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ORIGINAL

Environmental Impacts of Hydroelectric Power Plants: A Bibliometric Analysis from the Perspective of Sustainability

Impactos Ambientales de las Centrales Hidroeléctricas: Un Análisis Bibliométrico desde la Perspectiva de la Sostenibilidad

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ABSTRACT

Hydropower, as a renewable source, presents a complex balance between energy benefits and environmental impacts. This study examines recent scientific production on the environmental effects of hydroelectric power plants through a bibliometric analysis of articles indexed in Scopus (2020-2024), using VOSviewer. Network analysis tools were employed to explore patterns of scientific productivity, thematic trends, and conceptual relationships. The analysis identified three predominant thematic axes: alteration of aquatic ecosystems, greenhouse gas emissions, and socio-environmental conflicts. The results underscore the need for multidisciplinary approaches that integrate environmental, social, and political dimensions in the planning of hydropower projects. There is a particular urgency in developing frameworks that balance energy demands with ecosystem conservation and the rights of affected communities. The study suggests strengthening applied research that links scientific evidence with governance mechanisms and public policies in the energy sector.

Keywords: Hydropower; Environmental Impact; Sustainability; Ecosystem Management; Energy Policies.

RESUMEN

La energía hidroeléctrica, como fuente renovable, plantea un complejo equilibrio entre beneficios energéticos e impactos ambientales. Este estudio examina la producción científica reciente sobre los efectos ambientales de las centrales hidroeléctricas mediante un análisis bibliométrico de artículos indexados en Scopus (2020-2024), mediante la herramienta VOSviewer. Se utilizaron herramientas de análisis de redes, se exploraron patrones de productividad científica, tendencias temáticas y relaciones conceptuales. El análisis identificó tres ejes temáticos predominantes: alteración de ecosistemas acuáticos, emisiones de gases de efecto invernadero y conflictos socioambientales. Los resultados destacan la necesidad de enfoques multidisciplinarios que integren dimensiones ambientales, sociales y políticas en la planificación de proyectos hidroeléctricos. Se evidencia particular urgencia en desarrollar marcos que equilibren las demandas energéticas con la conservación de ecosistemas y derechos de comunidades afectadas. El estudio sugiere fortalecer la investigación aplicada que vincule evidencia científica con mecanismos de gobernanza y políticas públicas en el sector energético.

Palabras clave: Energía Hidroeléctrica; Impacto Ambiental; Sostenibilidad; Gestión de Ecosistemas; Políticas Energéticas.

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INTRODUCTION

Hydroelectric power plants have historically been a cornerstone in transitioning to low-carbon energy systems. Unlike fossil fuels, this technology harnesses the potential energy of water to generate electricity without direct emissions during operation.[1,2,3] However, Fan[4] argues that this apparent energy cleanliness hides a complex web of environmental impacts throughout the project's life cycle, from construction to decommissioning. The magnitude of these effects varies according to geographical and climatic factors and the technical characteristics of each dam.[5,6]

Li[7] and Yuan-Sheng[8] note that one of the most significant impacts occurs in aquatic ecosystems, where river fragmentation drastically alters natural hydrological regimes. The creation of reservoirs transforms dynamic river ecosystems into lentic systems and affects the composition of marine and terrestrial species. Schulthoff[9] and Zhang[10] emphasize how these modifications generate biodiversity loss, particularly in migratory species that depend on river connectivity. In addition, Broadley[11] states that changes in downstream sedimentation patterns can compromise the productivity of coastal and deltaic ecosystems.

Paradoxically, although promoted as clean energy, hydropower in tropical regions can be a significant source of greenhouse gases.[12,13] The decomposition of organic matter in reservoirs generates considerable methane emissions, a gas with a global warming potential 25 times greater than CO2. These emissions are particularly intense during the first few years after the reservoir is filled, although they persist over the long term.[14,15]

Social and cultural impacts are another critical dimension of the problem. The construction of large dams frequently involves the forced displacement of local communities, with profound consequences on their lifestyles and social structures.[16,17] According to Sergeant[18], these impacts are unevenly distributed, benefiting mainly urban and industrial centers while the burdens fall on rural and indigenous populations. The socio-environmental conflicts arising from these projects have led to developing new regulatory frameworks and international standards for impact assessment.[19,20] These approaches include technologies to reduce the impact of these projects.

These approaches range from technologies to reduce gas emissions to designs that maintain river connectivity. However, their implementation faces technical, economic, and political barriers that limit their widespread adoption.[21,22]

The growing body of research on these impacts evidences the need for systematic analyses that synthesize the current state of knowledge. This article is justified by the urgency of understanding patterns and trends in research on the environmental impacts of hydropower, particularly in the context of global climate commitments and sustainable development goals. This study aims to analyze the recent scientific production (2020-2024) on the environmental impacts of hydropower plants through bibliometric tools.

METHOD

This study was based on a bibliometric analysis to examine the scientific production on the environmental impacts of hydropower plants. The Scopus database was selected to ensure comprehensive coverage for its recognized breadth in indexing scientific research in environmental sciences, energy engineering, and sustainability studies. Data processing was done using VOSviewer software, which was recognized for its effectiveness in bibliometric network analysis and visualization of conceptual relationships.[23,24]

Phase 1. Definition of search criteria and data collection

The methodological process began with the development of a search strategy that integrated key terms related to three fundamental dimensions: the type of energy technology (including terms such as "hydroelectric" and "hydroelectric power"), the environmental impacts (with concepts such as "environmental impact" and "ecological impact") and the ecosystem components affected (such as "aquatic biodiversity" and "river ecosystems"). The search was limited to the period 2020-2024 and was performed on the title, abstract, and keyword fields; Boolean operators were used to refine the results (TITLE-ABS-KEY ("hydroelectric" OR "hydroelectric" OR "dam" OR "dam" OR "dam"). The structured search string combined these elements with filters by document type and time range, ensuring the retrieved studies' relevance.

Phase 2. Data extraction and filtering

The records obtained were subjected to a rigorous selection process in three consecutive stages. Initially, non-relevant documents such as conference proceedings or book chapters were eliminated, and only original scientific articles were retained. Subsequently, a filtering by language was applied, selecting only publications in Spanish and English to maintain the linguistic coherence of the analysis. As a final stage, an exhaustive manual review of titles and abstracts was carried out, and those works that did not directly address the environmental impacts of hydropower plants were discarded, which made it possible to obtain a refined and highly specialized corpus of documents.

Phase 3. Bibliometric analysis with VOSviewer

The refined sample was analyzed using VOSviewer software, which allowed us to examine various aspects of scientific production. This analysis included evaluating productivity by year and field of study and identifying thematic patterns through the analysis of keyword co-occurrence. Visualization through bibliometric maps revealed the conceptual structure of the field of study by highlighting the relationships between the different research topics and their temporal evolution.

Phase 4. Interpretation and synthesis of results

A qualitative analysis complemented the quantitative data obtained to contextualize the bibliometric findings. The thematic clusters identified were organized into three principal research axes: alteration of aquatic ecosystems, greenhouse gas emissions,

and socio-environmental conflicts. This interpretative process made it possible to establish connections between publication trends and practical challenges in the sustainable management of hydropower projects by identifying both areas of scientific consensus and those requiring further research attention.

This systematic methodology provided a robust framework for characterizing the current state of knowledge on the environmental impacts of hydropower by providing a solid empirical basis for guiding future research and policy in the energy sector. The combined quantitative-qualitative approach allowed us to overcome the limitations of purely statistical analyses by comprehensively understanding the research dynamics in this field.[25,26]

RESULTS

The information search formula employed yielded 586 documents that met the selection criteria used, the annual distribution of which is shown in table 1. It is observed that 27,8 % of the articles were distributed in 2024, which indicates an exponential growth in the research published on the subject in recent years, and the initial year (2020) represented a growth of 83,9 % in the following years.

Table 1. Annual distribution of publications

Year	f(%)
2020	94 (16,2)
2021	109 (18,6)
2022	93 (15,8)
2023	127 (21,6)
2024	163 (27,8)
Total	586 (100)

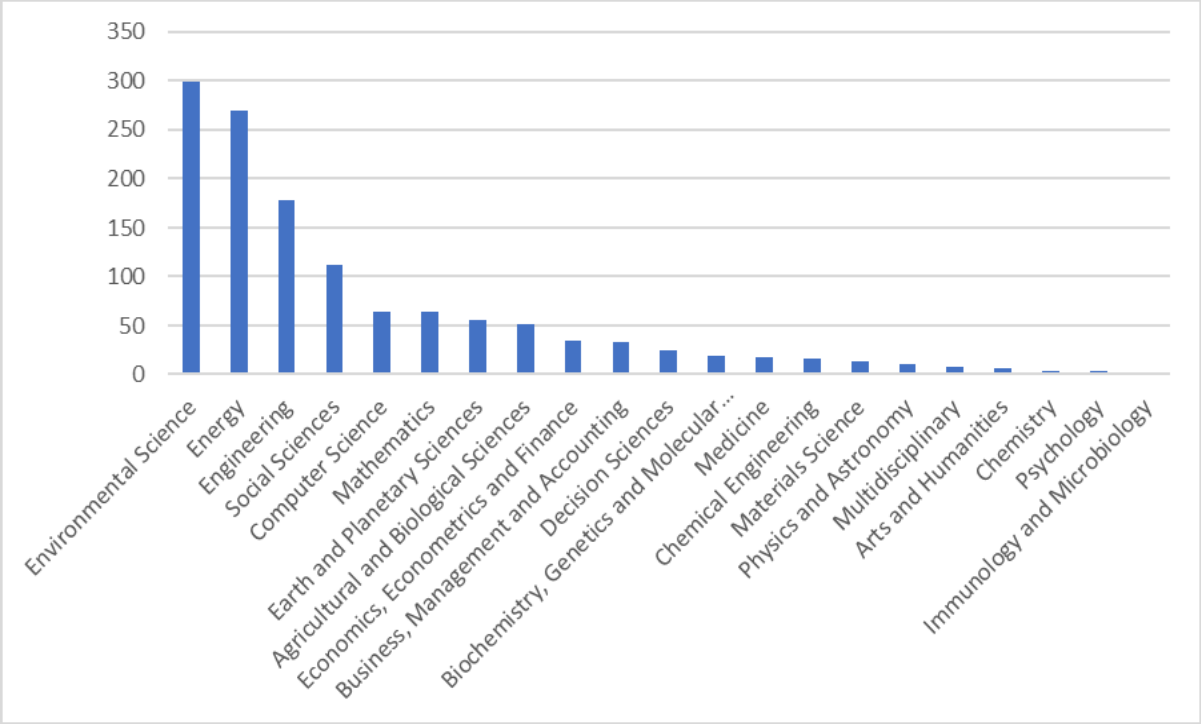


Figure 1. Distribution of publications by field of knowledge

As regards the distribution by subject area, environmental sciences occupy the main position in thematic production. Next, energy is in second place, and engineering is in third place. This indicates that scientific production on the environmental impacts of hydroelectric power plants is being analyzed from the perspective of the environmental and energy impacts they produce (figure 1).

The keyword confluence analysis indicates a multidimensional research landscape on the environmental impacts of hydropower plants. The findings of the keyword confluence analysis, presented in figure 2, make it possible to quantify the scientific production and design a structural view of how this issue has been addressed in recent years. This analysis makes it possible to identify three predominant thematic axes related to altering aquatic ecosystems, greenhouse gas emissions, and socio-environmental conflicts. These axes, distributed in the literature, indicate central concerns of the scientific community. As seen in the interrelationships, these semantic networks do not operate in isolation but interact in a complex web where ecological, climatic, and social factors are intertwined.

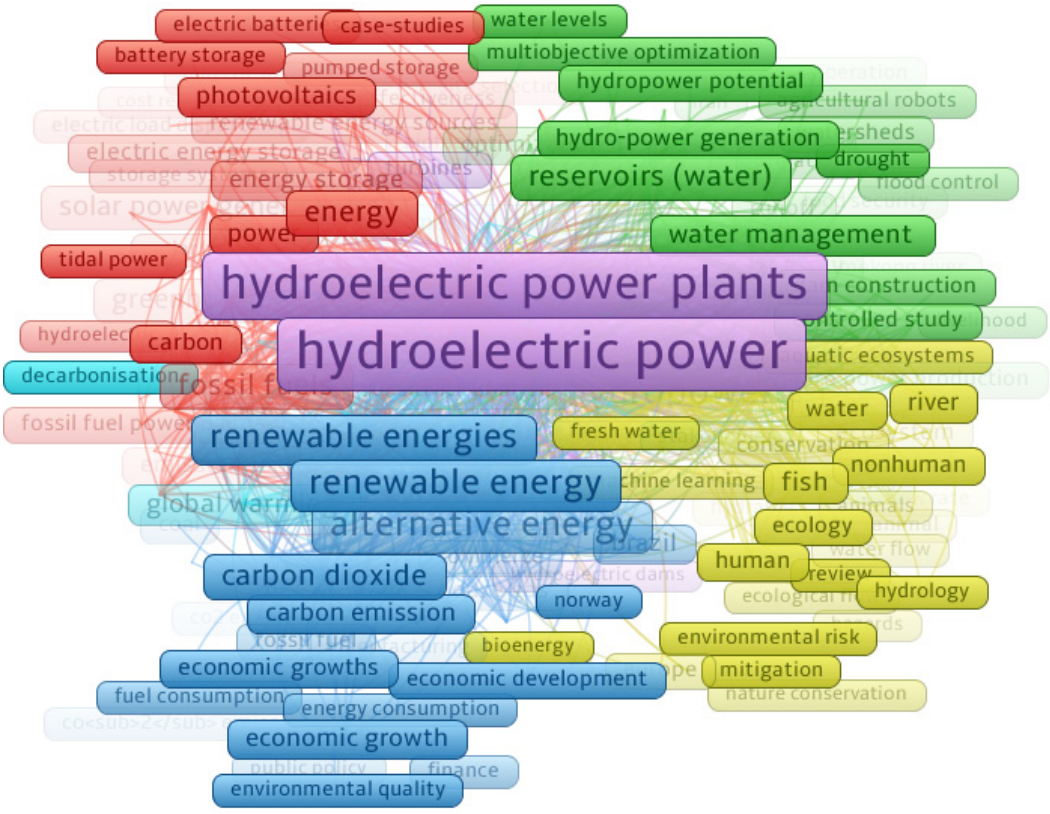


Figure 2. Keyword confluence network

Alteration of Aquatic Ecosystems

The construction and operation of hydroelectric power plants generate profound transformations in river ecosystems, affecting their structure and functioning.[27,28] The fragmentation of rivers through dams interrupts the natural flows of water, sediments, and nutrients, altering the hydrological regimes that sustain aquatic biodiversity. Chardon[29] and Williams[30] point out that these modifications can reduce river connectivity by up to 80 % in highly intervened watersheds, with critical impacts on migratory species such as fish and macroinvertebrates.

At the ecosystem scale, the impacts extend beyond the flooded area. Cattanéo[31] suggests that sediment retention in reservoirs deprives the lower reaches of essential materials for maintaining deltas and floodplains, which can trigger coastal erosion and salinization of aquifers. These cascading effects underscore the importance of evaluating hydropower projects from an integrated watershed perspective.[12,16]

Mitigation strategies have evolved from traditional approaches, such as fish ladders, to more innovative designs that seek to simulate natural flow regimes.[4,22] However, Chadwick and Lamb[32] argue that their effectiveness varies with ecological and climatic context.

De Heredia[33] and Molisani[34] emphasize the need to integrate ecosystem criteria in the initial stages of planning, through tools such as Strategic Environmental Assessment (SEA). However, the application of these approaches is still limited, especially in countries with weak regulatory frameworks.[19,35] This gap highlights, in the authors' opinion, the urgency of strengthening environmental governance and promoting international standards that guarantee the sustainability of hydropower projects.

Greenhouse Gas Emissions

Although hydropower is promoted as a clean energy source, Mirzakhani[36] and Billah[37] show that they can be significant sources of methane (CH_4), a gas with a global warming potential 25 times greater than CO_2. These emissions come mainly from the anaerobic decomposition of organic matter in reservoirs, especially in tropical areas where high biological productivity and warm temperatures accelerate degradation processes. Satellite data have revealed that some reservoirs emit as much CH_4 as thermal power plants of similar capacity, calling into question their classification as "zero emissions" energy.[38]

The magnitude of emissions depends on multiple factors, such as the age of the reservoir, the type of vegetation inundated, and climatic conditions.[39,40] During the first 10 years after filling, emissions can be exceptionally high due to the decomposition of newly inundated biomass.[18,41]

Strategies to reduce emissions include pre-clearing vegetation and managing water levels. However, their implementation faces economic and logistical obstacles, especially in mega-projects.[42,43] Alternatives such as gas capture systems in reservoirs are in the experimental phase, with uncertain results.[44] In the authors' opinion, the lack of standardized methodologies and accurate local data is still a key challenge in assessing the actual climate impact of hydropower.

Socio-environmental Conflicts

Hydropower projects frequently generate tensions between actors with divergent interests: governments seeking "clean" energy, private companies prioritizing profitability, and local communities defending their territories and ways of life.[45,46] These cases reveal common patterns: insufficient prior consultation, forced displacement, and inequitable distribution of benefits.[31,47] Indigenous peoples are particularly vulnerable, as they are the most susceptible.

Indigenous peoples are particularly vulnerable, as their territories often coincide with areas of high hydropower potential.[48,49] This has prompted legal frameworks such as ILO Convention 169, although its implementation is still uneven.[50]

Baratov et al.[51] stress the importance of genuine participation mechanisms and fair benefit sharing. However, in countries with high inequalities, challenges persist in balancing energy development and human rights.[6,13,29] In the authors' opinion, social impacts are as critical as environmental ones. Moving towards sustainable hydropower requires not only technical improvements but also transformations in energy governance.

DISCUSSION

The results of this study show that research on the environmental impacts of hydropower has evolved towards more holistic approaches, overcoming the initial dichotomy between energy benefits and ecological costs.[52,53] Williams[30] demonstrates that environmental effects are not mere collateral damage, but systemic consequences that interact with climatic and social factors. This paradigm shift is reflected in the growing number of studies that adopt interdisciplinary perspectives, combining hydrology, ecology, and social sciences.[33,54] However, in the authors' opinion, significant asymmetries persist between the knowledge generated and its application in public policies, particularly in developing countries where regulatory frameworks prioritize energy development over environmental protection.

A key finding is the recognition that impacts vary substantially according to geographic conditions and time scales.[37,38] While progress has been made in mitigation in temperate regions through low-impact technologies, the challenges in tropical ecosystems are still critical due to their high ecological sensitivity and social complexity.[55,56] This variability questions the validity of standardized approaches and highlights the need for case-by-case assessments that consider local particularities. Furthermore, the analysis reveals that purely technical solutions are insufficient if they are not accompanied by robust governance and community participation mechanisms.

The increasing attention to social and climate dimensions in the literature reviewed marks an important shift in the field. Recent research is no longer limited to quantifying environmental damages but explores how hydropower reconfigures territories and socioecological dynamics.[45,48,57] This holistic approach is promising but requires greater articulation with decision-making processes. Future research should focus on translating scientific evidence into policy instruments that balance energy demands, environmental conservation, and social justice, especially in contexts of the climate crisis, where solutions require complex balances between mitigation and adaptation**.**

CONCLUSIONS

This study evidences that the environmental impacts of hydropower plants constitute a multidimensional challenge that requires integrated management approaches. The results highlight the need to overcome fragmented analyses and move towards holistic assessments that simultaneously consider ecological, climatic, and social aspects. While progress has been made in the scientific understanding of these impacts, a critical gap persists between the knowledge generated and its application in energy development policies and practices.

Future research should focus on improving methodological frameworks for comprehensive assessments, strengthening governance mechanisms that ensure environmental sustainability and social justice, and developing adaptive technologies that minimize impacts according to specific ecological contexts. Only through this multidimensional approach will it be possible to reconcile global energy demands with the protection of ecosystems and the well-being of local communities.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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