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Impact of Electromagnetic Fields from Submarine Cables on Marine Life

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ABSTRACT

Submarine cables cause ecological impacts on benthic habitats and disturb fragile ecosystems, which threaten marine biodiversity. Actions to mitigate climate change have led to the adoption of renewable energy sources such as wind, wave, and tidal energy. However, the installation of submarine cables required to harness these resources has had negative impacts on marine flora and fauna. In this context, this research aimed to determine the effects of submarine cables on marine flora and fauna through a systematic review. The PRISMA 2020 statement was used. Inclusion and exclusion criteria were based on aspects that covered the largest number of relevant studies, and studies were retrieved from five databases. The compound annual growth rate of scientific output was calculated using a digital tool (Calcuvio), and data analysis was performed using Microsoft Office Excel. The country with the highest scientific output was Poland, and the year with the highest output was 2023. The compound annual growth rate of scientific output (2005–2023) was 17.42%. The most studied type of submarine cable, based on its function, was the energy transmission cable. The most studied marine organisms were fish, and the effects of electromagnetic fields included attraction to the submarine cable, behavioral changes, reduced mobility, and altered distribution. It is recommended that research be conducted on the entire life cycle of marine species (e.g., octopuses, lobsters, jellyfish, anemones, starfish, sea urchins), as well as on submarine cables used for telecommunications transmission and their effects on marine life.

1. INTRODUCTION

Worldwide, efforts are intensifying to mitigate climate change through renewable energy sources such as wind energy (projected to grow by 25% by 2030) [1], as well as wave and tidal energy, which are viable alternatives to fossil fuel-based energy [2-5]. Submarine cables are used to transport energy from marine environments to land, and they also carry over 95% of international voice and data communications (via optical fiber) [6-8].

The first submarine electrical cable was deployed across the Isar River in Germany in 1811. The transmission of electrical energy from one substation to another is achieved through two methods: HVDC (high-voltage direct current) and HVAC (high-voltage alternating current) [9]. In 1954, the first commercial HVDC submarine cable was installed in the Baltic Sea, linking Sweden with the island of Gotland [10]. Since then, submarine electrical cables have been deployed around the world. By 2015, the total length of all submarine cables (including telecommunication cables) was approximately 1.06 million km, with nearly 8,000 km being HVDC submarine cables [9].

Marine renewable energy can affect marine life and ecosystems through various factors, including acoustic pollution, collisions and entanglements, changes in natural currents, disturbances to physical habitats, sediment resuspension, heat emissions, and chemical pollution [8, 10-12]. Furthermore, the main negative impact caused by the electric current in submarine cables is the emission of electromagnetic fields, which are classified into electric fields and magnetic fields [13-15]. Electromagnetic fields affect many marine species in terms of orientation and navigation [11, 12, 16], as well as changes in development [17, 18], behavior [19, 20], and physiology [21, 22]. Additionally, there are potential alterations in the behavior of invertebrates [16, 23, 24].

This review contributes to identifying the impacts of submarine cables on marine life and the importance of renewable energy (wind and tidal) in electricity generation.

Accordingly, this study aimed to determine the effects of electromagnetic fields produced by submarine cables on marine flora and fauna through a systematic review. To achieve this, the following research questions (RQs) were formulated:

RQ1: Which country and year have the highest scientific production?

RQ2: What is the compound annual growth rate of scientific production?

RQ3: According to the function of the cable, which is the most studied submarine cable?

RQ4: Which marine fauna or flora is the most studied?

RQ5: What are the effects of submarine cables?

RQ6: What are the keywords that appear most frequently in the studies found?

2. MATERIAL AND METHODS

The PRISMA 2020 statement, the method used for the systematic review [25], will help to outline and better understand the study [26, 27].

2.1 Eligibility criteria

Inclusion criteria: (1) scientific research articles, (2) studies worldwide, (3) studies in multiple languages, and (4) from the first study up to November 2024.

Exclusion criteria: (1) duplicate studies between search queries, (2) paywalled studies, (3) studies where the title or abstract is not related to the research objective, and (4) other scientific publications (reviews, conference papers, letters, short communications, etc.). Pay studies were excluded because the corresponding budget was not available, which could have limited the inclusion of some articles; nevertheless, an exhaustive search was carried out in open-access articles, where the findings reflect a sample of the available literature.

2.2 Search information and strategies

Boolean operator "AND" was used to combine words and the search was restricted to the title, abstract, and keywords of the articles, which allowed a more precise approach. The search in the 5 databases was performed from July 5 to November 20, 2024, with the following search methods (Table 1):

Table 1. Search procedure

Digital Databases	Search Methods
1. Scopus 2. ScienceDirect 3. Taylor & Francis 4. Wiley 5. EBSCO	TITLE-ABS-KEY ("submarine cable" AND effects) TITLE-ABS-KEY ("submarine cable" AND impact) TITLE-ABS-KEY ("renewable energy" AND "submarine cables")

2.3 Selection and data extraction

The authors were divided into 2 groups, thus forming 5 authors per group, so that each group would search for a search equation. Inconsistencies and doubts were resolved at the end of the selection process with the first author (Manuel Rategui-Inga). For organizing the articles, an online tool was used to create the PRISMA 2020 flow diagram [28]. Initially, there were 7,684 articles, and after applying the eligibility criteria, 18 remained for the review (Figure 1).

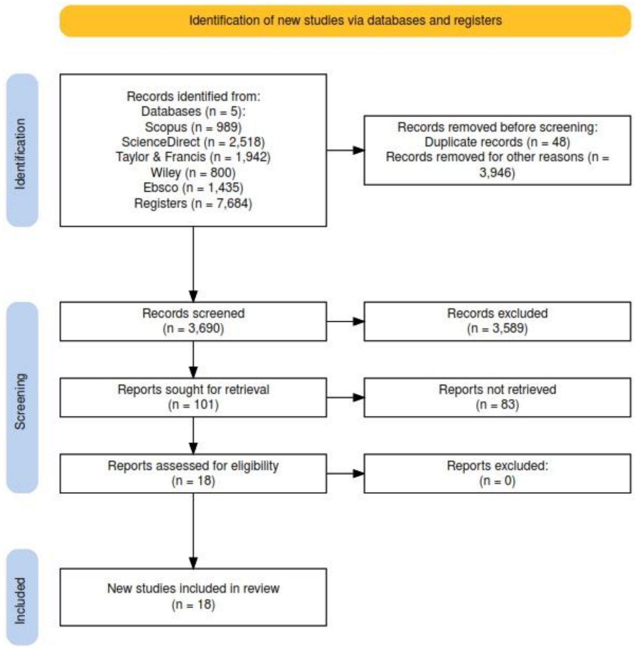

Figure 1. Item selection process

2.4 Compound annual growth rate (CAGR)

The CAGR indicates the annual growth rate of scientific production (percentage) from 2005 to 2023, and its value was determined using the online calculator [29], applying the formula:

$$CAGR\% = 100 * \left(\left(\frac{V_f}{Vi} \right)^{\frac{1}{t}} - 1 \right)$$

where, V_i=Initial value; V_f=Final value; t=Years.

2.5 Meta-analysis of the data

The information was compiled (CSV format) and processed in Excel 2016 to visualize the distribution of research by year and country. VOSviewer 1.6.19 was used for the keyword co-occurrence networks.

3. RESULTS AND DISCUSSIONS

The year with the highest scientific production is 2023, with 4 studies (Figure 2). On the other hand, scientific production has an annual growth rate of 17.42%, which indicates a slow and progressive annual growth.

In recent years, the large amounts of greenhouse gases emitted (mainly CO_2) into the atmosphere, with 77% coming from the energy sector, have been causing negative environmental consequences [30, 31]. As a result, the need to mitigate climate change has led to the replacement of energy generated from fossil fuels with renewable energy sources [1, 32]. Among the different sources of renewable energy, offshore wind energy is a promising source in terms of commercialization, policy frameworks, technological development, and installed capacity [33-36]. Therefore, offshore wind farms are being built worldwide at an increasing pace [37, 38], and to transport the energy generated by these installations, submarine cables are used, with an expected increase in the coming years [39]. Thus, given the importance and growing environmental awareness, there is a need to assess the effects of the electromagnetic field produced by submarine cables, leading to a continuous increase in research in recent years.

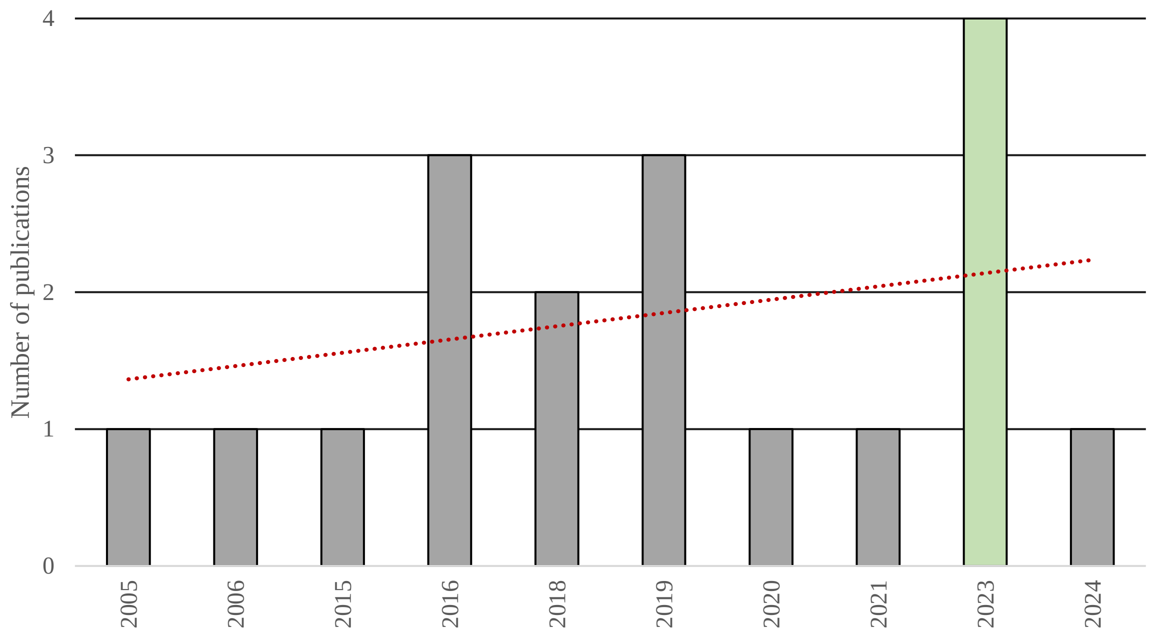

Figure 2. Evolution of scientific production per year

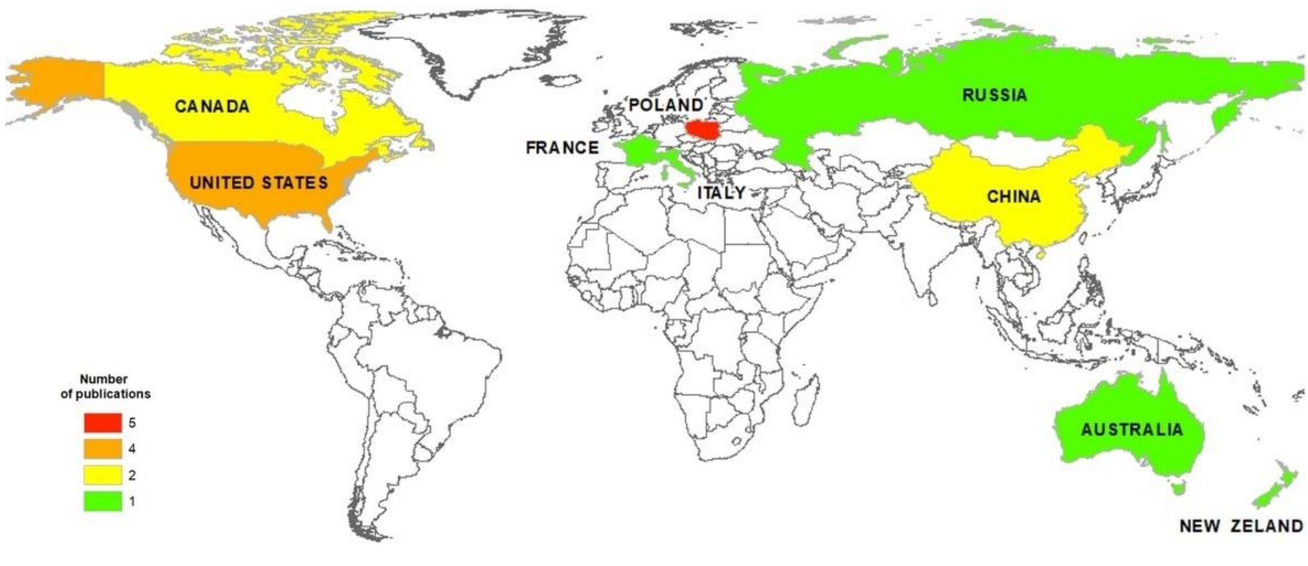

Figure 3. Evolution of scientific production per country

The country with the highest number of studies is Poland, with 5 studies (Figure 3). This aligns with the review conducted by the study [40], which showed that the mentioned country also leads in the highest number of studies regarding the effects of electromagnetic fields on bees. The demand for electricity in Poland increases each year [41]. In addition, the country faces the need to explore alternative energy generation methods, as only about 14% of electricity generation comes from renewable energy sources [42, 43]. By 2030, Poland is expected to have installed an additional 6 GW of electricity generation through offshore wind farms, and by 2040, between 8 and 11 GW of additional energy [43, 44]. In this regard, the construction of offshore wind farms has recently become a key policy and holds significant potential, contributing to the reduction of power plants that, until 2020, operated with coal and lignite [45, 46]. On the other hand, this situation is favorable for technological development, contributing to sustainable development and economic growth [47]. The United States is the second country with 4 studies, as the planning of marine renewable energy is growing, thanks to environmental management policies aimed at combating the climate crisis in the country [48].

Of the 18 studies (Table 2), the most studied function of submarine cables is energy transmission (16 studies), transferring energy generated at sea to land. This is due to the global need to replace energy produced by fossil fuels with renewable energy, as well as the aim to provide electricity services to more people. In this regard, it is a priority to study the effects of these cables that serve this function.

The effects of submarine electrical cables occur during the installation, maintenance, and decommissioning phases [10]. Table 2 shows the 18 reviewed studies, detailing the effects of the electromagnetic field on marine flora and fauna by species. Fish are the most studied, with 8 studies (6 on the same species and 2 on their larvae). The effects found include attraction to electromagnetic fields, reduced mobility, and increased migration. Additionally, there is evidence that the magnetic field aids in the navigation of migratory fish (Pacific salmon) [49, 50]. Other species, especially elasmobranchs, have electroreceptors that allow them to detect other fish [51]. On the other hand, attraction to the magnetic field, changes in orientation, migratory behavior, and behavioral responses of fish have been reported [21, 52-54]. Electromagnetic fields affect electroreception to detect prey in sharks and rays [53], experimental studies indicate that it can interfere with neuronal activity in electric fish [52, 54]. In eggs, delays in hatching and impaired embryonic development have been observed [55-57].

Further research is required to fully understand the physiological mechanisms involved and their relevance under natural conditions. Future policies should include mandatory environmental impact assessments for submarine cable installations.

The co-occurrence network represents that "submarine cable" and "marine environment" have the highest number of occurrences with 5 and 3 respectively, on the other hand, 2 clusters (red and green) have been formed that interact with each other (Figure 4).

Table 2. Effects of the electromagnetic field on marine flora and fauna

Function of the Submarine Cable	Impacted Fauna or Flora	Species	Effects	Ref.
Energy transmission	Ichthyofauna	*	**	[58]
	Epifauna Infauna		Few changes in abundance and distribution.	
Telecommunications transmission	Anemones	*	It showed greater abundance near the cable than in the surrounding marine bottom habitats dominated by sediments.	[59]
	Fish		They were abundant near the cable.	
	Glass sponge reef		The sponge cover was lower along the cable transects compared to the control areas.	
Energy transmission	Megafauna, shrimp, and arthropods	*	The total abundance was slightly lower along the cable transects.	[60]
Energy transmission	Fish	*	Decrease in mobility and distribution.	[61]
	Fish	*Acanthopagrus schlegeli* and *Cynoglossus semilaevis*		
Energy transmission	Mollusk	*Meretrix meretrix* and *Nassarius variciferus*	Changes in behavior.	[62]
	Crab	*Helice tientsinensis*		
Telecommunications transmission	Epibenthic	*	Light disturbance of benthic ecosystems.	[63]
Energy transmission and telecommunications	Benthic communities	*	**	[64]
Energy transmission	Fish	*Oncorhynchus tshawytscha*	Increase in migration	[65]
Energy transmission	Benthic and demersal fish	*	**	[15]
Energy transmission	Polychaete	*Hediste diversicolor*	- Increase in digging activity. - The positive energy balance was maintained, with a large amount (85% of the assimilated energy) of energy available for individual production (growth margin). - Reduction in the ammonia excretion rate.	[22]
Energy transmission	Fish larvae Polychaete Clam	*Oncorhynchus mykiss* *Hediste diversicolor* *Limecola balthica*	High genotoxic and cytotoxic activity.	[66]
Energy transmission	Lobster	*Homarus gammarus*	**	[67]
Energy transmission	Fish larvae	*Oncorhynchus mykiss*	They are attracted to the electromagnetic field of the cable.	[68]
Energy transmission	Cockle	*Cerastoderma glaucum*	- It maintained a positive energy balance. - The filtration rate and the energy available for individual production were lower. - The ammonia excretion rate was significantly lower. - Protein carbonylation increased. - Significant inhibition of acetylcholinesterase activity.	[7]
Energy transmission	Mollusk	*Elysia leucolegnote*	- Increased oxidative stress, blood glucose levels, and blood lipids.	[69]

			- Decreased immunity and physiological conditions.	
Energy transmission	Fish	*Cyclopterus lumpus*	**	[70]
Energy transmission	Polychaete	*Ficopomatus enigmaticus*	Significant reduction in fertilization rate in sperm.	[71]
Energy transmission	Crab	*Cancer productus*	**	[72]

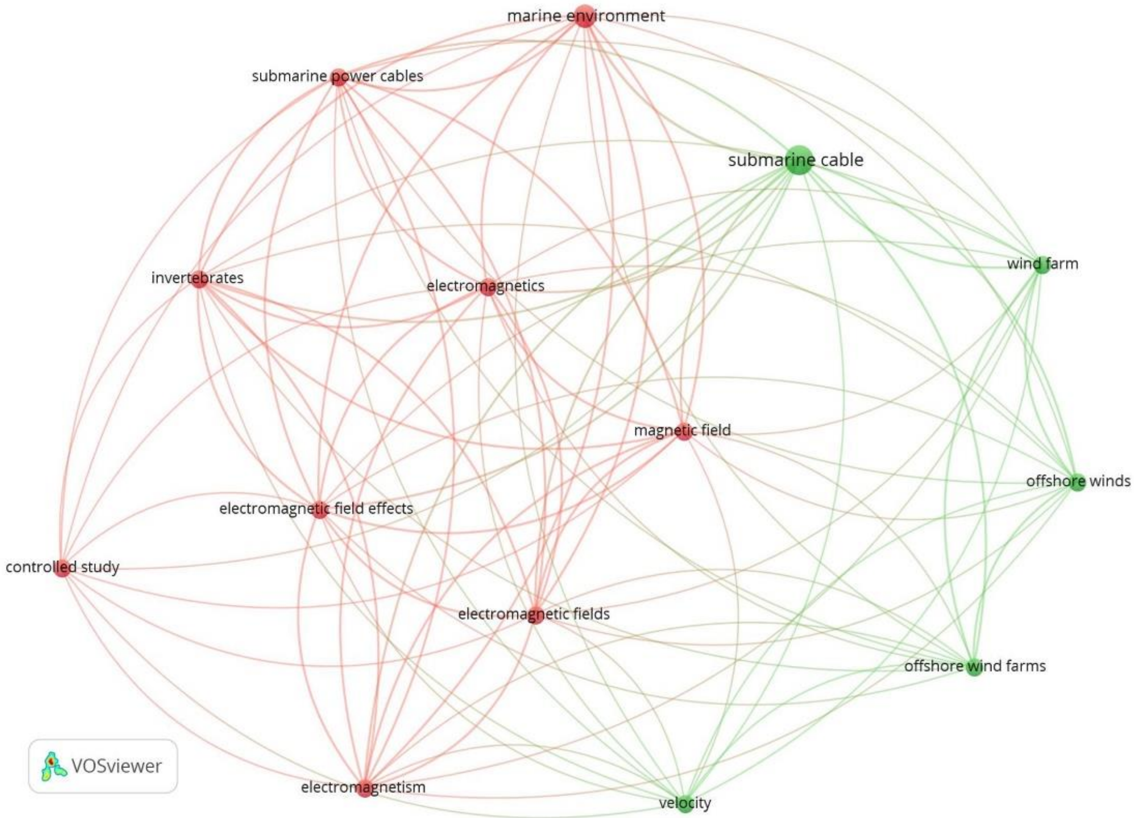

Figure 4. Keyword co-occurrence network

4. CONCLUSIONS

In the coming years, scientific output will continue to increase due to advancements in harnessing clean energy (wind, wave, and tidal) to mitigate climate change. Poland will remain a pioneer in scientific output due to its potential for generating electricity through offshore wind farms and its government policies aimed at expanding renewable energy distribution nationwide. Wind, wave, and tidal energy are renewable sources currently on the rise, which, in turn, is increasing the number of submarine cables (primarily used to transport energy to land) deployed in marine environments. The review found that a large portion of the research focuses on the effects of electromagnetic fields on fish, including reduced mobility, behavioral changes, and attraction to the cables' electromagnetic fields. Future research should broaden studies on the effects of electromagnetic fields throughout the entire life cycle of marine species such as octopuses, lobsters, jellyfish, anemones, starfish, and sea urchins. Additionally, research has shown that there is limited study on telecommunication cables as a source of electromagnetic fields. Finally, the study provides important information for the planning of underwater infrastructure in the field of renewable energy, as well as guiding environmental policies aimed at the conservation of marine habitats.

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