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Bibliometric Analysis of Nanotechnological Optical Sensors for the Detection of Environmental Pollutants

Santiago M. Benites[1], Magaly De La Cruz-Noriega[1], Renny Nazario-Naveda[1], S. Jonathan R.-F.[1*], Daniel Delfin-Narciso[2]

[1]Vicerrectorado de Investigación, Universidad Autónoma del Perú, Lima, Peru; srojasfl@autonoma.edu.pe, santiago.benites@autonoma.pe, mdelacruzn@autonoma.edu.pe, renny.nazario@autonoma.pe
[2]Grupo de Investigación en Ciencias Aplicadas y Nuevas Tecnologías, Universidad Privada del Norte, Trujillo 13011, Peru; daniel.delfin@upn.edu.pe

***Abstract* -** The bibliometric analysis of nanotechnological optical sensors for detecting environmental pollutants addresses the growing concern over the presence of heavy metals, aromatic hydrocarbons, and pesticides in the environment. These pollutants pose a significant threat to human health and ecosystems due to their toxicity and bioaccumulation potential. While traditional analytical techniques offer high precision, their use is limited by high costs and the lack of real-time data, driving the search for more accessible and efficient alternatives such as optical sensors based on nanomaterials. The methodology employed is based on a bibliometric analysis of scientific output in the Scopus database from 2010 to 2025. Tools such as VOSviewer and Bibliometrix in RStudio were applied to identify research trends, collaboration networks, and key actors. Search criteria were established, considering terms like "nanotechnology," "optical sensors," and "environmental pollutants," with filters by document type and publication year. Impact metrics, author and institutional collaboration, and thematic patterns were also analyzed through keyword co-occurrence maps.The results reveal exponential growth in scientific output and a rising interest in the application of artificial intelligence in optical sensors. The most extensively studied nanomaterials include metallic nanoparticles and quantum dots, highlighting advancements in sensitivity and selectivity for pollutant detection. Finally, research consolidation in specialized journals and the strengthening of collaboration networks indicate a rapidly expanding field with high potential for environmental monitoring.

***Keywords*:** Nanotechnology, optical sensors, environmental pollutants, artificial intelligence, sustainability.

1. Introduction

The increasing presence of environmental contaminants has become a global concern due to their persistence, toxicity, and accumulation in living organisms [1]. Heavy metals such as lead, mercury, and arsenic cause severe neurological and physiological damage, while polycyclic aromatic hydrocarbons (PAHs) and pesticides are linked to cancer and endocrine disruption [2]. Although conventional analytical techniques—such as high-performance liquid chromatography (HPLC) and inductively coupled plasma mass spectrometry (ICP-MS)—offer high precision in detecting these compounds, their use is limited by high costs, complex sample preparation processes, and the inability to obtain real-time data [3]. In response to these challenges, nanotechnology-based optical sensors have emerged as an efficient alternative [4]. These devices stand out for their high sensitivity and selectivity, enabling the detection of contaminants at minimal concentrations with immediate results [5]. Manufactured using nanomaterials such as metallic nanoparticles, carbon nanotubes, and quantum dots, these sensors not only enhance environmental monitoring but also facilitate integration into portable platforms, allowing for more accessible and precise detection across various settings [6]. Materials like quantum dots, gold nanoparticles, carbon nanotubes, and graphene oxide exhibit unique optical properties that improve sensitivity and selectivity in contaminant identification [7]. Nanotechnology-based optical sensors are distinguished by their rapid response, portability, and ability to perform on-site measurements [8]. Furthermore, they operate based on optical principles such as fluorescence, surface plasmon resonance (SPR), colorimetry, and surface-enhanced Raman spectroscopy (SERS), enabling the detection of trace amounts of harmful substances [9].

Given the rapid advances in this field, bibliometric analysis provides a systematic and quantitative evaluation of research trends, key contributors, and emerging topics in nanotechnology-based optical sensors for contaminant detection [10,11]. This methodology examines scientific output, collaboration networks, and the impact of publications, offering a detailed perspective on the evolution of this area [12]. Additionally, it helps identify knowledge gaps, highlight influential institutions and authors, and guide future research toward high-potential innovation areas [13]. Bibliometric studies analyze publication trends, citation networks, and priority research topics, providing a comprehensive overview of scientific progress [14]. In the field of nanotechnology-based optical sensors applied to environmental contaminants, such analyzes reveal exponential growth over the past two decades [15], reflecting the increasing interest in nanotechnology-driven solutions for environmental challenges. Specialized journals such as Biosensors and Bioelectronics, ACS Sensors, and Sensors and Actuators B: Chemical have played a crucial role in disseminating innovative advancements [16].

Bibliometric analysis also identifies the countries and institutions with the greatest research impact. Nations with strong investments in nanotechnology—such as the United States, China, India, and several European countries—lead scientific output in this field [17]. Collaboration between universities and industry has accelerated technological development, facilitating the transition from prototypes to commercial devices [18]. Furthermore, keyword co-occurrence analysis and thematic mapping have uncovered emerging trends, such as the use of artificial intelligence to interpret sensor data and the design of smartphone-integrated devices for real-time detection [19]. So far, no bibliometric study has systematically outlined the research landscape of nanotechnology-based optical sensors for environmental contaminant detection [20]. Evaluating trends, collaboration networks, and emerging applications will lay the foundation for future research and optimize this technology for sustainable environmental monitoring.

This study aims to systematically assess the evolution of scientific output in nanotechnology-based optical sensors for contaminant detection, identifying trends, key contributors, and emerging research areas. To achieve this, it will analyze the temporary growth of publications, determining which countries, institutions, and authors lead the field. Additionally, it will examine collaboration networks and their impact on technological advancements, as well as dominant trends, such as artificial intelligence integration and advanced materials for improved performance. Ultimately, this analysis will provide valuable insights to guide future research, foster innovation, and facilitate the widespread implementation of these sensors in large-scale environmental monitoring strategies.

2. Methodology

This bibliometric analysis of scientific production in nanotechnology-based optical sensors is grounded in the Scopus database, widely recognized for its extensive collection of peer-reviewed literature. A refined search strategy was implemented to ensure data quality, focusing on research related to environmental pollutant detection using optical nanotechnology. The selection criteria included key terms such as "nanotechnology," "optical sensors," "heavy metal detection," "environmental pollutants," and "nanomaterials," along with filters for publication years (2010–2025), document type (articles and reviews), and citation impact, as detailed in Table 1. However, certain limitations must be acknowledged, such as the exclusive reliance on Scopus and the restriction to English-language documents, which may introduce linguistic biases and exclude relevant studies published in other languages or indexed in alternative databases. Enhancing transparency by providing a brief explanation of these limitations and the selection process would facilitate a clearer interpretation and improve the reproducibility of the study, aligning with standard academic practices in bibliometric research.

Table 1. Search strategy for scientific documents.

TS	(TITLE-ABS-KEY (("nanotechnology" OR "nano*" OR "nanoscale" OR "nanomaterials") AND ("optical" OR "light" OR "photonic" OR "spectroscopic") AND ("sensors" OR "detectors" OR "devices" OR "instruments")) AND TITLE-ABS-KEY ("Heavy metal detection"))
Languages	English
Document types	Articles
Period	2010-2025

Dartabase	Scopus
Total documents	83

The analysis incorporates specialized bibliometric tools such as VOSviewer, which visualizes thematic networks and collaboration patterns among researchers, and Bibliometrix in RStudio, which quantifies publication dynamics and keyword evolution. Additionally, Excel was used to structure the collected data and generate descriptive statistics to support trend evaluation. The tables listing leading authors and journals are highly informative, yet it would be beneficial to clarify the selection criteria, making the analysis more accessible and reproducible for readers. Together, these methodologies provide a comprehensive view of the interdisciplinary nature of the field, highlighting emerging trends and influential contributors. The findings indicate a growing academic interest in nanotechnology-based optical sensors for environmental monitoring, particularly in detecting heavy metals and persistent pollutants. This progression suggests future research directions, including the integration of artificial intelligence, the development of advanced nanomaterials, and the creation of portable devices for real-time monitoring, driving more accessible, precise, and sustainable solutions to global pollution challenges.

3. Results and Analysis

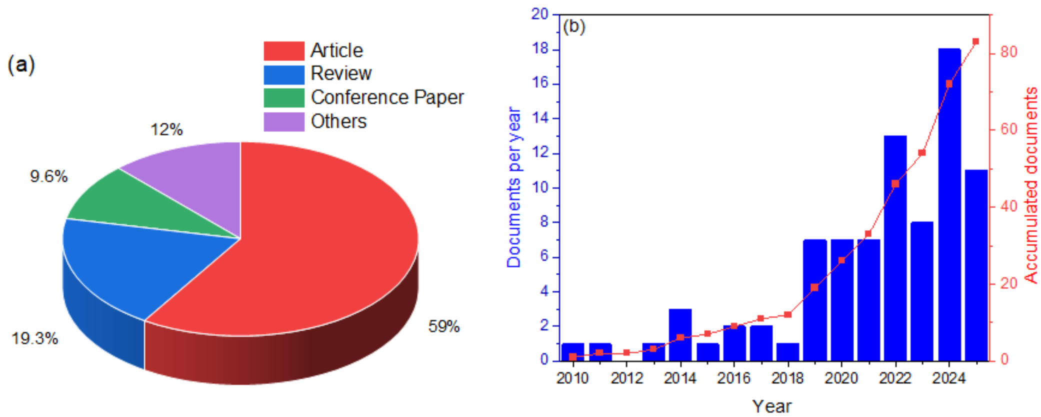

Figure 1. (a) Distribution and (b) Publication Trends in Nanotechnological Optical Sensors (2010–2024).

Figure 1 presents a visual analysis of scientific production on nanotechnological optical sensors for environmental pollutant detection between 2010 and 2024. Figure 1(a) shows that the majority of scientific output consists of research articles (59%), followed by reviews (19.3%), conference papers (9.6%), and other types of documents (12%). The prevalence of research articles indicates the consolidation of studies in this field, while the significant number of reviews underscores the interest in synthesizing prior knowledge and assessing research trends [21]. Although conference papers represent a smaller share, they highlight the role of specialized conferences in fostering academic discussions and new collaborations. Figure 1(b) illustrates the upward trend in the number of documents published annually, with continuous growth since 2018. This exponential increase reflects the rising interest in nanotechnological optical sensors, driven by the need to develop efficient technologies for environmental pollutant detection [22]. The red line, representing the cumulative number of documents, reinforces this trend by showing an acceleration in recent scientific output. The bibliometric analysis in Figure 1 confirms significant growth in the field, highlighting advancements in the applicability of nanomaterials for environmental monitoring.

Figure 2 presents a keyword co-occurrence network generated using *VOSviewer*, revealing key trends and thematic relationships in research on nanotechnological optical sensors for detecting environmental pollutants. The most prominent terms, such as *gold nanoparticles, metal nanoparticles,* and *quantum dot*, reflect the dominance of metallic nanomaterials and quantum dots in sensor development, leveraging their unique optical properties for the detection of toxic substances. The presence of keywords like *fluorescence* and *fiber optic sensors* underscores the significance of advanced optical techniques, which enable sensitive and selective real-time measurements. Meanwhile, terms such as *heavy metals* and *heavy metal detection* confirm the primary focus on heavy metals, which are critical contaminants due to their persistence and toxicity. The connection between *bioremediation* and *metal detectors* suggests growing interest in integrated solutions that combine detection with environmental remediation strategies. Additionally, the inclusion of *VOSviewer* in the network highlights the application of bibliometric tools in analyzing the evolution of this field. The proximity between *silver nanoparticles* and *carbon dot* indicates emerging research on alternative nanomaterials, while the dispersion of terms such as *property* and *metal ions* reveals studies centered on the physicochemical properties of pollutants and their interactions with sensors [23]. Overall, the network not only synthesizes the technological pillars of this field (*nanomaterials*, *optics*, and *environmental applications*) but also reveals research gaps, such as the limited mention of artificial intelligence techniques or integration with portable devices. These insights could help guide future interdisciplinary innovations [24].

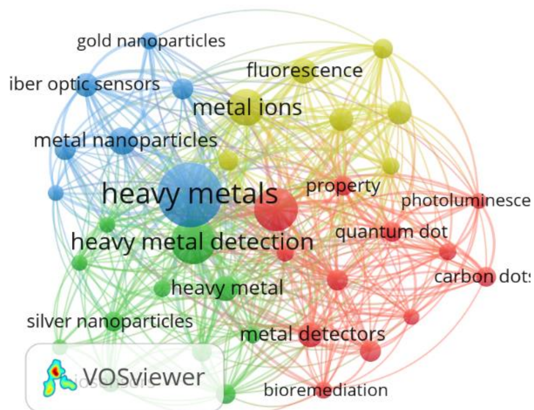

Figure 2. Keyword Co-occurrence Network in Research on Nanotechnological Optical Sensors for Environmental Pollutant Detection.

Table 2. Leading Scientific Journals on Nanotechnological Optical Sensors for Environmental Pollutant Detection.

Journal	NP	Publisher	h-index	g-index	m-index	TC	Year Established	Journal
1	IEEE Sensors Journal	3	IEEE	3	3	0.429	89	2019
2	Microchemical Journal	3	Elsevier	2	3	0.400	127	2021
3	ACS Nano	2	ACS Publications	2	2	0.125	579	2010
4	Chemosensors	2	MDPI	2	2	0.333	213	2020
5	Journal of Environmental Chemical Engineering	2	Elsevier	2	2	0.333	181	2020

Table 2 provides a bibliometric analysis of the five most relevant journals in the field of nanotechnological optical sensors for environmental pollutant detection. IEEE Sensors Journal leads in productivity with three publications (NP = 3) and an h-index of 3, reflecting its recent influence in the field, as evidenced by its high m-index (0.429) and relatively recent establishment (2019). While Microchemical Journal matches in publication volume (NP = 3), its impact is slightly lower (h-index = 2), though it maintains a competitive m-index (0.400), indicating a notable contribution in recent years. ACS Nano stands out for its high total citation count (TC = 579), demonstrating its historical authority in the field, although its low m-index (0.125) suggests diminishing influence over time due to its earlier establishment (2010). Chemosensors and Journal of Environmental Chemical Engineering, both with two publications, show similar performance (h-index = 2, m-index = 0.333), but Chemosensors has more accumulated citations (TC = 213), likely due to its specialized focus on chemical sensors. The presence of publishers such as IEEE, Elsevier, and MDPI highlights the interdisciplinary nature of the field, bridging engineering, materials science, and environmental chemistry. Despite a relatively modest volume of publications compared to more established areas like energy storage, the field is experiencing growth, with emerging journals (e.g., Microchemical Journal) gaining relevance [25,26]. The disparity in citation counts (ranging from 89 to 579) suggests that researchers should balance historical visibility (ACS Nano) with recent impact (IEEE Sensors Journal) when selecting publication outlets. Future studies could explore why certain journals with lower NP achieve higher TC, investigating article quality or interdisciplinarity.

Table 3. Bibliometric Analysis of Leading Authors in Nanotechnological Optical Sensors.

No.	Author	Number of Publications (NP)	h-index	Country	Total Citations (TC)	MCP%*	Average Citations per Article
1	Huang Y	4	3	China	120	25.0%	30.00
2	Kumar S	3	2	India	42	33.3%	14.00
3	Burratti L	2	2	Italia	182	50.0%	91.00
4	Rosposito P	2	2	Italia	182	50.0%	91.00
5	Wan H	3	2	China	160	20.0%	65.00

Table 3 reveals key patterns regarding the productivity and impact of leading researchers in the field of nanotechnological optical sensors for pollutant detection. Italian researchers Burratti L and Rosposito P stand out significantly, with only two publications each yet accumulating a total of 182 citations (TC), translating to an impressive average of 91 citations per article. This exceptional performance suggests their works are fundamental references in the field, likely due to their focus on innovative applications or groundbreaking materials [27]. In contrast, Huang Y from China has a higher publication volume (4 articles) but a relatively lower citation impact (30 citations per article), which is typical of researchers covering multiple research lines. Kumar S (India) presents a balance between international collaboration (MCP% = 33.3%) and productivity (3 articles), although with modest citation counts (14 per article), possibly indicating more theoretical studies or early-stage developments. Meanwhile, Wan H (China) emerges as a promising figure with 160 TCs and an average of 65 citations per article, reflecting specialization in high-demand topics. The predominance of Chinese and Italian authors aligns with global trends in which these countries lead environmental nanotechnology research [28]. Notably, authors with the highest MCP% (Burratti L and Rosposito P at 50%) also exhibit the greatest impact, reinforcing the value of international collaborations. However, the gap in average citations (ranging from 14 to 91) highlights disparities in research influence, possibly linked to the type of applications (fundamental vs. applied) or the visibility of the journals where their works are published. These findings highlighted that, while the field is relatively young compared to areas such as energy storage, it already contains niches of excellence that could guide future strategic collaborations [29].

The geographical distribution of research in nanotechnological optical sensors reveals significant patterns of collaboration and specialization (Figure 3). India emerges as the undisputed leader, contributing 33.7% of the total articles (28 publications), though with a moderate international collaboration rate (MCP% = 17.9%). This dominance suggests strong local research capacity, likely driven by national policies in environmental nanotechnology. China, ranking second in production (15.7%, 13 articles), exhibits greater openness to collaboration (MCP% = 30.8%), reflecting its integration into global research networks. Several contrasting cases stand out: while the United States, Egypt, Iran, and Italy exclusively produce papers without international collaboration (MCP% = 0%), Pakistan and Sweden record a 100% co-authorship rate, indicating reliance on partnerships for productivity. The United Kingdom and Malaysia present balanced models, combining domestic research (SCP) and collaborative efforts (MCP% = 25–33.3%). India's high proportion of SCP (23 out of 28 articles) may signal strengths in technological autonomy but also potential risks of scientific isolation. Conversely, the full dependence on collaboration in Pakistan and Sweden (with only two articles each) limits their capacity for endogenous knowledge generation [30]. These findings highlight that while Asian countries lead quantitatively, European and Western nations prioritize qualitative strategies based on international networks [31]. India's lower MCP% (17.9% vs. 30.8% in China) suggests opportunities to strengthen alliances, while the absence of collaboration in major players such as the U.S. and Italy could reflect specialization in strategic areas or institutional barriers. This mapping of scientific production demonstrates that the field benefits both from strong local research bases and global synergies, making it essential to balance both approaches to drive disruptive innovations [32].

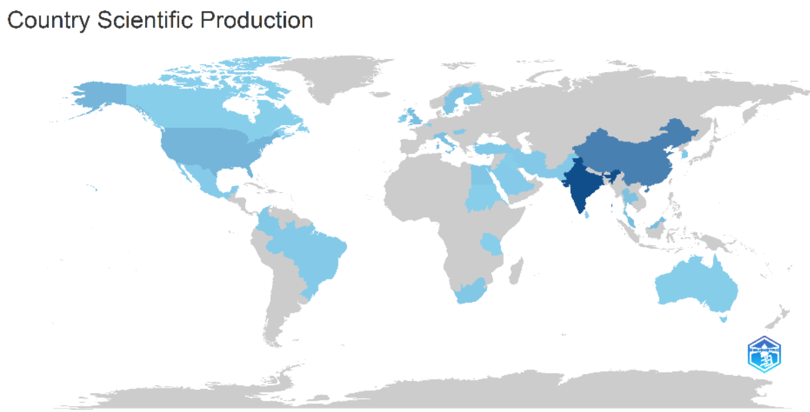

Figure 3. Scientific Production Analysis by Country in Nanotechnological Optical Sensors.

Future Research Trends in Nanotechnological Optical Sensors for Environmental Pollutant Detection

Bibliometric analysis confirms the rapid growth of research in nanotechnological optical sensors, with several emerging trends set to shape the field in the coming years [33]. One of the most significant developments is the integration of artificial intelligence (AI) and machine learning algorithms to optimize sensor data interpretation. These tools will not only enhance pollutant detection capabilities but also enable the prediction of pollution patterns and support real-time decision-making [34]. This evolution will be further driven by advancements in portable platforms and Internet of Things (IoT) devices. The incorporation of sensors into smartphones and other mobile technologies will democratize access to environmental monitoring, particularly in regions with limited infrastructure or centralized testing facilities [35]. Another key research frontier is the development of novel nanomaterials, including functionalized quantum dots, hybrid nanostructures, and bioinspired materials. These innovations are expected to significantly improve the sensitivity, selectivity, and stability of optical sensors. When combined with advanced optical techniques—such as surface-enhanced Raman spectroscopy (SERS) and high-resolution fluorescence—these materials will enable the detection of contaminants at ultralow concentrations, even in complex environmental matrices [36].

Sustainability has also become a central focus. The development of biodegradable or recyclable sensors aligned with circular economy principles reflects a growing commitment to environmentally responsible innovation. International collaboration continues to be a major driver of scientific impact, as evidenced by the high citation rates of researchers involved in multinational projects (e.g., Burratti L. and Rosposito P.) [37]. However, addressing geographical disparities remains a challenge. Strengthening academic-industry partnerships and directing targeted funding to researchers in developing countries will be essential to fostering inclusive progress. Additionally, regulatory frameworks and standardization will become increasingly important to ensure the reliability, interoperability, and global acceptance of these technologies [38,39]. Collectively, these trends suggest a future in which nanotechnological optical sensors evolve beyond passive monitoring tools to become active components of smart environmental systems—integrating detection, analysis, and remediation to contribute to a safer and more sustainable world [40].

4. Conclusion

The bibliometric analysis of nanotechnological optical sensors for environmental pollutant detection highlights sustained growth in scientific output from 2010 to 2024. The predominance of research articles (59%) over other publication types indicates a maturing field, while the rise in review papers (19.3%) reflects increasing interest in synthesizing knowledge and evaluating technological progress. Geographically, India and China lead in publication volume, though their international collaboration patterns differ. India exhibits high research productivity with a modest international collaboration rate (MCP% = 17.9%), whereas China has a stronger presence in global research networks (MCP% = 30.8%), facilitating knowledge exchange and innovation. Keyword analysis reveals that metallic nanoparticles, quantum dots, and carbon nanotubes are the most extensively studied nanomaterials, owing to their unique optical properties that enhance pollutant detection. AI applications in this field are also gaining prominence, aiming to improve sensor accuracy and responsiveness. Research has largely focused on detecting heavy metals due to their toxicity and persistence in the environment. The integration of sensors with mobile technologies and IoT platforms is an emerging trend, emphasizing the push toward accessible, real-time monitoring solutions. While scientific output in this field remains modest compared to more established domains—such as nanotechnology for energy storage—key researchers and specialized journals are playing a pivotal role in driving innovation. The findings underscore the importance of fostering interdisciplinary research at the intersection of nanotechnology, sustainability, and artificial intelligence to develop the next generation of efficient, scalable, and accessible environmental sensing devices.

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