Energy Reports 16 (2026) 109675

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review article

Balancing energy and ecology: Environmental impacts of offshore wind farms and mitigation strategies – A scientometric review

Prangon Das [a,*,1], Joya Biswas [b,2]

[a] Department of Mechatronics Engineering, Rajshahi University of Engineering & Technology, Rajshahi 6204, Bangladesh
[b] Fisheries & Marine Resource Technology Discipline, Khulna University, Khulna, Bangladesh

ARTICLE INFO

Keywords:
Offshore Wind Farms
Environmental Impacts
Marine Ecosystems
Electromagnetic Fields (EMFs)
Underwater Sound
Vibration
Light Pollution
Artificial Reef Effect
Scientometric Analysis
Mitigation Strategies

ABSTRACT

Offshore wind farms have become a cornerstone of the global transition to sustainable energy. This scientometric review explores the evolution of research on their environmental impacts from 2010 onward, analyzing key trends, citation patterns, and influential contributions. The study provides a comprehensive review of both positive and negative effects on the marine environment, alongside mitigation strategies proposed by researchers and industry stakeholders. It emphasizes the importance of innovative engineering, robust policy frameworks, and eco-friendly practices in addressing eco-logical challenges. The findings aim to inform sustainable offshore wind energy development, highlighting the need for interdisciplinary approaches to balance energy production with marine environmental preservation.

1. Introduction

The urgent demand for sustainable energy sources has driven global interest in offshore wind farms, which are increasingly recognized for their ability to produce renewable energy at large scales and contribute to the reduction of greenhouse gas emissions (Cui et al., 2020; Sadorsky, 2021). Offshore wind technology is especially advantageous due to stronger and more consistent wind resources at sea compared to onshore sites, allowing for higher energy output and reduced land use conflicts (deCastro et al., 2019). As of recent years, several countries have ramped up investments in offshore wind infrastructure to meet renewable energy targets, with projects spanning Europe, Asia, and North America (DeCastro et al., 2019; Tufan and Dalcalı, 2025).

However, the deployment of offshore wind farms is not without environmental implications, particularly concerning the marine ecosystem. Offshore wind installations introduce various forms of energy into the marine environment, such as electromagnetic fields (EMFs), underwater noise, vibration, light, and heat, which can significantly alter marine habitats (Galparsoro et al., 2022). EMFs generated by subsea cables, for instance, are known to affect sensitive marine species like elasmobranchs, which rely on natural electromagnetic fields for navigation and hunting (Hutchison et al., 2020). Similarly, underwater noise from turbine operations and construction activities can disrupt marine mammals and fish, leading to behavioral changes or even habitat displacement (Erbe et al., 2019; Hawkins and Popper, 2017). Additionally, the structural presence of wind turbines can lead to the artificial reef effect, wherein marine life colonizes turbine foundations, impacting local biodiversity in both positive and negative ways (Glarou et al., 2020).

Recognizing these environmental challenges, the research community and industry stakeholders have developed various mitigation strategies aimed at minimizing negative impacts on marine life. For example, EMF shielding for subsea cables, noise reduction technologies during pile driving, and strategic placement of turbines to minimize habitat disruption are actively researched solutions (Gill et al., 2014; Koschinski and Lüdemann, 2020). Furthermore, some industry players are incorporating environmental monitoring programs and developing eco-friendly designs for wind farm infrastructure (Hermans et al., 2020). Despite these efforts, the effectiveness and long-term implications of these mitigation strategies remain topics of ongoing study.

This paper provides a scientometric review of the literature on environmental impacts associated with offshore wind farms, focusing on trends from 2010 onward. By employing bibliometric analysis, key

* Corresponding author.
E-mail addresses: prangon@mte.ruet.ac.bd (P. Das), joya2580biswas@gmail.com (J. Biswas).
[1] https://orcid.org/0000-0002-6135-5732
[2] https://orcid.org/0009-0003-3386-4956

https://doi.org/10.1016/j.egyr.2026.109675
Received 8 November 2025; Received in revised form 7 July 2026; Accepted 17 August 2026

Nomenclature

AI	Artificial Intelligence
OWF	Offshore Wind Farm
BOEM	Bureau of Ocean Energy Management
EEA	European Environment Agency
EIA	Environmental Impact Assessment
EMF	Electromagnetic Fields
GES	Good Environmental Status
ICES	International Council for the Exploration of the Sea
IEA	International Energy Agency
MPA	Marine Protected Area
MSP	Marine Spatial Planning
NINA	Norwegian Institute for Nature Research
NPWRC	Northern Prairie Wildlife Research Center
NREL	National Renewable Energy Laboratory
RWE	Rheinisch-Westfälisches Elektrizitätswerk (German energy company)
SINTEF	Foundation for Scientific and Industrial Research (Norway)

themes, influential studies, and emerging areas of research are highlighted. The review further examines both positive and negative ecological impacts and evaluates mitigation measures advanced by the research community and industry. Findings are intended to identify critical knowledge gaps and propose future research directions for a sustainable integration of offshore wind energy.

1.1. Study Positioning and Contribution

While numerous studies have explored the environmental impacts of offshore wind farms (OWFs), this paper distinguishes itself through its comprehensive, multidisciplinary approach and the integration of scientometric analysis with thematic literature review. Unlike prior works that typically focus on isolated aspects, such as electromagnetic field effects (Gill et al., 2014), ecosystem services (Mangi, 2013) or floating wind-specific impacts (Farr et al., 2021), this study spans a broader temporal and thematic spectrum (2010–2025), providing both quantitative and qualitative insights. By employing advanced bibliometric tools like VOSViewer and Scopus, it maps the evolution of research clusters and identifies knowledge gaps, an aspect absent in most earlier reviews. Furthermore, this work uniquely consolidates mitigation strategies from both academic and industrial perspectives, offering practical and actionable insights through structured comparison tables.

This dual emphasis on scientific rigor and real-world applicability, along with its balanced treatment of both positive and negative environmental impacts, positions this study as a more impactful and forward-looking contribution in the offshore wind energy literature. Table I highlights comparative overview of key literature on the environmental impacts of offshore wind farms. The table summarizes focus areas, methodologies, coverage periods, mitigation strategies, and contributions of previous studies in relation to the current scientometric review.

2. Scientometric and Bibliometric Review

This section presents a quantitative mapping of the research landscape surrounding the environmental impacts of offshore wind farms, analyzing publication trends, geographic and institutional contributions, funding patterns, and keyword co-occurrence networks to establish the thematic foundation for the literature review that follows in Section 3.

2.1. Data Collection

This research leverages the Scopus database, a comprehensive and authoritative source of peer-reviewed literature across diverse fields, which includes 2250 active titles from 767 unique publishers. Scopus's extensive database ensures access to high-quality, reliable articles, particularly in critical areas such as biological sciences, social sciences, physical sciences, and health sciences. The advanced search functionality in Scopus was utilized to identify relevant studies within the timeframe of 2010–2025, specifically focusing on environmental impacts associated with offshore wind farms. The keywords, search string, and publication count used in this study are summarized in Table II.

The search strategy was carefully constructed by examining prior review methodologies and refining search terms through Boolean operators (AND, OR, NOT). The OR operator connected related keywords, while AND linked distinct thematic groups, and NOT excluded non-relevant terms to increase specificity. As a result, a total of 1208 peer-reviewed articles, comprising primarily of research articles and reviews, were identified. To ensure relevance, initial filtering was based on titles, abstracts, and keywords, followed by a more detailed review of the introduction, discussion, and conclusion sections for selected articles. This rigorous screening process resulted in a focused selection of studies that provides a robust foundation for further scientometric and thematic analysis.

2.2. Research Trends and Statistical Insights

The statistical analysis in this study draws insights from the data to inform conclusions about research trends, populations, and processes, aiding in evidence-based decision-making. In examining the core research questions, this analysis highlights patterns, relationships, and trends within the offshore wind farm environmental impact literature, offering a comprehensive view of the field's evolution. Specifically, the analysis reveals key metrics such as the annual growth in publications, the types of documents published, publication counts by country, prolific authors, and major funding sponsors that support this research area.

Fig. 1 shows the growth in publications on offshore wind farms' environmental impacts from 2010 to 2025. Research activity remained low until 2010 but began increasing steadily, with a notable surge from 2020 onwards. This rise aligns with heightened global efforts to expand renewable energy and address environmental concerns. By 2025, publication counts reached approximately 500, reflecting the growing focus on understanding and mitigating the ecological effects of offshore wind farms.

Fig. 2 depicts that research articles constitute the largest portion of publications (62%), followed by conference papers (23.7%) and reviews (6.3%). This distribution indicates a strong focus on original research within the field, with conference papers playing a key role in sharing preliminary findings. The presence of reviews suggests efforts to consolidate existing knowledge, while other formats, including book chapters and editorials, contribute minimally to the overall literature.

Building on the insights of different document types from Fig. 2, Fig. 3 further delineates the geographic landscape of scholarly contributions on offshore wind farms' environmental impacts. The concentration of research in China, the United States, and the United Kingdom, with China leading at 586 publications, underscores a focused commitment within regions that are at the forefront of offshore wind deployment. European countries, particularly Germany and Denmark, also contribute substantially, reflecting a robust alignment between policy support, investment in renewable energy infrastructure, and academic inquiry. The interplay between document type and geographic distribution, as depicted in Figs. 2 and 3, underscores a cohesive global effort to advance knowledge on the ecological implications of offshore wind energy, driven predominantly by nations actively shaping the field through both empirical research and strategic dissemination of findings.

Fig. 4 highlights the significant role of national and international

Table I

Comparative summary of key studies on offshore wind farm environmental impacts and mitigation approach.

Study	Title	Focus Area	Methods Used	Time Range Covered	Mitigation Strategies Covered	Scientometric/ Bibliometric Analysis	Industry Practices Included?	Positive & Negative Impacts Balanced?	Notable Contribution
This Study	*Balancing Energy and Ecology: Environmental Impacts of Offshore Wind Farms and Mitigation Strategies – A Scientometric Review*	Comprehensive environmental impacts + mitigation	Scientometric (VOSViewer + Scopus), thematic literature review	2010–2025	✓ Detailed (Tables III & IV)	✓ Extensive (keyword co-occurrence, density, funding, geography)	✓ Yes – multiple industry case studies	✓ Thoroughly addressed across all environmental impact categories	Combines scientometrics, policy, engineering, ecology, and industry mitigation in a single integrated study
Watson et al. (2025) Watson et al., (2025)	*Assessing, monitoring and mitigating the effects of offshore wind farms on biodiversity*	Biodiversity impacts of offshore wind farms	Narrative review	Up to 2025	✓ Mainly biodiversity focused mitigation	✗ No	~ Limited	~ Limited to biodiversity effects	Biodiversity focused mitigation and ecological assessment.
Watson et al. (2024) Watson et al., (2024b)	*Global impact of OWFs on ecosystem services*	Ecosystem services globally	Review of case studies	Until 2023	✓ Broadly discussed	✗ No	✗ No	✓ Discussed broadly	Focus on services, less on species-specific or policy/ industry practices
Farr et al. (2021) Farr et al., (2021)	*Potential environmental effects of deepwater floating OWFs*	Floating wind-specific impacts	Review-based impact assessment	Recent focus (2015–2021)	✓ Some mentioned	✗ No	✗ No	✓ Balanced	Focused on floating OWFs; doesn't include bibliometric data
Gill et al. (2014) Gill et al., (2014)	*Marine renewable energy, electromagnetic (EM) fields and EM-sensitive animals*	EMF-specific ecological effects	Narrative literature review	Up to 2014	✗ No	✗ No	✗ No	✗ Partial	Early work focused on EM-sensitive species; lacks broad thematic scope
Mangi (2013) Mangi (2013)	*Impact of OWFs on marine ecosystems from an ecosystem services perspective*	Ecosystem services	Conceptual analysis	Up to 2013	✗ No	✗ No	✗ No	✗ Emphasized positive services only	Introduced the ecosystem service framework but lacked mitigation focus
Leung & Yang (2012) Leung and Yang (2012)	*Wind Energy Development and its Environmental Impact*	General wind energy impacts	Literature synthesis	Before 2012	✗ Very limited	✗ No	✗ No	✗ Light discussion	Mainly on onshore wind; minimal marine-specific content

Table II
Keywords, search string and number of publications.

Keywords	Search String	No. of Publications
Offshore wind farm, Offshore wind energy, Offshore wind power, Environmental impact, Environmental effects, Ecological impact, Ecological effects, Environmental assessment, Marine environment, Ecosystem, Biodiversity, Habitat, Electromagnetic fields, EMF, Underwater sound, Vibration, Light, Heat, Artificial reef effect	(TITLE-ABS-KEY("offshore wind farm" OR "offshore wind energy" OR "offshore wind power") AND TITLE-ABS-KEY ("environmental impact" OR "environmental effects" OR "ecological impact" OR "ecological effects" OR "environmental assessment" OR "marine environment" OR "ecosystem" OR "biodiversity" OR "habitat" OR "electromagnetic fields" OR EMF OR "underwater sound" OR "vibration" OR "light" OR "heat" OR "artificial reef effect"))	**2250**

funding agencies in advancing research on offshore wind farms' environmental impacts. Leading contributors include the National Natural Science Foundation of China and the Ministry of Science and Technology of the People's Republic of China, reflecting China's strong research investment in this field. Other major funders, such as the Horizon 2020 Framework Programme and the U.S. Department of Energy, underscore the global commitment to understanding and mitigating environmental challenges associated with offshore wind energy. This distribution of funding sources indicates the prioritization of offshore wind research by countries heavily involved in renewable energy initiatives.

The Technical University of Denmark emerges as the leading institution in publication volume on offshore wind farms' environmental impacts, underscoring its significant contribution to advancing research in this field, as shown in Fig. 5. Other prominent contributors include the Royal Belgian Institute of Natural Sciences, Wageningen University & Research, and Ghent University, reflecting a strong European focus on offshore wind studies. This concentration aligns with substantial regional investments in offshore wind infrastructure, particularly in countries like Denmark, Belgium, and the Netherlands. Collectively, Fig. 5 highlights the critical role of these institutions in fostering scientific understanding and supporting sustainable practices within the offshore wind energy sector.

2.3. Keyword and Cluster Analysis

A scientometric review systematically tracks and evaluates the historical development of research on the environmental impacts of offshore wind farms, providing a quantitative map of influential studies and emerging trends within the field. By analyzing publication data, this review offers a visual and structural representation of the interrelationships among key research themes and topics. Scientometric analysis for this study was conducted using VOSViewer and Scopus to construct a network of co-occurring keywords, authorship patterns, and institutional affiliations, thereby revealing the thematic clusters and research frontiers. This approach enables a deeper understanding of the field's knowledge structure, highlighting prominent research areas such as ecosystem impacts, engineering challenges, policy considerations, and mitigation strategies. The resulting network not only demonstrates the interdisciplinary nature of the field but also facilitates the identification of research gaps and future directions for advancing sustainable offshore wind energy development.

The indexed keyword co-occurrence network in Fig. 6 visualizes the knowledge structure surrounding offshore wind farms' environmental impacts, segmented into five distinct clusters. The network includes 243 items, with 13,256 links and a total link strength of 59,549, indicating strong interconnectedness among key themes. Each cluster represents a thematic area within the research field. The red cluster centers on "wind power" and "environmental impact," covering topics like fossil fuels, greenhouse gases, and energy policy. The green cluster focuses on "ecosystems" and "biodiversity," linking terms related to marine life, habitat, and ecosystem assessments. The blue cluster relates to "offshore wind turbines," encompassing technical terms like foundations,

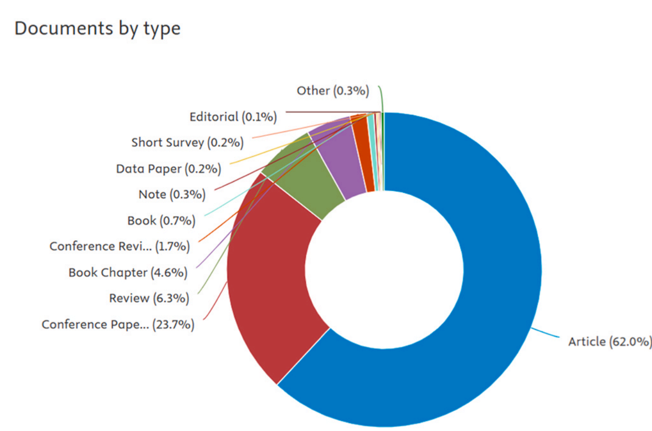

Fig. 2. Distribution of document types on offshore wind farms' environmental impacts.

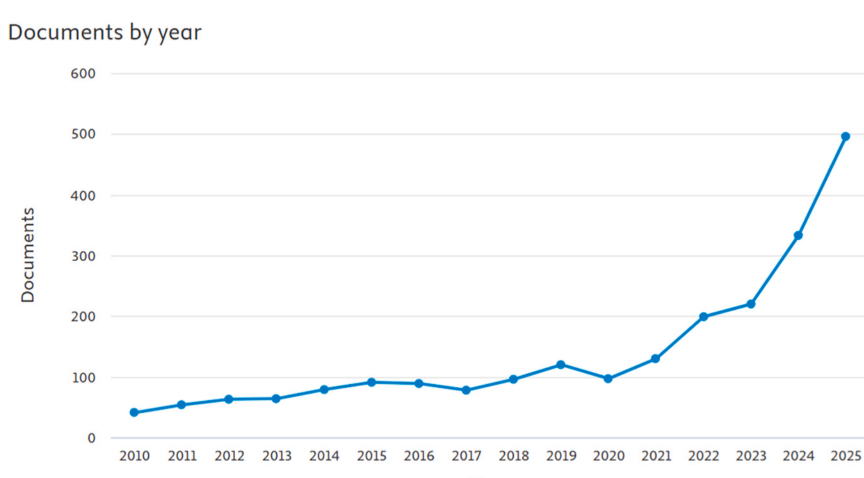

Fig. 1. Annual publication trends on environmental impacts of offshore wind farms (2010–2025).

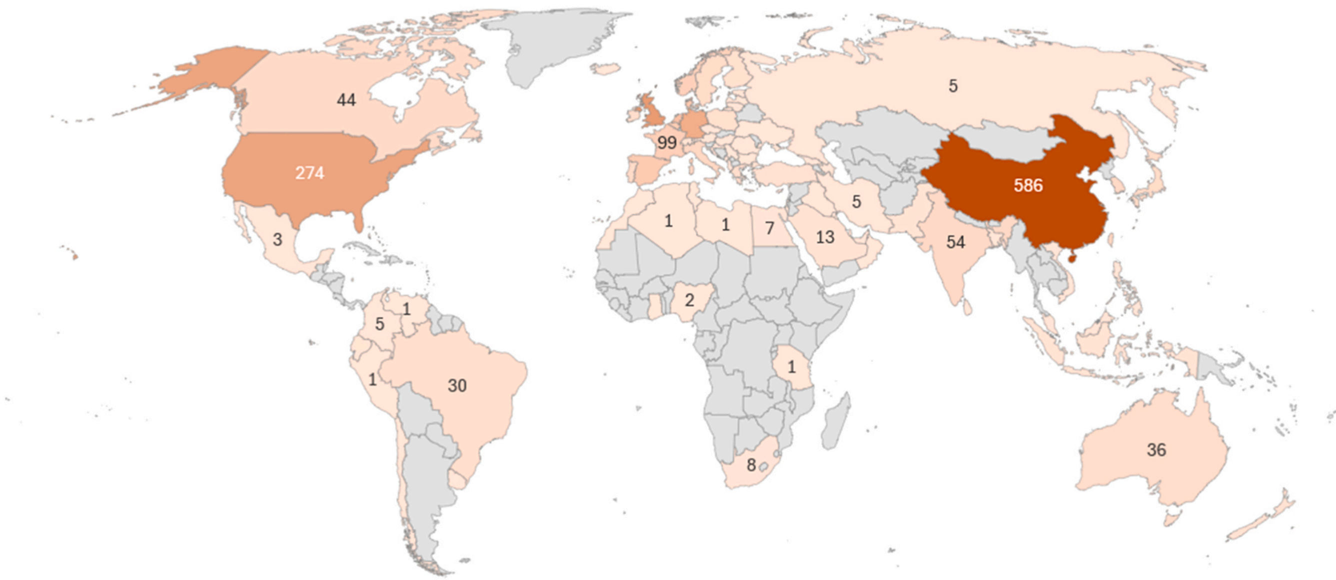

Fig. 3. Geographic distribution of publications on offshore wind farms' environmental impacts.

Fig. 4. Major funding sources for publications on offshore wind farms' environmental impacts.

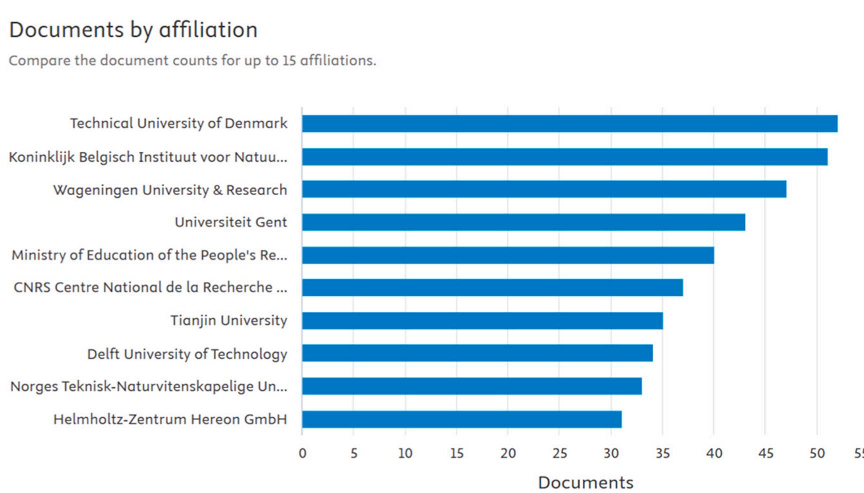

Fig. 5. Leading affiliations by number of publications on offshore wind farms' environmental impacts.

vibration analysis, and monopiles, highlighting the engineering aspects of offshore structures. The yellow cluster addresses "acoustic noise" and "pile driving," indicating studies on noise pollution and its effects on marine life. Finally, the purple cluster includes topics like "site selection" and "economics," reflecting broader decision-making and planning factors.

The VOSViewer-generated keyword co-occurrence network highlights core research themes surrounding "environmental impact" in

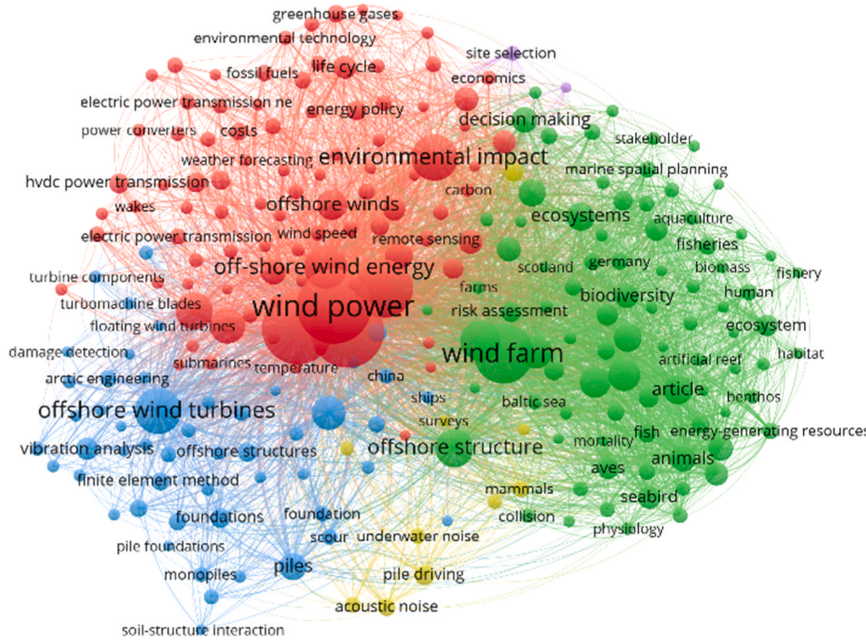

Fig. 6. All indexed keyword co-occurrence network.

offshore wind energy studies as shown in Fig. 7. The term "environmental impact," belonging to Cluster 1 with 224 links, a link strength of 2583, and 266 occurrences, indicates its central role in the research landscape. The network reveals five distinct thematic clusters. The red cluster focuses on "wind power" and sustainability topics like greenhouse gases and energy policy. The green cluster centers on "ecosystems" and "biodiversity," exploring impacts on marine habitats and wildlife. The blue cluster emphasizes engineering aspects of "offshore wind turbines," including foundations and vibration analysis. The yellow cluster addresses "acoustic noise" and underwater sound, reflecting noise impact concerns, while the purple cluster involves decision-making and site selection issues.

The density visualization map in Fig. 8, illustrates the concentration of research themes in the study of offshore wind farms' environmental impacts. High-density areas, indicated by warmer colors, reflect central topics such as "wind power," "environmental impact," "offshore wind turbines," and "wind farm," highlighting the primary focus on energy generation and its ecological consequences. Terms like "ecosystems," "biodiversity," and "renewable resource" also appear prominently,

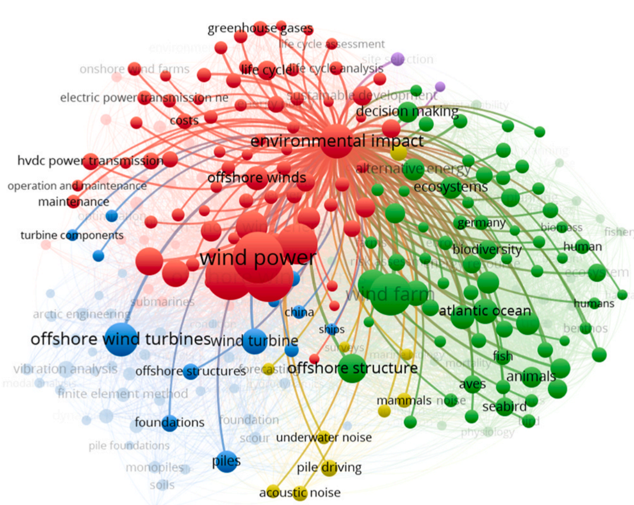

Fig. 7. "environmental impact" keyword co-occurrence network.

indicating a strong research emphasis on environmental and ecological considerations. The spread of keywords such as "acoustic noise," "pile driving," and "marine spatial planning" in cooler colors suggests secondary but relevant themes addressing specific impacts on marine life and spatial dynamics.

This visualization underscores the interconnected nature of offshore wind research, encompassing engineering, environmental, and policy-driven themes to address both energy and sustainability objectives.

Moreover, this network also demonstrates the multidisciplinary nature of offshore wind research, interlinking environmental science, engineering, and policy. The strong link strength and high occurrence of key terms suggest that research on the environmental impacts of offshore wind farms is both extensive and interconnected, driven by an urgent need to understand and mitigate the effects on marine ecosystems.

The keyword and cluster analysis presented in Section 2.3 provides the thematic basis for the subsequent literature discussion in Section 3. The identified clusters reveal the main research directions in offshore wind farm environmental studies, including ecosystem and biodiversity related impacts, engineering and structural considerations, acoustic noise and pile driving effects, and broader planning and policy concerns. Based on these cluster patterns, Section 3 is organized to examine the positive and negative environmental impacts of offshore wind farms, followed by mitigation strategies proposed by both the research community and industry. In this way, the scientometric findings do not only describe the research landscape quantitatively but also guide the thematic structure of the review.

3. Thematic Literature Review

Following the five keyword clusters identified in Section 2.3, this section examines the environmental impacts of offshore wind farms thematically, covering positive impacts, negative impacts, and mitigation strategies proposed by both the research community and industry.

3.1. Positive Environmental Impacts

Offshore wind farms (OWFs) are pivotal in transitioning to renewable energy, offering significant environmental benefits alongside energy generation. Below are the key positive impacts based on current

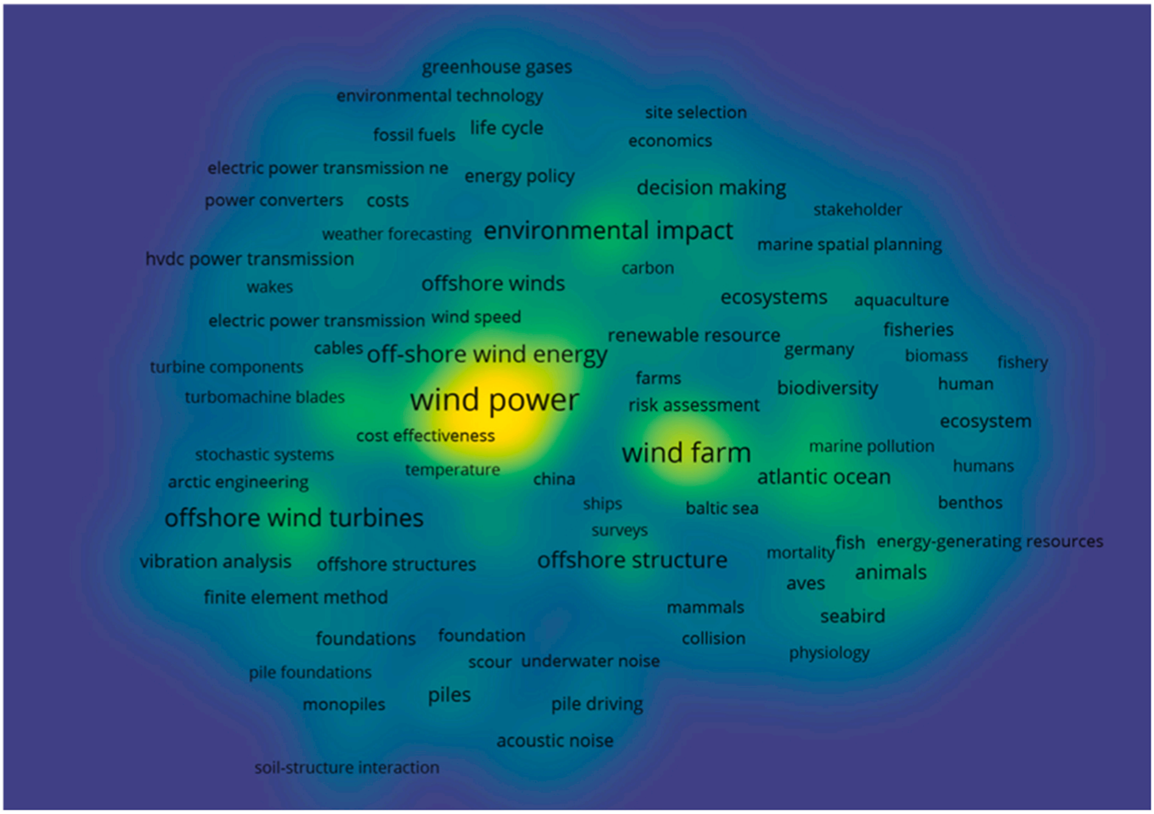

Fig. 8. Density visualization map of research on offshore wind farms' environmental impacts.

research and industry findings:

3.1.1. Marine Biodiversity Enhancement

Offshore wind farms significantly enhance marine biodiversity by serving as artificial reefs (Hockenos, 2022). The structural foundations of turbines offer hard surfaces that facilitate the colonization of marine organisms such as corals, sponges, and mollusks. Over time, these structures evolve into vibrant marine habitats, supporting a diverse array of species, including fish and crustaceans. This "reef effect" fosters ecological recovery, offering essential habitats for feeding, breeding, and sheltering marine life. Additionally, the restricted zones around turbines often function as marine protected areas (MPAs), limiting human activities like fishing and shipping, which allows marine populations to flourish undisturbed (Riefolo et al., 2016; Vaissière et al., 2014).

3.1.2. Climate Change Mitigation

OWFs significantly reduce greenhouse gas emissions, playing a crucial role in combating climate change. By replacing fossil fuel-based energy sources, offshore wind energy reduces the carbon footprint of electricity generation (Wang et al., 2019; Equinor). Life cycle assessments have shown that modern advancements in turbine technology and recycling strategies further reduce resource depletion, ensuring long-term sustainability (Leung and Yang, 2012; Li et al., 2022). These projects also contribute to biodiversity net gain by fostering habitat creation alongside emissions reductions (Vaissière et al., 2014).

3.1.3. Carbon Payback and Lifecycle Benefits

OWFs have an initial carbon footprint associated with the manufacturing, transportation, and installation of turbines and infrastructure. However, they achieve a carbon payback period relatively quickly—often within the first year of operation (Department of Climate Change, Energy, Environment and Water, 2024). Studies indicate that OWFs generate electricity with an average carbon intensity of approximately 6 g of CO_2 per kilowatt-hour, compared to coal-fired plants, which produce 900 g of CO_2 per kilowatt-hour (Wang et al., 2019). Over their typical 25-year lifespan, OWFs contribute minimal emissions, making them a sustainable and environmentally friendly alternative to fossil fuel-based energy systems (Bonou et al., 2016). This rapid offset of construction emissions underscores their role in reducing the overall carbon footprint of energy production.

3.1.4. Ecosystem Services and Conservation

The presence of OWFs contributes positively to ecosystem services by stabilizing marine environments and reducing industrial activities in their vicinity. By providing structured habitats, they support fish aggregation, benefiting commercial and recreational fisheries. Moreover, OWFs facilitate carbon sequestration, contributing to climate regulation while promoting ecological stability (Watson et al., 2024a). Floating wind farms open possibilities for renewable energy in deeper waters, reducing industrial impacts in nearshore areas (Rezaei et al., 2023).

3.1.5. Decommissioning Benefits

Partial decommissioning of OWFs sustains long-term environmental benefits. By leaving certain structures intact, they continue to serve as artificial reefs, supporting marine biodiversity even after their operational phase. This approach minimizes habitat disruption while balancing ecological preservation with structural removal (Hall et al., 2020, 2022). Tailored decommissioning strategies and environmental impact assessments (EIAs) ensure that OWFs maximize their long-term ecological contributions (Hall et al., 2022).

3.1.6. Advancement of Sustainable Policies

The integration of offshore wind farms into marine spatial planning promotes sustainable development by aligning with Good Environmental Status (GES) criteria. These policies ensure that OWFs not only minimize their ecological footprint but also contribute positively to marine conservation efforts. Streamlined licensing processes and innovative approaches adopted in mature markets like the UK and Denmark further exemplify global efforts to maximize OWFs' benefits (de Vasconcelos et al., 2022). Systematic reviews show that sustainable siting of OWFs aligns with global sustainability goals by mitigating land-use conflicts and enhancing marine biodiversity (Gkeka-Serpetsidaki et al., 2024).

3.2. Negative environmental impacts

Offshore wind farms (OWFs) are a pioneer of renewable energy, but their development is not without significant environmental concerns. The following outlines the key negative impacts based on current research and industry findings:

3.2.1. Marine Biodiversity Loss

OWFs can disrupt marine ecosystems during both construction and operation. Recent humpback whale deaths along the U.S. East Coast have raised concerns about links between offshore wind projects and marine mammal fatalities, calling for thorough environmental reviews (Associated Press). The installation of turbines disturbs the seabed, impacting the habitats of various marine species (Ayyildiz and Erdogan, 2024; Dannheim et al., 2020). Increased human activity, such as noise and sediment suspension, further stresses marine biodiversity (Dorrell et al., 2022; Bureau of Ocean Energy Management BOEM). These disruptions can lead to species loss in sensitive areas, undermining ecological stability (Bailey et al., 2014; Cai et al., 2023).

3.2.2. Wildlife Collisions

Birds and bats face collision risks with wind turbine blades, particularly during migration periods and in poorly planned wind farm locations (Bailey et al., 2014). Onshore evidence provides useful context for understanding turbine-related bird mortality. For example, Nilsson et al. (2023) estimated approximately 0.6 small passerine bird fatalities per turbine per GWh at onshore wind turbines (Nilsson et al., 2023). However, this value can differ in offshore wind farms because onshore environments are dominated by terrestrial passerines, raptors, and bats, and mortality estimates are usually based on carcass-search correction methods that are more feasible on land.

In offshore environments, collision risks change because the exposed species are mainly seabirds and migratory birds, and risk depends strongly on species-specific flight height, avoidance behaviour, weather visibility, distance from shore, and turbine layout (Johnston et al., 2014; Davies and Band, 2012; Fauchald et al., 2024). Unlike onshore sites, direct carcass recovery is extremely difficult at sea; therefore, offshore collision risk is commonly assessed through modelling, flight-height distributions, radar/GPS tracking, and seabird vulnerability mapping rather than direct mortality counts (Johnston et al., 2014; Fauchald et al., 2024; Desholm et al., 2006). Offshore studies also report collision estimates in different units; for example, work on the Nysted offshore wind farm estimated approximately 1.4 Common Eider collisions per turbine per year (Desholm et al., 2006). Therefore, collision risks in onshore and offshore wind farms should be interpreted separately, as both environments differ in species presence, flight patterns, exposure conditions, and monitoring approaches.

3.2.3. Sound Pollution

The construction phase, which involves pile driving and other activities, generates intense underwater noise. This acoustic disturbance can adversely affect marine mammals and fish, leading to behavioural changes, stress, or even physical harm (Mooney et al., 2020; Baltic Wind, 2024). Although operational noise is less intense, it continues throughout the wind farm's lifespan and may disrupt communication and navigation among marine species (Mooney et al., 2020; Cai et al., 2023).

3.2.4. Hydrographical and Structural Risks

OWFs can alter natural water flow and sediment dynamics. The placement of turbines may cause changes in sediment suspension and turbidity, fish migration, impacting water clarity and nutrient distribution (Dorrell et al., 2022; Bureau of Ocean Energy Management BOEM). These hydrographical alterations can contribute to local eutrophication, negatively affecting water quality and marine life (Bureau of Ocean Energy Management BOEM). Meanwhile, OWFs are vulnerable to operational accidents and structural failures that further threaten marine ecosystems. The collapse of a turbine blade in the Vineyard Wind project underscores the vulnerability of wind farm components to manufacturing defects or material fatigue (Magazine; The Martha's Vineyard Times, 2024). Such incidents can scatter debris into the ocean, potentially harming the marine ecosystem (Arcadis US, Inc., 2024).

3.2.5. Corrosion and Material Toxicity

The corrosion of turbine structures can release large quantities of metals into marine environments (Brijder et al., 2022). The survey of corrosion-protection system for offshore wind farms reports that galvanic anodes (typically ~95% aluminium, 2.5–5.75% zinc, 0.015–0.04% indium) are dissolving into seawater and sediment around turbines (Kirchgeorg et al., 2018; Hengstmann et al., 2025). Additionally, conventional protective coatings are themselves a potential source of toxic chemical release, which further endanger aquatic organisms (Juhl et al., 2024).

3.2.6. Electromagnetic Field (EMF) Effects

Submarine cables associated with OWFs generate electromagnetic fields, which can interfere with the navigation and communication of sensitive marine species, such as sharks and rays (Ibraheim and Khater, 2013; Hutchison et al., 2020; Gill et al., 2014; Hutchison et al., 2021). Measured magnetic-field intensities at or near the cable surface vary widely with cable type, configuration and load: HVAC/HVDC model and field measurements report peak B-fields spanning from < 1 μT up to several 100 s μT at the cable surface, with values dropping to background (tens of nT–μT) within a few meters to tens of meters depending on cable design and bundling (Hutchison et al., 2021).

3.2.7. Decommissioning Impacts

If not managed properly, the decommissioning process poses risks of further habitat disturbance and marine pollution. The complete removal of infrastructure can eliminate artificial reef habitats that may have formed during the operational phase, reversing the biodiversity benefits (Spielmann et al., 2023).

3.2.8. Carbon Footprint

While OWFs contribute to renewable energy, the manufacture, installation, operation, and eventual decommissioning of offshore wind turbines emit carbon dioxide (Wang et al., 2019). These emissions may offset some of the environmental benefits, especially during the initial phases. Most emissions happen once per turbine, but maintenance over its 25-year life adds about 10%, leading to around 6 g of CO_2 per kilowatt-hour of electricity produced (Ørsted).

3.3. Research-Based Mitigation Strategies

Table III illustrates key strategies proposed by the research community, including institutions like the National Renewable Energy Laboratory (NREL), the European Environment Agency (EEA), Northern Prairie Wildlife Research Center (NPWRC), Bureau of Ocean Energy Management (BOEM), Carbon Trust, SINTEF, Bird Life International, Norwegian Institute for Nature Research (NINA), and the International Energy Agency (IEA), along with research contributions from various studies, to mitigate the environmental impacts of offshore wind farms. These strategies include early-stage plan to integrate Marine Spatial

Table III
Mitigation of impact proposed by research community.

Topic	Focus	Brief Description	Critical Evaluation	Authors (Year)
Early-stage Assessments	Integrated Planning	Careful implementation of all the phases from exploration of the sites to decommissioning.	Effective in principle but requires strong regulatory enforcement and cross-sector coordination, which is inconsistent across jurisdictions.	(European Environment Agency, 2024)
	Site Selection	Choosing locations with minimal environmental impact.	Well-established practice but baseline ecological data quality varies significantly across regions, limiting reliability.	(Williams et al., 2024)
	Site Selection	Decision-making tools to search for a suitable new location for wind farms where the risk to wildlife is lower.	Useful for screening but tools require continuous updating as species distribution data evolves with climate change.	(Northern Prairie Wildlife Research Center NPWRC, 2023)
	Site Selection	Avoiding predicted high-risk areas for constructing new wind farms.	Effective when risk maps are comprehensive, but predictive models carry uncertainty in data-scarce regions.	(SINTEF, 2024); (Fauchald et al., 2024)
	Data Collection	Collecting crucial environmental and ecological data during the planning stage.	Fundamental to all downstream mitigation but often underfunded and conducted over insufficient baseline periods.	(Jones et al., 2025)
	Marine Spatial Planning (MSP)	This structured approach integrates environmental and social considerations in the offshore wind sector ensuring other marine activities smoothly.	Proven effective in mature markets such as the UK and Netherlands, but implementation is fragmented in emerging OWF regions.	(Spijkerboer et al., 2020)
	Environmental Impact Assessment (EIA)	Comprehensive frameworks for conducting EIAs specific to offshore wind projects based on the marine Good Environmental Status (GES).	Provides a structured legal framework but assessment quality depends heavily on the scope of ecological indicators selected.	(Abramic et al., 2022)
	Environmental Impact Assessment (EIA)	Assessing offshore wind impacts on marine mammals and seabirds in deep waters, highlighting the importance of strong baseline data and industry insights to refine risk assessments.	Highlights the critical role of baseline data but acknowledged limitations in monitoring coverage for deep-water species.	(Alawady et al., 2024)
	Multitrophic Modelling	Applying dynamic, multitrophic, multiscalar ecosystem modelling frameworks during the planning stage to assess cumulative OWF effects on shelf sea ecosystems.	Promising but computationally demanding and requires high-resolution species interaction data rarely available at proposed sites.	(Isaksson et al., 2025)
Marine Biodiversity	Robust Engineering Design	Ensuring turbines are designed to minimize disturbance to marine habitats.	Increasingly integrated into design standards but ecological performance varies by foundation type and seabed conditions.	(Ayyildiz and Erdogan, 2024)
	Mitigation Strategies	Limiting OWFs in high-biodiversity and protected areas. Region-Specific Impact.	Reduces direct habitat conflict but may displace development pressure to less studied areas with unknown ecological sensitivity.	(Farr et al., 2021)
Wildlife Collisions	Painting Turbine Blades with Black	At the Smola wind farm, bird mortality was reduced by 70% after one of the three rotor blades was painted black.	Strong field evidence from a single site; broader applicability across species assemblages and turbine sizes remains to be confirmed.	(May et al., 2020)
	Advanced Monitoring	Implementing real-time tracking to detect and address environmental disruptions early.	Technically effective but high installation and maintenance costs limit deployment at smaller or remote OWF sites.	(Ayyildiz and Erdogan, 2024)
	Preventing Bird Collisions	Active control of wind turbines by adjusting rotor speed.	Reduces collision risk effectively but results in energy production losses that require economic justification.	(Garcia-Rosa and Tande, 2023)
	Bird Curtailment	Radar and video-based systems, predictive curtailment, real-time local curtailment and bird migration predictive model.	High detection accuracy demonstrated but curtailment-induced energy losses create an economic trade-off that limits widespread adoption.	(Ballester et al., 2024)
	Automated Curtailment Systems	Reduce wildlife collision with wind turbines.	Effective for well-studied species but algorithm performance declines for rare or poorly monitored species with limited training data.	(McClure et al., 2021)
	Turbine Upscaling	Deploying higher-capacity turbine models reduces the total number of individual units in the wind farm, lowering the number of collision hazards in the airspace.	Supported by modelling evidence but upscaling also increases rotor diameter, which may offset collision risk reduction for some species.	(Johnston et al., 2014)
	Increasing Hub Height and Blade Clearance	Raising the minimum blade clearance above the sea surface positions the rotor-swept area above the primary low-altitude flight bands of most seabird species, allowing birds to pass safely beneath the rotor.	Effective for low-flying seabird species but offers limited benefit for high-altitude migrating raptors and passerines.	(Davies and Band, 2012)
Noise Mitigation	Construction Noise	Using bubble curtains and sound-dampening devices during construction. Monitoring noise levels and adjusting activities based on marine life presence.	Effective in calm sea states but performance degrades in strong tidal currents and deep water, limiting applicability at far-offshore sites.	(Mooney et al., 2020)
		Bubble curtains for noise reduction and species observers or passive acoustic for sensitive marine species detection during construction.	Combined approach improves both mitigation and detection but requires trained marine mammal observers, adding operational complexity.	(SEER, 2022)
		Scheduling high noise construction activities - specially pile driving, outside sensitive breeding, calving, and high occurrence periods of marine	Practical and low-cost but effectiveness depends on accurate species occurrence data,	(Degraer et al., 2013)

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Table III (*continued*)

Topic	Focus	Brief Description	Critical Evaluation	Authors (Year)
		mammals to reduce disturbance, displacement, and acoustic stress.	which is often incomplete in new development zones.	
	Operational Noise	Monitoring noise during operation and applying sound-dampening technology to minimize impact.	Operational noise levels are lower than construction noise but chronic long-term exposure effects on marine species remain insufficiently studied.	(Stöber and Thomsen, 2021)
	Both Operation and Constructional Noise	Real-time Passive Acoustic Monitoring (PAM), Vibratory Pile Driving, Prioritize low noise foundations, Sound field verification (SFV).	Comprehensive multi-tool approach but integration across all methods simultaneously requires substantial coordination and cost investment.	(Bureau of Ocean Energy Management (BOEM))
Ecological Balance	Nutrient Management	Ensuring OWFs are placed in areas with adequate water renewal to prevent eutrophication.	Preventive and cost-effective at the planning stage but difficult to enforce retrospectively for already-consented projects.	(Abramic et al., 2022)
Hydrographical Changes	Sediment Suspension Reduction	Optimizing turbine spacing and implementing techniques to control sediment suspension.	Modelling-based evidence is available but site-specific hydrodynamic conditions make generalization across locations challenging.	(Cai et al., 2023)
	Turbidity and Mixing Management	Optimizing turbine design and placement to minimize effects on water movement and turbidity.	Theoretically sound but quantitative field validation of turbidity reduction outcomes is limited in the current literature.	(Rivier et al., 2016)
	Eco-Friendly Structural Design	Designing turbine foundations to support natural water flow and promote habitat stability.	Increasingly adopted in newer projects but standardized design criteria for ecological flow compatibility are not yet established.	(Farr et al., 2021)
Decommissioning	Partial Decommissioning	Leaving structures as artificial reefs post-decommissioning to support marine life.	Documented biodiversity benefits at Belgian and Danish sites but regulatory frameworks for intentional reef creation vary significantly across jurisdictions.	(Spielmann et al., 2023)
	Careful Timing	Scheduling decommissioning to avoid sensitive species' breeding seasons.	Low-cost and practical but requires up-to-date species phenology data, which may be lacking for less-studied marine species.	(Spielmann et al., 2023)
	Multi-criteria Decommissioning Assessment	A multi-criteria framework integrating life cycle assessment, benthic biodiversity evaluation, and public preferences to identify optimal decommissioning scenarios, from full removal to partial retention of foundations as artificial reefs.	Transferable and comprehensive but data-intensive; practical adoption depends on availability of long-term ecological monitoring records at the site.	(Stranddorf et al., 2026)
Corrosion	Substitute Toxic Materials	Developing eco-friendly coating materials and applying Life-Cycle Assessment (LCA) principles to evaluate sustainability.	Promising but bio-based alternatives currently have shorter service lives than conventional coating, requiring more frequent maintenance.	(Juhl et al., 2024)
	Predictive Maintenance	Using condition-based maintenance to prevent severe corrosion-related issues.	Technically mature onshore but offshore deployment is constrained by accessibility challenges and the cost of remote sensor infrastructure.	(Brijder et al., 2022)
Electromagnetic Fields	EMF Shielding	Applying cable shielding techniques to reduce the impact of electromagnetic fields on marine life.	Cable burial is the most reliable mitigation measure but introduces seabed disturbance during installation, creating a short-term ecological trade-off.	(Gill et al., 2014); (Hutchison et al., 2021)
Predictive Maintenance	Lubricant Leakage Prevention	Applying condition monitoring, oil condition analysis, vibration monitoring, and SCADA based anomaly detection before severe failure occurs.	Systems are technically effective, but offshore deployment costs are high and real-time data transmission from remote turbines remains a practical challenge.	(Qiao and Lu, 2015); (Cardoni et al., 2021)

Planning (MSP) and Environmental Impact Assessments (EIA) to ensure a structured approach to sustainable offshore wind development. In addition, robust turbine engineering to minimize marine habitat disruption, noise reduction techniques during both construction and operation, and the use of eco-friendly materials to prevent corrosion. Moreover, optimized turbine placement is recommended to maintain ecological balance and partial decommissioning is proposed to transform retired structures into artificial reefs to support marine biodiversity. Further, electromagnetic field (EMF) shielding, predictive maintenance, and adaptive management strategies based on real-time monitoring allow for proactive responses to environmental changes, reducing harm to marine species.

3.4. Industry-Based Mitigation Strategies

Table IV depicts mitigation efforts adopted by industry leaders such as Ørsted, RWE, Vattenfall, Siemens Energy, Siemens Gamesa, and Hitachi Energy to minimize environmental impacts. Noise reduction methods, such as bubble curtains, vibratory pile driving, jetting technology, and quieter foundation technologies, are employed to reduce underwater noise pollution and its detrimental impact on marine life. Industries enhance the artificial reef effect, designing turbine foundations that attract marine life and promote ecosystem stability to support biodiversity. Additionally, artificial nests have been installed to protect seabirds, and turbine blade colour modifications have been implemented to reduce bird collisions.

The industry also prioritizes environmental monitoring programs, real-time marine life monitoring, integrating AI-powered biodiversity tracking and eDNA analysis to assess ecological impacts. Further, advanced cable shielding and burial techniques mitigate the effects of EMFs, while sustainable innovations such as low-carbon steel towers, recyclable turbine blades, and circular value chain initiatives demonstrate the industry's long-term environmental commitments

4. Limitations and Future Directions

While this review offers a broad and systematic mapping of the field, certain methodological limitations should be acknowledged. The scientometric search was conducted exclusively through the Scopus database, and relevant studies indexed only in Web of Science or Google

Table IV
Mitigation of impact proposed by industry.

Topic	Focus	Brief Description	**Critical Evaluation**	Industry (Year)
Noise Reduction	Bubble Curtain Technology	Reducing impact of noise on marine life during pile driving.	Widely deployed and field-proven, but effectiveness is site-specific and can decline under strong currents and greater water depths because bubble dispersion and air-volume requirements increase.	(Ørsted, 2025)
	Bubble Curtain Technology	Reducing underwater noise by up to 90% during the construction.	High noise attenuation is reported, but performance depends on site-specific parameters such as airflow, nozzle spacing, current, waves, and water depth, requiring project-specific calibration.	(Hitachi Global Air Power, 2025)
	Jetting Technology for Monopile Installation	This technology completely replaced the conventional pile driving method and reduced noise by over 99%.	Exceptional noise reduction performance but applicability is limited to specific seabed types; unsuitable for hard rock substrates and not yet proven for very large monopiles above 10 m diameter.	(Baltic Wind, 2024)
	Vibratory Pile Driving	Using vibration instead of hammering to reduce underwater noise emissions.	Reduces impulsive noise effectively but generates continuous low-frequency vibration that may still affect fish behaviour and has not been fully assessed for chronic exposure effects.	(Durakovic, 2021)
	Suction Bucket and Gravity-Based Foundations	Quiet offshore wind fixed foundation technology.	Eliminates pile driving noise entirely but is currently limited to softer seabed conditions and has not been demonstrated at commercial scale for turbines above 10 MW.	(Kihlström, 2017)
	Hydrosound Damper	Hydrosound damper systems use nets or frames fitted with gas filled elastic elements and foam materials around the pile to absorb and scatter underwater sound during offshore pile driving.	Effective across a broad frequency range and does not require compressed air supply, but installation and retrieval add operational complexity and cost compared to bubble curtains.	(Elmer and Savery, 2014)
	Encapsulation Curtain	Encapsulation curtain systems enclose the pile driving area with a physical curtain to reduce direct sound propagation into the surrounding marine environment.	Achieves consistent noise reduction of 13–17 dB and performs well in tidal currents where bubble curtains fail, but the steel enclosure requires significant vessel capacity for deployment.	(Bellmann et al., 2020)
	Combined Noise Mitigation Systems	Combining methods such as big bubble curtains, hydrosound dampers, and encapsulation systems can improve underwater noise attenuation compared with using a single technique, especially for large monopile installation.	Can achieve high attenuation levels, with reported reductions up to 24 dB, but require coordination of multiple systems, additional offshore equipment, and higher installation costs.	(Noise and Team, 2024)
Wildlife and Biodiversity	Artificial Reef Effect	Attracting marine life and enhancing biodiversity by providing hard surfaces and habitat structures for colonization.	Well-documented ecological benefit at multiple European OWF sites, but reef quality depends strongly on foundation type, scour-protection material, surface texture, and water depth, and may favour non-native species in some regions.	(Dickson, 2024); (RWE, 2024a)
	Artificial Nest	Artificial nesting structures were built offshore/ nearshore to provide nesting habitat for black-legged kittiwakes as compensation for potential OWF impacts.	Innovative and targeted compensation approach for kittiwakes, but its long-term success depends on colonization, breeding productivity, and monitoring; broader applicability to other seabird species remains limited.	(Ørsted, 2023; reNEWS)
	Painting Turbine Blades with Black	Painting one out of three turbine blades black to increase rotor visibility and reduce bird collision risk; effectiveness was monitored using cameras, motion/vibration sensors, thermal imaging, and 3D bird radar.	Field evidence from Smøla suggested strong collision reduction, but the later Eemshaven industry pilot did not find a significant reduction, showing that effectiveness may depend on site background, species composition, and local conditions.	RWE (2025)
	Sustainable Food Production	Win@Sea Project integrates cultivation of algae, mussels and seaweed in the offshore wind farms.	Promising co-use concept with biodiversity and economic co-benefits but faces regulatory barriers related to food safety certification in marine industrial zones and logistical challenges for harvest operations.	(Vattenfall, 2023)
Ecosystem Monitoring	Initiating DemoSATH Lab	Monitoring environmental impacts, underwater noise, bird activity, and marine life interactions.	Comprehensive multi-parameter monitoring platform but findings are site-specific to floating OWF conditions and may not be directly transferable to fixed-bottom installations.	(RWE, 2024b)
	Enhanced Biodiversity Monitoring	Initiated the SeaMe project, which employs AI-powered cameras both underwater and on the turbines, along with environmental DNA (eDNA) technology to identify biodiversity. The project takes a holistic, ecosystem-based approach to data collection and analysis.	Technically advanced and capable of detecting a wide range of species non-invasively, but eDNA methods require standardized protocols for data interpretation and AI camera systems need extensive training data to achieve reliable species identification.	(DHI, 2024)
	WhaleAlert App	This application will track whale's location and sends real-time information to mariners to help vessels avoid collisions.	Effective for whale–vessel collision avoidance near offshore wind activity, but it depends on consistent whale-detection data input and may have limited coverage in remote or deep-water areas with sparse monitoring infrastructure.	(Ørsted)

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Table IV (*continued*)

Topic	Focus	Brief Description	**Critical Evaluation**	Industry (Year)
	FINO Research Platform	FINO research platforms in the North Sea and Baltic Sea provide long term offshore monitoring data on meteorological, oceanographic, ecological, and environmental conditions.	One of the most comprehensive long-term OWF environmental monitoring programmes globally, but platforms are fixed at specific locations and cannot capture spatial variability across the broader OWF development zone.	(Federal Maritime and Hydrographic Agency BSH, 2003–2009)
EMF Reduction	Cable Shielding and Burial	Advanced shielding and burial reduce EMF exposure to sensitive species.	Cable burial is the most effective and widely adopted EMF mitigation measure, but the burial process introduces localized seabed disturbance during installation, creating a short-term ecological trade-off that is rarely assessed systematically.	(Vattenfall Wind Power Ltd., 2018); (Hutchison et al., 2021)
Recycling	Low-Carbon Steel Towers and Blades from Recycled Materials	Buy and install at least 25% low-carbon steel towers in joint projects. Also, making new blades by breaking down old blades and reusing the epoxy resin.	Represents a meaningful supply chain decarbonization commitment but the 25% target leaves substantial room for improvement, and the availability of certified low-carbon steel at the volumes required for large-scale OWF development remains a supply chain constraint.	(Vestas, 2023)
	Recyclable Blades	Circular value chain, waste management and concrete opportunities.	Addresses one of the most persistent end-of-life challenges in the wind sector but chemical recycling infrastructure for recovered materials remains limited globally, constraining scalability beyond early commercial deployments.	(Siemens Gamesa)
		Siemens Gamesa Recyclable blades are being used at RWE's Sofia offshore wind farm in the United Kingdom. The recyclable blades use a special resin system that allows blade materials to be separated and recycled at the end of operational life.	Landmark commercial deployment demonstrates technical feasibility at scale but long-term recycling quality and the availability of downstream chemical processing facilities at sufficient capacity will determine whether this becomes an industry standard.	(RWE Offshore Wind, 2023)
Eco-friendly Electrical Infrastructure	Innovative, Compact and Reliable Transformers and Switchgear Solutions	Innovative, compact, and reliable transformers and switchgear solutions ensure resilience against sudden movements, strong vibrations, salt mists, and corrosion. Eco-friendly WindSTAR transformers use biodegradable ester fluids for insulation, enhancing fire safety and sustainability.	Biodegradable ester fluids represent a clear improvement over conventional mineral oil in terms of environmental risk from leakage, but their higher cost and the limited availability of servicing infrastructure offshore may slow adoption across the broader industry.	(Hitachi Energy, 2022)

Scholar may not have been captured. Additionally, the Boolean keyword-based search strategy, while carefully constructed, carries an inherent risk of excluding studies where relevant concepts appear under alternative terminology. Furthermore, as a scientometric and thematic review, this study does not generate or validate primary experimental data, and conclusions regarding the effectiveness of mitigation strategies are therefore dependent on the quality and representativeness of the existing reviewed literature. The temporal boundary of January 2024 also means that more recent publications fall outside the scope of the analysis, although key 2025 and 2026 studies have been incorporated during revision.

As offshore wind energy continues to expand globally, interconnected priorities emerge for future research and practice, as illustrated in Fig. 9. Sustainable technology advancement remains central to reducing the environmental footprint of offshore wind development. Future efforts should prioritize eco-friendly turbine materials, improved recycling processes, and corrosion-resistant coatings (Jensen and Skelton, 2018). Enhancements in noise reduction technologies alongside EMF shielding can further mitigate adverse effects on marine life (Dähne et al., 2017; CMACS, 2003). The expansion of floating wind farms into deeper waters also presents an opportunity to reduce ecological disturbances in coastal regions, though this transition requires robust engineering solutions and comprehensive environmental impact assessments (Danovaro et al., 2024).

Ecosystem-based management approaches are essential for ensuring that offshore wind farms coexist harmoniously with marine biodiversity. Adaptive management strategies informed by ecosystem dynamics and long-term monitoring can optimize turbine placement and operational

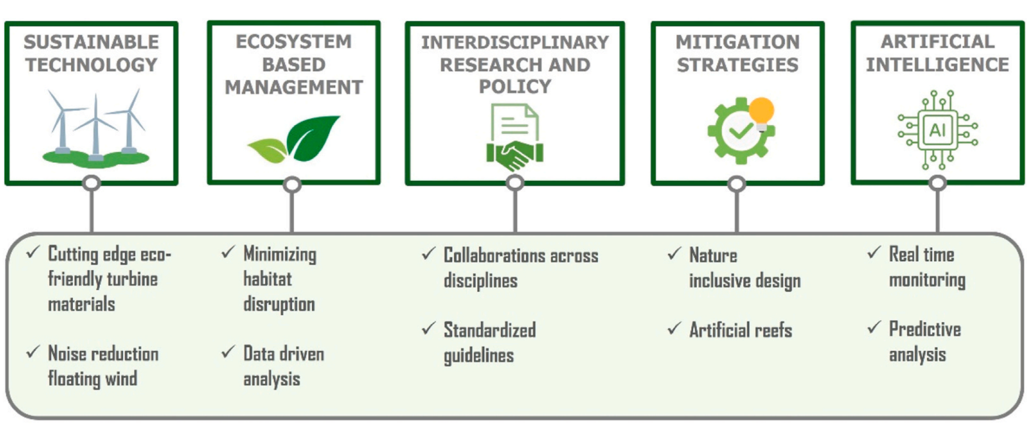

Fig. 9. Future aspects of renewable energy in marine environments.

practices to minimize habitat disruption (Galparsoro et al., 2022). A dedicated systematic comparison of nearshore and far-offshore wind farm environmental impacts also represents a valuable direction for future research, as nearshore fixed-bottom installations interact more intensively with coastal bird flyways and shallow benthic communities, whereas far-offshore floating installations present distinct challenges related to deeper water foundation disturbance, longer export cable routes, and reduced accessibility for ecological monitoring.

Innovative mitigation strategies, particularly nature-inclusive foundation designs and the deliberate creation of artificial reef structures around turbine bases, offer promising pathways for enhancing marine biodiversity at operational wind farm sites (Degraer et al., 2020; Raoux et al., 2017). The multi-criteria decommissioning framework proposed by (Stranddorf et al., 2026) further demonstrates how end-of-life decisions can be optimized to balance ecological, environmental, and societal outcomes simultaneously.

Interdisciplinary research and global policy harmonization are vital for addressing the complex interactions between offshore wind energy and marine ecosystems. Collaborative studies between marine biologists, engineers, and policymakers are necessary to explore cumulative impacts, species-specific responses, and ecosystem services (Copping et al., 2020). Establishing standardized guidelines and mitigation frameworks across regions will ensure consistent environmental practices and facilitate knowledge exchange, aligning sustainability goals with energy development (Dibo et al., 2025).

Artificial intelligence represents a transformative frontier for environmental management in the offshore wind sector. Real-time AI-powered monitoring systems enable continuous biodiversity tracking, early detection of ecological disturbances, and dynamic curtailment decisions, while predictive analytics can support proactive maintenance and reduce unplanned environmental risks (Song et al., 2024; Das et al., 2024). Integrating AI with eDNA sampling and autonomous survey technologies offers a particularly promising pathway for cost-effective, high-resolution ecological surveillance at operational OWF sites.

5. Conclusion

Offshore wind farms have emerged as a cornerstone of sustainable energy development, contributing significantly to climate change mitigation and energy security. While OWFs offer notable ecological benefits, such as artificial reef formation, carbon emissions reduction, and enhanced biodiversity; they also pose challenges to marine ecosystems, including noise pollution, habitat disruption, and electromagnetic interference.

This review presents a comprehensive assessment of both positive and negative environmental impacts, integrating scientometric analysis with thematic literature evaluation. It highlights innovative mitigation strategies introduced by researchers and industry leaders, including noise reduction technologies, EMF shielding, sustainable materials, and adaptive monitoring systems.

Despite these advances, knowledge gaps remain, particularly regarding long-term ecosystem responses. Moving forward, sustainable offshore wind development will require interdisciplinary collaboration, continuous environmental monitoring, and harmonized policy frameworks. By addressing these priorities, offshore wind energy can evolve as a model for ecologically responsible renewable energy deployment, fostering a sustainable balance between energy generation and marine conservation.

CRediT authorship contribution statement

Joya Biswas: Writing – review & editing, Writing – original draft, Investigation. **Prangon Das:** Writing – review & editing, Writing – original draft, Methodology.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Open AI in order to grammatical corrections only. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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