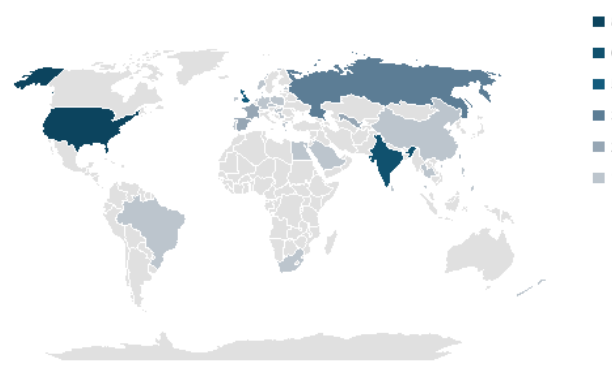


Figure 1 shows that there was gradual annual growth, except in 2022 and 2023, when the number of articles published remained at seven. Of note is 2025, which is currently underway, with 11 publications on quantum sensors applied to environmental monitoring and sustainability.

The global overview of countries that have published on the topic is shown in Figure 2, which covers a total of 31 countries. The United States leads scientific production, with 8 publications in the Scopus database, followed by India (6), the United Kingdom (5), and Russia (3). France, Spain, Taiwan, and Uzbekistan have a total of 2 publications each. The other nations identified published only 1 scientific article associated with quantum technologies and sustainability.

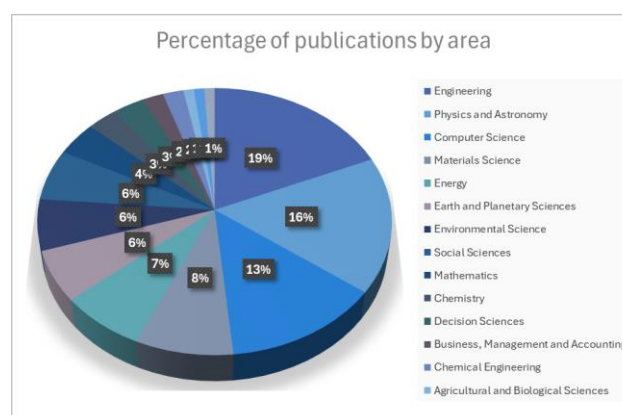
Figure 2. Graphic representation of paper by country

Number of publications by country

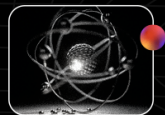


Another result obtained was the number of publications by field of study (Figure 3). The graph shows the concentration of scientific production among different areas of knowledge, highlighting important disparities in the structure of academic research.

Figure 3. Graphic representation of percentage of publications by area



Engineering dominates publications with 19%, followed by Physics and Astronomy (16%) and Computer Science (13%), while areas such as Chemistry (8%), Mathematics (8%), and Social Sciences (8%) represent a significantly smaller proportion. This uneven distribution may reflect both historical patterns of investment in research and structural differences in the nature of the disciplines.



STEM (Science, Technology, Engineering, and Mathematics) areas clearly predominate, accounting for approximately 60% of all publications, which may indicate greater availability of funding, more intense pressure to publish, or differences in publication patterns between disciplines.

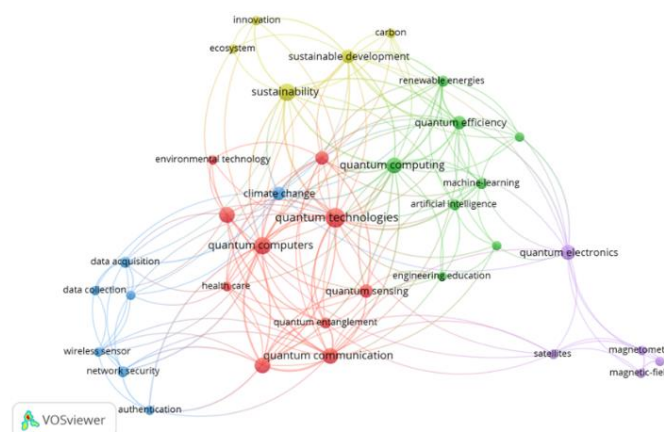
This disparity may raise important questions about equity in access to research resources and scientific promotion policies in areas that are equally relevant to social and economic development. The concentration of publication may also reflect differences in disciplinary publication patterns, where some areas may favor publications in books and others in journal articles, or have longer research cycles.

The main themes related to quantum sensors in the context of environmental monitoring and sustainability were identified through bibliometric analysis performed using VOSviewer software.

The keyword co-occurrence map shown in Figure 4 revealed the existence of five major thematic clusters that demonstrate the diversity and interdisciplinarity of the field.

The analysis performed using VOSviewer revealed a broad and interconnected thematic structure, demonstrating the interdisciplinary nature of studies on quantum sensors. First, the central cluster related to quantum technologies was observed, with emphasis on the terms: *quantum sensing*, *quantum communication* and *quantum computers*.

Figure 4. Keyword co-occurrence and clusters

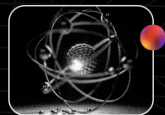


Quantum algorithms such as VQE have already demonstrated their ability to solve complex problems in natural resource management, signaling the potential of these systems in environmental applications [7].

In addition, the cluster linked to sustainability stands out, bringing together terms such as *sustainable development*, *carbon* and *renewable energies*. This relationship shows that a significant part of scientific production has sought to align technological development with energy efficiency and environmental impact reduction goals. Quantum technologies can act as cross-cutting platforms to integrate sustainable solutions across different sectors. [8].

Another relevant group of publications is associated with the collection and analysis of environmental data, with keywords such as climate change, wireless sensor, and data acquisition. These elements reinforce the role of quantum sensors in climate monitoring and in generating reliable data to guide public policy.

In this sense, Osestad et al. (2025) developed a new sensor based on quantum fluctuations that



allows detecting minimal concentrations of CO₂ with high precision. In addition, the interconnection of clusters highlights the transdisciplinary nature of quantum technologies. The integration of sensors, artificial intelligence, sustainability, and educational innovation points to a scenario in which environmental solutions will require convergence across multiple areas of knowledge [9].

Therefore, these results point to a promising scenario in which the strategic use of quantum sensors could support more effective sustainable solutions based on high-quality scientific data.

3.2. Contextualization of Results

The evident climate crisis and geopolitical competition have highlighted the topic of quantum computing, which is on the rise. Along with increased research in this area, the development of quantum sensing technologies is emerging as the next step in this race, being called the “second quantum revolution,” which is generating a new class of tools with the potential to fundamentally alter our ability to perceive the environment. These topics have become an indispensable asset for achieving the global Sustainable Development Goals (SDGs) [10-11].

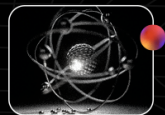
The growing need for accurate, real-time environmental monitoring, driven by climate challenges, has catalyzed the development of a new generation of detection technologies based on quantum principles. These sensors promise unprecedented sensitivity and accuracy, overcoming the limitations of classical methods

and offering new tools for understanding and mitigating environmental impacts. [10][12].

The emergence of quantum sensing for environmental applications occurred through technologies such as Optical Pumped Magnetometers (OPMs). These devices, which operate by manipulating the spin states of atoms in a vapor cell with lasers, have demonstrated extraordinary sensitivities. An early example of their potential application was the detection of magnetic droplets in a microfluidic channel, a system that, although not directly environmental, proved the ability of OPMs to perform high spatial resolution measurements. The development of the Spin Exchange Relaxation Free (SERF) regime was a milestone, allowing OPMs to achieve extreme sensitivities at room temperature, eliminating the need for cryogenic cooling and making them more practical for field implementations. [13-14].

The evolution of this research topic has seen a diversification beyond OPMs, with the emergence of more robust solid-state sensors, such as nitrogen-vacancy (NV) centers in diamond. An NV center is a defect in the crystal structure of diamond whose spin state is sensitive to magnetic fields and can be read optically.

NV center sensors are inherently more durable and capable of operating over a wide range of temperatures and pressures because they are solid-state systems. This makes them ideal for hostile environments, such as deep-sea exploration aboard Autonomous Underwater Vehicles (AUVs), where they can be used for



geophysical mapping, infrastructure monitoring, and magnetic anomaly detection. Successful field tests in the manned submersible have validated the ability of these sensors for dynamic vector magnetometry in underwater environments, confirming their potential for environmental and navigation applications [15].

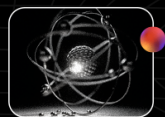
An even more innovative frontier in environmental detection exploits fluctuations in the quantum vacuum. A theoretical model proposes a gas sensor based on this principle, using nanoparticles optically trapped inside a hollow-core fiber. The introduction of a target gas, such as carbon dioxide (CO₂), disrupts the thermal motion of the nanoparticles through scattering forces. By analyzing changes in the oscillation frequencies of the particles with a neural network, the system can reconstruct gas concentrations with high accuracy, potentially detecting CO₂ at parts per million (ppm) levels. This method offers the promise of fast, continuous, and non-invasive gas monitoring, which is essential for emissions control and climate studies [16].

For truly comprehensive environmental monitoring, which requires understanding interconnected systems across large areas, the evolution is moving toward distributed quantum sensor networks. Instead of relying on isolated data points, these networks use quantum entanglement to correlate measurements from multiple sensors, allowing them to act as a single, coherent entity. This approach enables the measurement of global properties, such as the

average concentration of a pollutant in a region, with an accuracy that exceeds classical limits. [17-18].

The rapid advancement of these technologies is driven not only by scientific necessity, but also by a strong geopolitical context. Nations around the world have launched strategic quantum initiatives to accelerate research and development, with an eye toward economic and national security [17]. Many quantum sensor technologies are dual-use in nature. For example, magnetometers in AUVs are valuable for geophysical surveys and environmental monitoring as well as for defense applications such as magnetic navigation (MagNav) in GPS-denied environments and the detection of submerged objects [6].

In 2018, the US passed the National Quantum Initiative Act, allocating hundreds of millions annually to quantum information research. At the same time, the EU launched a “Quantum Flagship” with an investment of €1 billion for quantum technologies. The existence of these initiatives confirms that government’s view quantum sensing as strategic. In Latin America, FAPESP launched the QuTiA (QuTiA) program in December 2024, with a budget of R\$31 million over five years, aiming to accelerate R&D and train personnel in quantum technologies, including sensors for health, agriculture, and biodiversity. This demand is reinforced by the climate context evidenced by initiatives such as Quantum4Climate and Quantum Energy Initiative, which emphasize environmental and sustainability goals in quantum research [15-17].



However, there is already a global race for quantum leadership and the United States, China, the European Union, Japan, and other nations are investing heavily to keep up. In practice, there are already measures restricting the export of quantum technology in the US, which is motivating emerging countries to develop their own quantum sensors locally. These efforts reflect recognition that, in a second quantum revolution, technological independence and leadership in sensors can provide economic and strategic advantages. [19].

4. Conclusion

The results of this review show that the field of quantum sensors applied to environmental monitoring is rapidly expanding, characterized by a transdisciplinary nature that integrates knowledge from engineering, physics, computer science, and sustainability. The predominance of STEM fields in publications reflects not only the technological complexity inherent in quantum sensors, but also the need for convergence between multiple disciplines for the development of effective environmental solutions. Emerging technologies, such as optical pumping magnetometers and quantum fluctuation-based sensors, demonstrate revolutionary potential to overcome the limitations of classical monitoring methods, offering extraordinary sensitivities and real-time detection capabilities.

The evolution toward distributed quantum sensor networks represents a transformative paradigm for global environmental monitoring, enabling correlated measurements through quantum

entanglement with precision that exceeds classical limits. This systemic approach is essential for addressing contemporary climate challenges and supporting public policies based on robust scientific evidence. For future work, it is recommended to strengthen interdisciplinary collaboration and invest in research that explores practical applications of these technologies, aiming to accelerate the transition from laboratory prototypes to field implementations that can effectively contribute to environmental sustainability and climate change mitigation.

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