Marine Environmental Research 216 (2026) 107916

Contents lists available at ScienceDirect

Marine Environmental Research

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

Electromagnetic fields from submarine power cables: A 35 Year synthesis of effects on aquatic biota

Elizabeth James [a,*], Mojtaba Ghodsi [b], Alex T. Ford [a,**]

[a] Institute of Marine Science, School of the Environmental and Life Sciences, University of Portsmouth, UK
[b] Faculty of Technology, School of Electrical and Mechanical Engineering, University of Portsmouth, UK

ARTICLE INFO

Keywords:
Marine renewable energy
Environmental impact
Magnetoreception
Behavioural ecology
Physiological responses
Marine spatial planning
Early life stages
Sex-specific responses

ABSTRACT

Submarine power cables (SPCs) associated with offshore renewable energy developments emit electromagnetic fields (EMFs) that can influence aquatic biota. Although research on this topic has increased, a comprehensive, systematic synthesis of observed effects across taxa and life stages, and biological contexts has been lacking. Following PRISMA 2020 guidelines (PROSPERO ID: 1138188), we systematically reviewed peer-reviewed and grey literature published between 1990 and 2024. Of 1637 records screened, 67 eligible field and laboratory studies were included. Significant behavioural and physiological responses to EMF exposure were reported in 66% of studies, with early life stages (embryos, larvae, juveniles) and magnetosensitive taxa, particularly fishes and crustaceans being most frequently affected. Effects occurred even at environmentally relevant intensities (<250 μT). Laboratory experiments more frequently detected effects than field studies, which were generally fewer, shorter in duration, and methodologically heterogeneous. Sensitivity heatmaps identified developmental stages and freshwater species as particularly sensitive, with notable taxonomic disparities. EMFs from SPCs can elicit ecologically relevant responses in aquatic biota, particularly during sensitive developmental windows and in magnetically responsive taxa. Emerging evidence further indicates that sex specific responses represent an important and previously under recognised dimension of EMF sensitivity. However, major uncertainties persist regarding chronic, population and ecosystem level impacts. Future research should prioritise standardisation of exposure characterisation and reporting, routine inclusion of sex and life stage as biological variables and co-ordinated laboratory to field validation. Integrating EMF considerations into marine spatial planning, environmental regulation, and biodiversity conservation frameworks will be essential to support proportionate ecological risk assessment and management of offshore renewable energy infrastructure.

1. Introduction

The transition to green energy, primarily driven by increasing global demand for cleaner, renewable sources of electricity, poses significant environmental challenges to marine ecosystems (Degraer et al., 2020; Isaksson et al., 2023). As nations strive to meet climate targets, there has been a rapid expansion of offshore wind farms (OWFs) and island interconnectivity, accompanied by a corresponding increase in the installation of submarine power cables (SPCs) (Gandini et al., 2024). SPCs are essential for transmitting electricity from marine renewable energy devices (MREDs), and for international interconnectors, thereby supporting the decarbonisation of energy systems. However, while SPCs provide clear sustainability benefits, they also introduce anthropogenic pollution into aquatic ecosystems through the emission of electromagnetic fields (EMFs), stressors that remain insufficiently integrated into environmental assessments and marine biodiversity protection frameworks.

SPCs generate both electric fields (E-fields) and magnetic fields (B-fields), which in conductive seawater may induce secondary electromagnetic fields (Cada et al., 2011; Hutchison et al., 2020a,b). The characteristics of these emissions vary according to cable type, operational load, and configuration. Alternating current (AC) cables,

* Corresponding author. University of Portsmouth, School of the Environment and Life Sciences, University House, Winston Churchill Avenue, Portsmouth, PO1 2DT, UK.
** Corresponding author. University of Portsmouth, School of the Environment and Life Sciences, University House, Winston Churchill Avenue, Portsmouth, PO1 2DT, UK.
E-mail addresses: Elizabeth.james@port.ac.uk (E. James), alex.ford@port.ac.uk (A.T. Ford).

https://doi.org/10.1016/j.marenvres.2026.107916
Received 16 October 2025; Received in revised form 2 February 2026; Accepted 9 February 2026
Available online 9 February 2026

commonly used for inter-array connections, produce low frequency, oscillating E− and B-fields in the range of 0.04–18 μT at 50–60 Hz (Cada et al., 2011; Hermans et al., 2024; Hutchison et al., 2020a,b). Direct current (DC) export cables, transmitting electricity over long distances, generate static fields typically ranging from 50 to 275 μT, with peaks up to 3200 μT under high load (Cada et al., 2011; Hutchison et al., 2020a,b; Kavet et al., 2016; Scott et al., 2021; Woodruff et al., 2013), Fig. 1. Some older monopolar systems and experimental set-ups report higher values, in extreme cases reaching several millitesla (Albert et al., 2020; Taormina et al., 2018). While burial alters the distribution of fields in the aquatic environment, it does not attenuate them, as propagation is governed by the Biot–Savart law unless conductive materials are present in the substrate (Bochert and Zettler, 2004, 2006). These physical distinctions are ecologically important: some taxa detect magnetic fields, others electric fields, and a subset may respond to both (White et al., 2017).

Electromagnetic emissions from SPCs are considered in environmental impact assessments (EIAs) and licensing processes; however, treatment remains inconsistent across jurisdictions and is frequently limited in scope (Hutchison et al., 2020a,b; Scott et al., 2021). Methodological standards for EMF characterisation and biological testing are not uniformly applied, restricting comparability across studies and limiting integration into risk assessments. Moreover, as OWFs expand globally and cable routes increasingly intersect productive coastal waters and, in some cases, biodiversity hotspots (Hermans et al., 2024; Hutchison et al., 2020a,b; Preziosi et al., 2024), exposure risk to a wide range of species and life stages grows in ecological relevance.

The body of scientific evidence is heterogeneous, spanning laboratory experiments with magnetic coils, in situ monitoring around operational cables, and species-specific exposure trials (Andrulewicz et al., 2003; Kuhnz et al., 2008; Sherwood et al., 2016). While methodological inconsistency reduces cross-study comparability, these studies nonetheless provide cumulative insight into possible modes of interaction and highlight taxa of concern (Albert et al., 2020; Hutchison et al., 2021). Importantly, many laboratory experiments employed proxy exposures at intensities exceeding those generated by modern bipolar DC or three phase AC systems, raising questions about ecological realism (Bochert and Zettler, 2004; Taormina et al., 2018). Distinguishing responses to magnetic versus electric fields, and to AC versus DC exposures, is therefore essential for interpreting biological outcomes and informing marine management and conservation strategies.

Previous reviews have summarised SPC EMF impacts, but most are narrative in structure, region-specific, or limited in analytical scope (Albert et al., 2020; Copping, 2016; Gill, 2005; Hermans et al., 2024; Hutchison et al., 2020a,b; Taormina et al., 2018). This review applies Preferred Reporting Items for Systematic reviews and Meta Analyses (PRISMA) guidelines to provide a structured and transparent synthesis of the available evidence, ensuring methodological rigour in line with best practices for systematic reviews. We synthesise 67 peer-reviewed studies published over the past 35 years, critically appraising their methodological quality, quantifying evidence strength, and identifying trends across taxa, life stages, and exposure contexts. In addition, we project the potential global spatial footprint of SPC networks to 2050 and outline an urgency ranked research agenda. By providing an objective and transparent evidence synthesis, this review aims to inform both scientific understanding and the development of robust marine environmental assessment and policy frameworks.

This systematic review addresses five research questions:

1. What biological responses to SPC generated EMFs have been documented across aquatic taxa, life stages, and sexes, and what patterns emerge across marine ecosystems (with reference to freshwater systems where relevant)?
2. How do reported responses in behavioural studies compare with those in physiological studies, and what similarities, differences, and knowledge gaps are evident between these two domains in relation to marine biodiversity?
3. To what extent do methodological factors (e.g. laboratory versus field setting, AC versus DC exposure, EMF intensity, and exposure duration) explain variability in reported biological responses?
4. What critical knowledge gaps remain in the current literature, particularly with understudied taxa, ecosystems, and study designs that constrain interpretation for marine environmental risk assessments?
5. What overarching trends, areas of consensus, and unresolved uncertainties can be identified, and how can future research be sequenced according to feasibility and ecological relevance?

2. Materials and methods

A systematic literature review was conducted to assess the biological impacts of EMFs generated by SPCs on aquatic organisms. This review followed the PRISMA 2020 guidelines (Page et al., 2021) to ensure transparency, reproducibility, and comprehensive coverage of relevant studies. The review protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO;

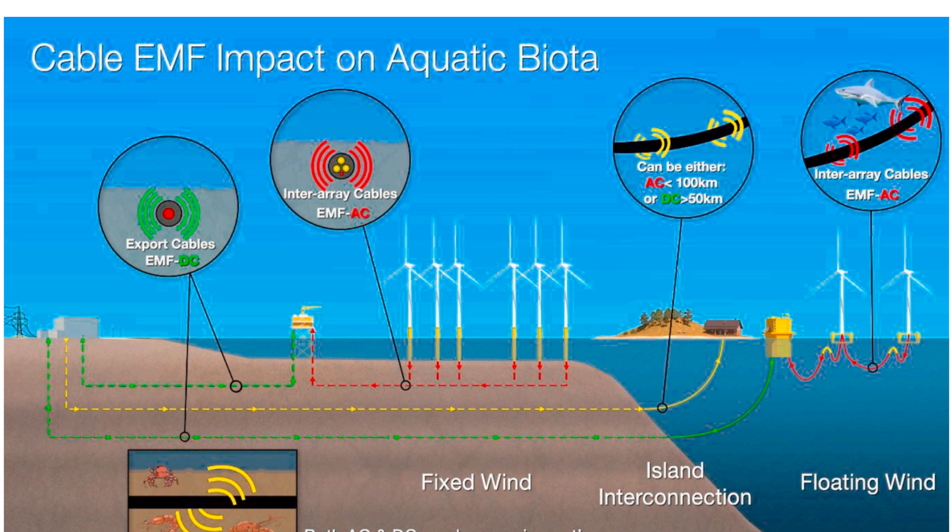

Fig. 1. Schematic of Submarine Power Cables (SPC) AC/DC potential electromagnetic field (EMF) Impact on Aquatic Biota.

Registration ID: 1138188). To ensure methodological robustness, reporting was additionally informed by complementary standards for systematic reviews (Whaley and Roth, 2022).

2.1. Literature search Strategy

Peer-reviewed studies published between 1990 and 2024 were identified using multiple scientific databases, including Google Scholar, Web of Science, EBSCO, ScienceDirect, and PubMed. Search terms combined keywords related to EMF, submarine power cables, aquatic environments, and biological responses. The final Boolean search strings included variations of: ("Electromagnetic*" OR "Electromagnetic field*" OR "EMF*" OR "MF*" OR "Magnetic Field*" OR "Static Magnetic Field*" OR "Anthropogenic magnetic Field*" OR "Anthropogenic") AND ("Submarine Power Cable*" OR "SPC*" OR "Cable*" OR "Underwater Cable*" OR "Subsea Power Cable*") AND ("Marine Renewable Energy Device*" OR "Marine Renewable Energy" OR "MRED* OR "Renewable Energy" OR "Offshore Renewable*" OR "Offshore Wind Farm*" OR "Wind Farm*") AND ("Marine organism*" OR "Marine environment" OR "Aquatic" OR "Freshwater" OR "Ecosystems" OR "Fish" OR "Crustacea*" OR "Invertebrate*" OR "Mollusc*" OR" Echinoderm*" OR "Polychaete") AND ("Behavio*r*" OR "Physiologic*"). Duplicates, non-peer-reviewed articles, and irrelevant publications were excluded. In addition, the reference lists of key reviews and empirical studies were screened for further eligible publications. A PRISMA flow diagram summarising the identification, screening, and inclusion process is provided in Fig. 2.

2.2. Inclusion criteria

Studies were included if they were published between 1990 and 2024; investigated behavioural, physiological, or developmental responses of aquatic organisms; focused on EMF exposure levels relevant to operational SPC conditions, defined here as up to 3200 μT (Bochert and Zettler, 2004, 2006). Both AC and DC fields were considered, and eligible study designs included laboratory experiments, field investigations, or combined approaches. Publications were excluded if they did not involve aquatic biota, investigated EMFs unrelated to SPCs (for example, medical imaging or terrestrial exposure), or lacked sufficient methodological detail to enable appraisal.

2.3. Data extraction and categorisation

From each included study that met the eligibility criteria, key variables were systematically extracted and categorised. These included the reported EMF strength, grouped into categories of ≤250 μT, ≤500 μT, ≤1000 μT, ≤3200 μT), and the taxonomic group investigated, such as fish, crustacea, molluscs, polychaetes, echinoderms or others. Information was also collected on the life stage (adult, juvenile, or early development); the type of biological response assessed (behavioural, physiological, or both), the environmental setting (marine, freshwater, or estuarine), the experimental design (laboratory, field, or combined)

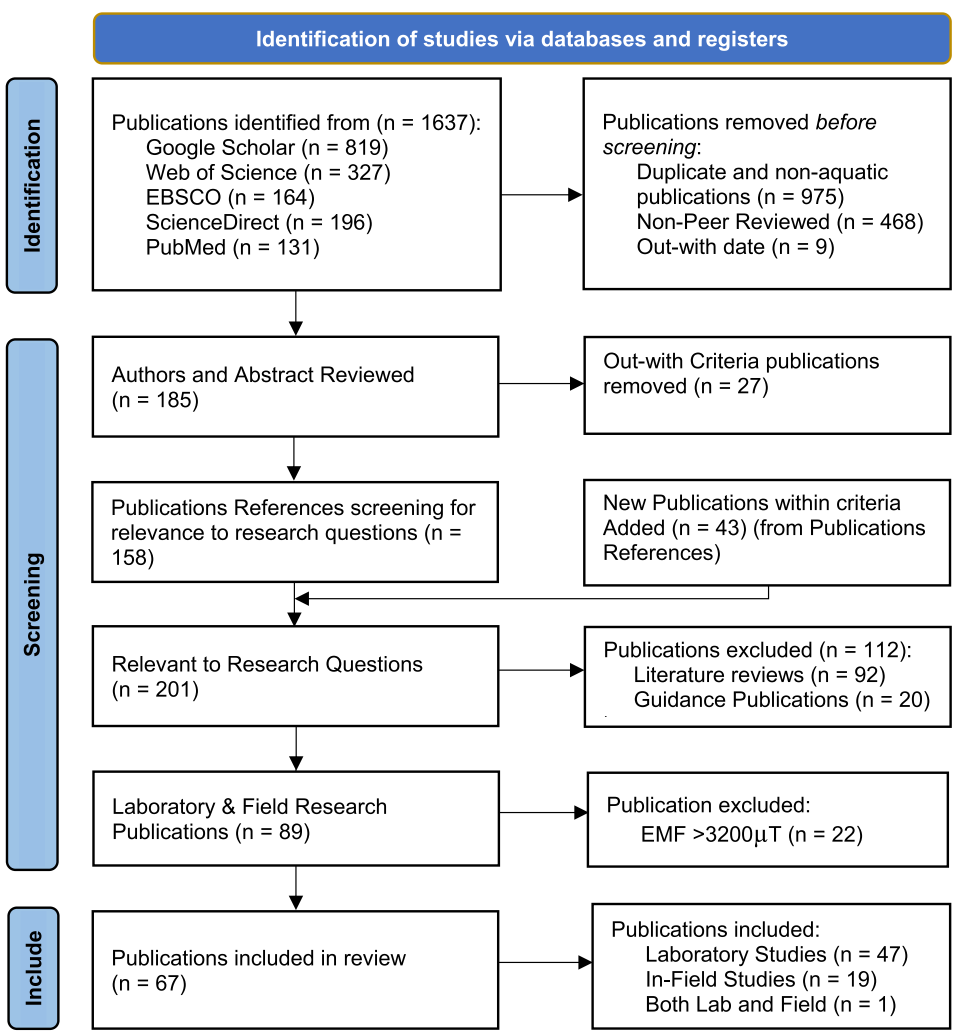

Fig. 2. Screening flowchart for EMF SPCs lab and field research publications.

and the EMF source (AC or DC, where reported). Where studies provided sex-specific analyses, these were recorded. Where possible, the significance and direction of biological effects were also noted, including endpoints such as attraction or avoidance behaviour, altered mobility, growth, reproduction, cellular stress, and mortality.

2.4. Critical appraisal of study quality

All included studies were subject to a critical appraisal of methodological reliability and ecological relevance. Appraisal criteria considered the extent to which studies reported EMF source characteristics (AC or DC, exposure intensities, gradients, and durations), the clarity and rigour of biological endpoints (behavioural, physiological, developmental), the statistical robustness of findings (sample sizes, replication, effect sizes). Ecological realism was also assessed, distinguishing between laboratory and field settings and considering whether life stage and sex were reported or incorporated into experimental design. This approach is consistent with the triage criteria (Whaley and Roth, 2022).

2.5. Analytical approach

A qualitative synthesis of the evidence base was conducted to identify patterns of biological response across taxa, EMF exposure levels, life stages, sexes and study types. A formal meta-analysis was considered but not undertaken because the reviewed studies exhibited substantial heterogeneity in exposure generation methods (coils, magnets, operational cables), field types (AC, DC, magnetic, electric), exposure metrics (field strength, gradients, duration), biological endpoints (behavioural, physiological, developmental), life stages, and response measures, which precluded meaningful quantitative standardisation and effect size comparison.

Instead, emphasis was placed on identifying consistently reported outcomes across studies, examining divergences between laboratory and field results, and highlighting methodological limitations that constrained inference, such as unreported EMF gradients or unrealistic exposure intensities. Attention was paid to ecologically meaningful patterns, including those observed in magnetosensitive taxa and during early developmental stages where impacts may be most consequential for population processes and ecosystem functioning.

3. Results

3.1. Study identification and characteristics

The systematic search initially returned 1637 publications, the majority of which were excluded as they focused on human health or terrestrial EMF applications. After applying the eligibility criteria, 185 articles were screened in full, of which 27 were excluded as not relevant to the research questions. Screening of reference lists identified an additional 43 relevant studies, resulting in 201 potentially applicable publications. Literature reviews, commentaries, and technical guidance documents were removed, yielding 89 empirical field and laboratory studies.

To ensure consistency with exposure conditions relevant to operational SPCs, studies exceeding 3200 μT were excluded. This threshold encompassed both the upper range of DC export cable fields reported in operational contexts and experimental exposures simulating high load conditions (Bochert and Zettler, 2004, 2006; Scott et al., 2021). After exclusions, 67 peer-reviewed studies were retained for full analysis, Table 1.

Of these 67 studies, 47 (70%) were laboratory-based, 19 (28%) were field-based, and one combined both approaches. Collectively, they represented 116 distinct investigations across 54 identified species, in addition to multispecies field surveys. Taxonomic representation included 26 fish species, 18 crustacean species, four molluscs, two polychaetes, three echinoderms, and several other vertebrates (e.g. elasmobranchs) and unicellular organisms. Fish comprised most studies (55%), followed by crustaceans (27%). One large field study reported effects across 41 fish species (9675 individuals) and 43 invertebrate species (30,523 individuals) (Milton S. Love, Nishimoto, Snook et al., 2017).

3.2. Biological responses by taxa and life stage

Across all taxa, 66% of the reviewed studies reported a statistically significant biological response to EMF exposure. Laboratory studies more frequently detected effects (72%) than field studies (47%).

Taxonomic differences were evident. Seventy three percent of fish studies reported significant responses, compared with 59% of crustacean studies and 40% of mollusc studies. Other invertebrates and echinoderms displayed variable results, though the evidence base for these groups remains sparse.

Ontogenetic stage strongly influenced sensitivity. Early life stages showed the highest responsiveness, with 93% of studies on fish embryos or larvae reporting significant impacts, compared with 86% for juveniles and 53% for adults. Crustaceans displayed a similar pattern, with early stages often more affected than adults. These findings suggest developmental stages may represent critical windows of susceptibility to EMFs in marine ecosystems. A summary of impact and no impact outcomes across major taxonomic groups is presented in Fig. 3.

3.3. Behavioural and physiology responses

The reviewed literature encompassed 32 studies focused on behavioural responses, 22 on physiological endpoints, and 13 that examined both.

Behavioural effects included changes in swimming speed, exploration, attraction or avoidance, and habitat use (Hutchison et al., 2020a, b). Physiological effects included altered haemocyte counts in crustaceans (Brysiewicz et al., 2017; Formicki and Winnicki, 1998), cardiac anomalies in fish embryos (Krylov et al., 2022) and metabolic disruption such as altered lactate cycling in *Cancer pagurus* (Scott et al., 2021). Chronic exposure to high DC fields (2800 μT) also produced changes in glucose metabolism and haemocyte counts in *C. pagurus*, although partial recovery after 24 h suggested circadian modulation and stress responses (Harsanyi et al., 2022).

The proportion of significant outcomes differed by response type. Ninety one percent of physiology focused studies reported significant effects, compared with 66% of behaviour only studies. In combined studies, 46% reported impacts in both domains.

3.4. Field versus laboratory studies

Laboratory studies more frequently reported significant biological responses to EMF exposure (72%) compared to field studies (47%) (Cresci et al., 2022a, 2022b; Harsanyi et al., 2022; Hutchison et al., 2020a,b; Scott et al., 2021). The single study combining laboratory and field approaches reported no significant effect (Elvidge et al., 2022). Helmholtz coils were the most widely used EMF source in laboratory studies, employed in 72% (n = 34) of experiments reporting methods (Albert et al. 2022, 2023; Albert et al., 2022a,b; Durif et al., 2023; Scott et al., 2018; Taormina et al., 2020). Approximately three-quarters of these studies reported significant biological responses. Other exposure generation systems included solenoid coils (Corte Rosaria and Martin, 2010; Hermans et al., 2024; Scott et al., 2021), static or permanent magnets (Bevelhimer et al., 2013; Brysiewicz et al., 2017; Formicki and Winnicki, 1998), ferrite magnets (Sadowski et al., 2007), and a Merritt coil system (Newton, 2024).

Taxonomic coverage within laboratory settings was broad, encompassing fishes, crustaceans, molluscs, and polychaetes. For example, *Cyclopterus lumpus* exhibited reduced motility and developmental abnormalities under EMF exposure (Durif et al., 2023). In *Scyliorhinus*

Table 1
EMF Impact Laboratory and field-testing research publications on aquatic biota, 1990-2024.

No.	Study Type	EMF Impact	Life stage	Group	Species	Response Type	Observed effects	EMF (μT)	Reference
1	Lab	Y	Early life stages	Crustacea	Ostracod *(Heterocypris incongruens)*	Physiological	Dynamic of hatchability/Juvenile survival to adulthood decreased significantly after incubation	151 ± 7.5	(Bieszke et al., 2020)
2	Lab	Y	Embryos	Fish	European whitefish *(Coregonus lavaretus vendace)*	Behavioural	Melanophores significant difference by altering positioning of pigment organelles (melanosomes) within cells	1000	Brysiewicz et al. (2017)
3	Lab	Y	Early life stages	Fish	Roach *(Rutilus rutilus: Cyprinidae, cypriniformes)*	Physiological	Statistically significant decrease in testing - Earlier hatching of pre-larvae, increase in the morphological diversity of juvenile fish, decrease in body lengths and weights, changes in number of yearlings vertebrae	150	(Chebotareva et al., 2009)
4	Lab	Y	Larvae	Fish	Atlantic haddock larvae *(Melanogrammus aeglefinus)*	Behavioural	Statistically significant reduced swimming activity	50-150	Cresci et al. (2022b)
5	Lab	Y Y	Larvae Larvae	Fish Fish	Atlantic cod *(Gadus morhua)* Atlantic haddock (*Melanogrammus aeglefinus*)	Behavioural	Significant reduced swimming activity	22-156	Cresci et al. (2023)
6	Lab	Y	Early life stages	Fish	Rainbow trout (*Oncorhynchus mykiss*)	Behavioural and Physiological	Significant Impact on enhanced yolk-sac absorption rate. No significant effect on embryonic or larval mortality, hatching time, larval growth, or larvae swim time	1000	Fey et al. (2019)
7	Lab	Y	Embryos/ Larvae	Fish Fish Fish Fish	Trout *(Salmo trutta)* Rainbow trout (*Oncorhynchus mykiss*) Pike *(Esox lucius)* and Carp *(Cyprinus carpio)*	Behavioural and Physiological	Slowed down embryonic development increase in a heart rhythm, particularly during the early pulsation period of the forming heart; significant inc. pectoral fin movement Sense of direction change Slowed down embryonic development; Gas exchange changes	1000-13000	Formicki and Winnicki (1998)
8	Lab	Y	Embryonic, larval	Crustacea Crustacea	European Lobster, *(Homarus gammarus)*	Behavioural and Physiological	Significant differences in life stage specific egg volume and larvae decreased carapace height, total length, and maximum eye diameter.	2800	Harsanyi et al. (2022)
					Edible Crab *(Cancer pagurus)*		Significant differences in life stage specific egg volume and larvae were consistently smaller across all measured parameters	2800	
9	Lab	Y	Larvae	Fish	Larval rainbow trout (*Oncorhynchus mykiss*)	Behavioural	Significant attraction to EMF source	1000	(Jakubowska et al., 2019)
10	Lab	Y	Fingerlings	Fish	Common carp *(Cyprinus carpio)*	Physiological	Stress and immune suppression significant increase in enzyme activity; reduction in immune markers	2000	Khoshroo et al. (2018)
11	Lab	Y	Eggs	Crustacea	Water flea *(Daphnia magna straus)*	Physiological	Increase in number of newborns; statistically significant days 2&3	high	Krylov (2008)
12	Lab	Y	Eggs	Crustacea	Water flea *(Daphnia magna straus)*	Physiological	Significantly different effect of development	75	Krylov (2010)
13	Lab	Y	Embryos	Fish	Zebrafish *(Danio rerio)*	Physiological	Increased embryo mortality; appearance of abnormal phenotypes and significant increase in heartrate	51.7	Krylov et al. (2022)
14	Lab	Y	Embryos	Fish	Japanese rice fish *(Medaka)*	Physiological	Hatchlings exposed to the EMF during development exhibited anxiety-like behaviour/developed faster	60	Lee and Yang (2014)
15	Lab	Y	Embryos & Fish	Fish	Zebrafish *(Danio rerio)*	Physiological	Delayed hatching and decreased heart rate at the early developmental stages. Apoptosis-related genes significantly upregulated	30, 100, 200, 400, 800	Li et al. (2014)
16	Lab	Y	Embryos & Fish	Fish	Nile tilapia *(Oreochromis niloticus)*	Physiological	Significantly suppressed growth performance and reduced digestive enzyme activity	30, 100, 150, 200	Li et al. (2015)

(continued on next page)

Table 1 (*continued*)

No.	Study Type	EMF Impact	Life stage	Group	Species	Response Type	Observed effects	EMF (μT)	Reference
17	Lab	Y	Fry	Fish	Caspian kutum *(Rutilus frisii kutum)*	Physiological	Activity of ALT (Alanine Aminotransferase) and AST (Aspartate Aminotransferase) was increased along with increasing SMF intensity & lysozyme level showed a significant decrease	17	Loghmannia et al. (2015)
18	Lab	Y	Sperm	Polychaete	Serpulid polychaete *(Ficopomatus enigmaticus)*	Physiological	Induce stress in sperm cells; increased mitochondrial activity, DNA damage, and reduced fertilization capacity. Larval development remains unaffected.	500, 1000	Oliva et al. (2023)
19	Lab	Y	Egg shells	Fish Fish Fish	Atlantic salmon *(Salmo salar)* Brown trout *(Salmo trutta)* Rainbow trout (*Oncorhynchus mykiss*)	Physiological	Increase in the egg-shell permeability to water; less distinct increase during the entire embryogenesis	2000	Sadowski et al. (2007)
20	Lab	Y	Embryos	Fish	Zebrafish *(Danio rerio)*	Physiological	Delay hatching	1000	Skauli et al. (2000)
21	Lab	Y	Embryos	Echinoderm	Sea urchin *(Strongylocentrotus purpuratus)*	Physiological	Significant delay in cell division	100	Zimmerman et al. (1990)
22	Lab	Y	Juvenile	Crustacea	Edible Crab *(Cancer pagurus)*	Behavioural and Physiological	Attraction Behaviour Suppression of side selection behaviour and significantly disrupted haemolymph L-Lactate and D-Glucose natural circadian rhythms	2800	Scott et al. (2018)
23	Lab	Y	Juvenile	Fish	Atlantic lumpfish *(Cyclopterus lumpus)*	Behavioural	Significant reduction in swimming speed/No significant differences for activity ratios, total distance travelled, or time spent in quadrants	230	Durif et al. (2023)
24	Lab	Y	Juvenile	Fish	Rainbow trout *(Oncorhynchus mykiss)*	Physiological	Significant changes in growth stimulation (enhanced weight gain, length and feed efficiency), metabolic regulation and Immune function	0.01, 0.1, 0.5, 5, 50	Nofouzi et al. (2017)
25	Field	Y	Juvenile	Fish	Chinook salmon *(Oncorhynchus tshawytscha)*	Behavioural	Higher proportions of fish crossing cable location south of their normal migratory route/No Sig impact proportion of migrating fish	Field	Wyman et al. (2018)
26	Field	N N	Smolt (Juvenile) Adult	Fish Fish	Chinook salmon *(Oncorhynchus tshawytscha)* Green Sturgeon *(Acipenser medirostris)*	Behavioural	Alterations to migratory routes and timing; but not considered strong barrier	Field	Klimley et al. (2017)
27	Lab	Y N	Juvenile Juvenile	Fish Fish	Lake sturgeon *(Acipenser fulvescens)* Paddlefish *(Polyodon spathula)*	Behavioural	Variety of altered swimming behaviours No reaction	1500	Bevelhimer et al. (2013)
28	Lab	N*	Adult	vertebrate	Small-spotted catshark (*Scyliorhinus canicula*)	Behavioural	No significant attraction or avoidance, no startle responses, and no increased use of shelter; 20% decrease in activity, with increased resting and higher swimming speeds when active, but not statistically significant	15 19.6	Hermans et al. (2024)
29	Lab	Y	Adult	Fish	Brook trout *(Salvelinus fontinalis)*	Physiological	Increased night-time pineal and serum melatonin levels	40	Lerchl et al. (1998)
30	Lab	Y Y N	Adult	Mollusc	Mediterranean mussel *(Mytilus galloprovincialis)*	Physiological	Heat Shock Protein (HSP) densitometric values were significantly higher Time-dependent increase in HSP expression None	600 400 300	Malagoli et al. (2006)
31	Lab	Y Y	Adult	Fish Fish	Big Skates *(Beringraja binoculata)* Longnose skates (*Caliraja rhina*)	Behavioural	Significant impact on velocity, spatial use, and body orientation with AC Slower, exploratory behaviours with DC	500 500	Newton (2024)
32	Lab	Y	Adult	Mollusc	Mediterranean mussel *(Mytilus galloprovincialis)*	Physiological	Significant increase in immunocyte values - cellular processes disruption	1000	Ottaviani et al. (2002)

(*continued on next page*)

Table 1 (*continued*)

No.	Study Type	EMF Impact	Life stage	Group	Species	Response Type	Observed effects	EMF (μT)	Reference
33	Lab	Y	Adult	Foraminifera	*Amphistegina lessonii*	Physiological	Significant deleterious effects on viability at higher densities and longer durations.	Low	Rebecchi et al. (2023)
34	Lab	Y	Adult	Crustacea	Freshwater crab *(Barythelphusa canicularis)*	Behavioural	Eyestalk-ablated significant difference and faecal matter excreted significantly higher	<3200	(Rosaria and Martin, 2010)
35	Lab	Y	Adult	Crustacea	Edible Crab *(Cancer pagurus)*	Behavioural and Physiological	Stress increased significantly, disrupting normal metabolic rhythms and immune responses. Increased attraction	500-1000	Scott et al. (2021)
36	Lab	Y	Adult Adult Adult	Fish Mollusc Polychaete	Larval rainbow trout (*Oncorhynchus mykiss*) Baltic clam *(Limecola balthica)* Ragworm (*Hediste diversicolor*)	Physiological	Increase in genotoxic and cytotoxic effects significantly elevated	1000	Stankevičiūtė et al. (2019)
37	Lab	Y Y	Adult Adult	Fish Fish	Longnose skate *(Beringraja rhina)* Big skate *(Beringraja binoculata)*	Behavioural	Significant impact on velocity, spatial use, and body orientation with AC Slower, exploratory behaviours with DC	54.6	(Toledo Marin, 2024)
38	Field	Y	Adult	Fish Crustacea	Little skate *(Leucoraja erinacea)* American lobster *(Homarus americanus)*	Behavioural	Significant difference - more exploratory activity Significant difference - more exploratory activity	Field	Hutchison et al. (2018)
39	Field	Y	Adult Adult	Fish Crustacea	Little skate *(Leucoraja erinacea)* American lobster *(Homarus americanus)*	Behavioural	Significant distance tracked - heightened exploration and foraging Increased time in enclosure zone and reduced height from seabed	Field	Hutchison et al. (2020)
40	Field	Y	Adult	Crustacea	Caribbean spiny lobster *(Palinurus argus)*	Behavioural	Significant movement change from initial course with exposure	Field	Lohmann et al. (1995)
41	Field	Y	Adult	Invertebrate Invertebrate Fish Vertebrate Vertebrate	Sand stars Black crinoids Fish Sharks Rays	Behavioural	Slight but statistically significant differences in densities: No Sig differences in overall composition No impact	91.4	Love et al. (2016)
42	Field	Y	Adult	Crustacea	Spiny check crayfish *(Oronectes limosus)*	Behavioural	Statistically significant difference and attraction behaviour	Field	Tański et al. (2005)
43	Field	Y.	Adult	Crustacea	Amphipod *(Goondogenia antartica)*	Behavioural	Significant spontaneous orientation disruption	Field	Tomanova and Vacha (2016)
44	Field	Y	Adult	Crustacea	Baltic isopod *(Idotea baltica basteri)*	Behavioural	Frequency significant individual distribution & movement change	Field	Ugolini and Pezzani (1995)
45	Field	Y	Adult	Fish	European eels *(Anguilla anguilla)*	Behavioural	Telemetered animals significantly lower swimming speeds	Field	Westerberg and Lagenfelt (2008)
46	Field	N	Adult	Fish	Green sturgen *(Acipenser medirostris)*	Behavioural	Altered swimming behaviour and increased transit time but not statistically significant*	Field	Wyman et al. (2023)
47	Lab	Y N N	Adult Adult Adult	Fish Crustacea Crustacea	Various American lobster *(Homarus americanus)* Dungeness crab *(Metacarcinus magister)*	Behavioural and Physiological	Varied impact – some significant No effect on spatial distribution No effect on spatial distribution and no effect of the level of agitation	1010 1010	Woodruff et al. (2013)
48	Lab	N	Larvae	Fish	Lesser sandeel larvae *(Ammodytes marinus)*	Behavioural	No effect	150	Cresci et al. (2022a)
49	Lab	N	Larvae	Fish	Rainbow trout *(Oncorhynchus mykiss)*	Behavioural/ Physiological	No effect on otolith fluctuating asymmetry	1000	Fey et al. (2020)
50	Lab	N	Juvenile	Fish	Thornback ray *(Raja clavata)*	Behavioural	No significant variance	450	Albert et al. (2022)
51	Lab	N	Juvenile	Crustacea	European lobster *(Homarus gammarus)*	Behavioural	No effects on the exploratory and shelter seeking behaviours	230	Taormina et al. (2020)
52	Lab	N	Adult Adult Adult Adult Adult Adult	Crustacea Crustacea Crustacea Crustacea Echinoderm Polychaete	North Sea prawn *(Crangon crangon)* Isopod *(Saduria entomon)* Round crab *(Rhithropanopeus)* Baltic prawn *(Palaemon sqilla)* Common starfish *(Asturia rubens)* Ragworm *(Hediste diversicolor)*	Behavioural and Physiological	No effects on spatial distribution No effects on spatial distribution No effects on spatial distribution No effects on oxygen consumption rate No effects on spatial distribution No effects on spatial distribution	2700 2700 2800 3200 2800 2800	Bochert and Zettler (2006)
53	Lab	N	Adult	Mollusc	Blue mussel *(Mytilus edulis)*	Behavioural Physiological	None on valve activity None on filtration rate	300	Albert et al. (2022)

(*continued on next page*)

Table 1 (*continued*)

No.	Study Type	EMF Impact	Life stage	Group	Species	Response Type	Observed effects	EMF (μT)	Reference
54	Lab	N	Adult	Crustacea	Velvet crab (*Necora puber)*	Behavioural	No attraction or repulsion	304	Albert et al. (2023)
55	Lab	N	Adult Adult	Invertebrate Invertebrate Crustacea Mollusc	Common starfish *(Asturia rubens)* *European sea urchin (Echinus esculentus)* Velvet swimming crab *(Necora puber)* Common periwinkle *(Littorina littorea)*	Behavioural and Physiological	No significant differences in righting reflex or total haemocyte/ coelomocyte counts	500	Chapman et al. (2023)
56	Lab	N	Adult	Molluscs Polychaete	Baltic clam *(Limecola balthica)* Ragworm (*Hediste diversicolor*)	Behavioural	None None on food consumption and respiration rates (increase in ammonia excretion) No effect on spatial distribution but some slight behavioural changes	850-1050 1000	Jakubowska et al. (2019)
57	Lab	N	Adult	Mollusc	Mediterranean mussel *(Mytilus galloprovincialis)*	Physiological	No permanent cell damage provoked	400	Malagoli et al. (2003)
58	Lab	N	Adult	Mollusc	Mediterranean mussel *(Mytilus galloprovincialis)*	Physiological	No change	400	Malagoli et al. (2006)
59	Field and Lab	N	Adult	Fish	Sunfish (*Lepomis spp.)*	Behavioural and Physiological	No significant impact	Low	Elvidge et al. (2022)
60	Field	N	Adult	Invertebrate	Various macrozoobenthos	Behavioural	No significant changes in species composition, abundance, or biomass	Field	Andrulewicz et al. (2003)
61	Field	N	Adult	Fish	Reef Fish	Behavioural	None	Field	Kilfoyle et al. (2018)
62	Field	N	Adult Adult	Crustacea Crustacea	Edible red crab *(Cancer productus)* Yellow rock crab *(Metacarcinus anthonyi)*	Behavioural	No effect on distribution	Field	Love et al. (2015)
63	Field	N	Adult Adult	Crustacea Crustacea	Dungeness crab *(Metacarcinus magister)* Edible red crab *(Cancer productus)*	Behavioural	No effect on catchability	Field	Love et al. (2017a)
64	Field	N	Adult Adult Adult Adult Adult	Invertebrate Invertebrate Fish Vertebrates Vertebrates	Sand stars *(Astrecten spp.)* Black crinoids *(Antedon spp.)* Fish Sharks Rays	Behavioural and Physiological	None No significant attraction or repulsion	91.4	Love et al. (2017b)
65	Field	N N	Adult Adult	Fish, Invertebrate	Fishes- 41 species comprising 9675 individuals Invertebrates 43 species comprising 30,523 individuals	Behavioural and Physiological	No significant attraction or repulsion by fish or invertebrates	<100	Love et al. (2017c)
66	Field	N	Adult	All	Various benthic species	Behavioural	No significant difference	0.072	Rijkswaterstaat (2020)
67	Field	N	Adult	Crustacea	Red rock crab *(Cancer productus)*	Behavioural	No significant impact to crab harvest rates	Field	Williams et al. (2023)

canicula, exposure was associated with a 20% reduction in locomotor activity, characterised by increased resting and higher swimming speeds when active (Hermans et al., 2024).

Field studies exhibited greater variation in design and outcome. Some incorporated telemetry, behavioural tracking, or exposure validation (Hutchison et al., 2020a,b; Klimley et al., 2021), whereas others were observational or relied on indirect assumptions of exposure. Long-term monitoring was uncommon, with only one study extending beyond one year to assess biomass and species composition near SPCs (Andrulewicz et al., 2003). Most field studies did not stratify responses by sex or life stage.

A recent study published outside the present search window reported significantly greater attraction of female shore crabs to cable associated EMFs fields than males, (James et al., 2025), illustrating the limited representation of sex-specific analyses within relevant EMF literature.

3.5. Exposure types: AC, DC, magnetic and electric components

Among the reviewed studies, approximately half investigated DC exposures, one third investigated AC, and the remainder either combined both or did not specify the current type. Most studies focused exclusively on magnetic fields, with very few explicitly addressing electric fields.

DC studies typically examined static magnetic fields ranging from a few μT to several mT, often generated by coil systems or permanent magnets. AC exposures, generally at 50–60 Hz, were less frequently reported but remain directly relevant to inter array transmission cables. Only a small number of studies included explicit measurements or experiments targeting electric field components, although in situ field surveys implicitly incorporated both magnetic and electric elements (Klimley et al., 2021).

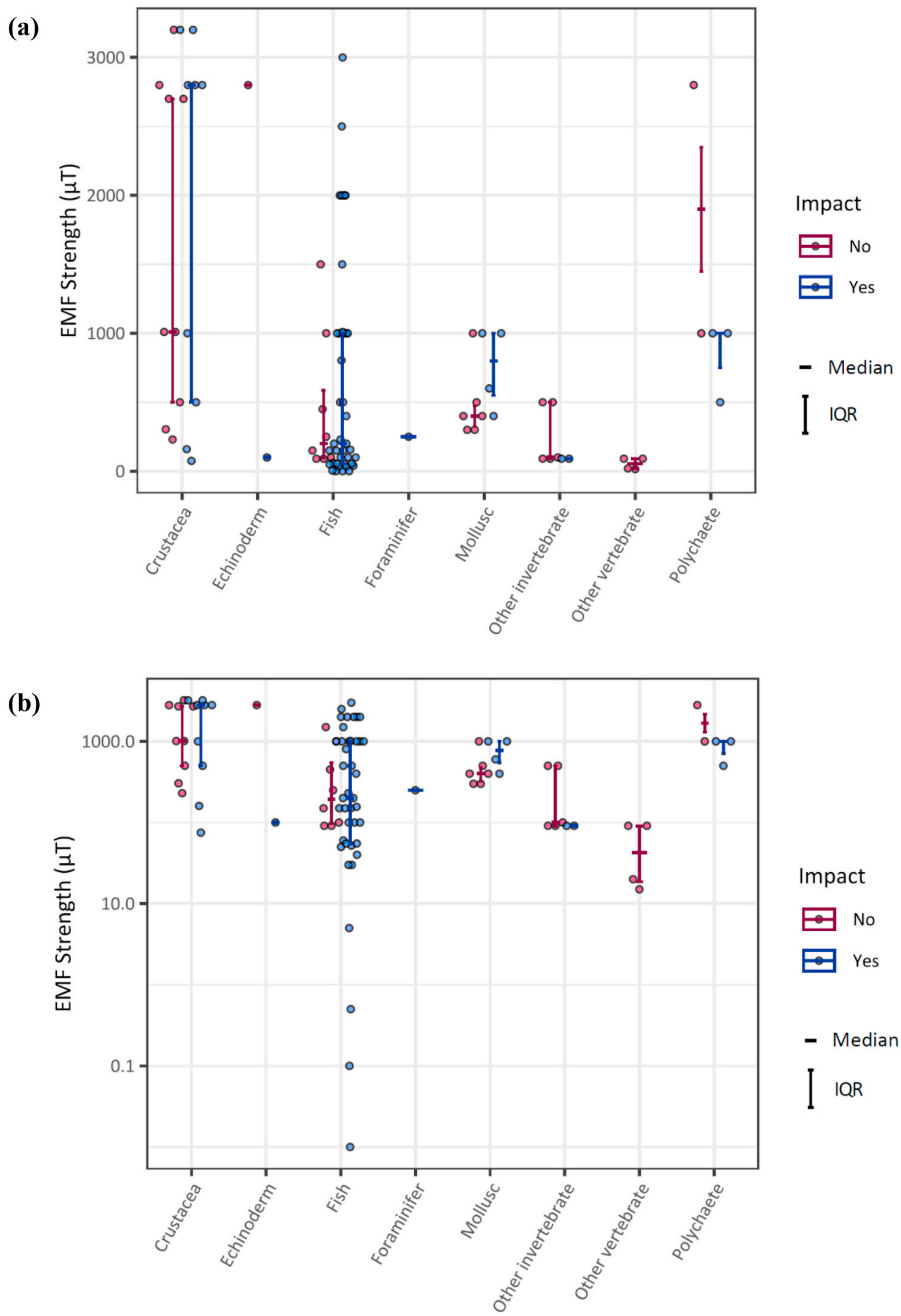

Fig. 3. EMF exposure studies by the most researched taxonomic groups, showing reported biological impact (blue) or no impact (red), Median and Interquartile Range (IQR) by (a) distribution by group, and (b) log scale of tested EMF levels. Field studies without specified EMF values are excluded. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.6. Scale of SPCs global impact

While several assessments have evaluated the environmental impacts of offshore energy infrastructure more broadly (Katovich, 2024; Li et al., 2022, 2023), few studies have directly quantified the marine spatial footprint of SPCs or MREDs. Regional projections suggest that Europe will require over 250,000 km of additional transmission capacity by 2050, though this figure includes both terrestrial and subsea systems (Schell et al., 2017). Global estimates indicate that SPCs could reach approximately 23,000 km by 2050 to support a market capacity of 260 GW (Zhang et al., 2024). Broader renewable energy expansion, potentially exceeding 2000 GW worldwide (DNV, 2023), implies substantially greater subsea transmission requirements.

Based on these projections, a conservative estimate of ~100,000 km of SPCs by 2050 was used for this review. Assuming a 50 m corridor width, this equates to a direct seabed footprint of ~5000 km^2 (0.017% of the global continental shelf). Expanding the influence zone to 200 m increases this area to ~20,000 km^2, or ~0.07% of the shelf (Taormina et al., 2018), as summarised in Table 2.

Table 2
Estimated global marine spatial footprint of SPCs by 2050.

Metric	Estimate	Reference
Total Ocean area	~361 million km^2	Charette and Smith (2010)
Global continental shelf area	~22–45 million km^2	Laruelle et al. (2018)
Estimated future SPC length (2050)	~100,000 km	Based on extrapolation from current trends and projections in offshore renewable energy development (Schell et al., 2017)
Direct SPC footprint (e.g., trench)	~5000 km^2 (0.017% of continental shelves)	100,000 km of SPCs with a 50m direct impact width (Zhang et al., 2024)
Ecological influence zone (200 m width)	~20,000 km^2 (0.07% of continental shelves)	Expanding the direct footprint to account for broader ecological effect (Taormina et al., 2018)

3.7. Synthesis of research trends

Research on SPC generated EMFs has increased steadily over the past decade, with a corresponding rise in both laboratory and field-based investigations.

One of the most important patterns is the disproportionate sensitivity of early developmental stages across taxa. Heatmap analysis of laboratory data (Fig. 4) revealed that embryos and larvae of fish, crustaceans, polychaetes, and echinoderms exhibited consistently higher rates of EMF related effects compared with juveniles and adults. For example, 93% of early-stage fish studies reported significant impacts, compared with 73% of juveniles and 53% of adults. Crustaceans showed a similar pattern, with 100% sensitivity in early stages but only 41% in adults. By contrast, molluscs and other invertebrates showed comparatively low responsiveness, particularly at adult stages.

A complementary analysis of biological responses relative to exposure intensity (Fig. 5) indicated that significant effects were reported across the full spectrum of EMF levels tested, including <250 μT. Early life stages were consistently the most responsive, while juveniles and adults more often required higher intensities to elicit measurable effects.

Geographic and taxonomic representation was uneven. Most studies were concentrated in temperate systems and focused on a narrow set of commercially important species, such as eels, edible crabs, and European lobster (Harsanyi et al., 2022; Scott et al., 2021). Freshwater studies were included, but remain peripheral compared with marine investigations, and limited evidence suggests high response rates. Similarly, ecosystems in the tropics and Southern Hemisphere have received little attention.

Key synthesis findings and knowledge gaps are summarised in Table 3.

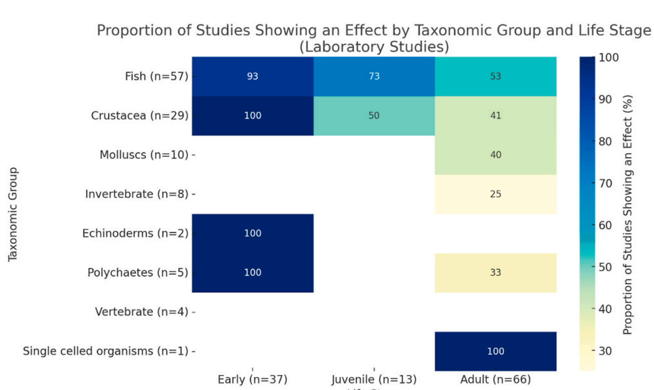

Fig. 4. EMF sensitivity heatmap by taxonomic group and life stage (lab studies).

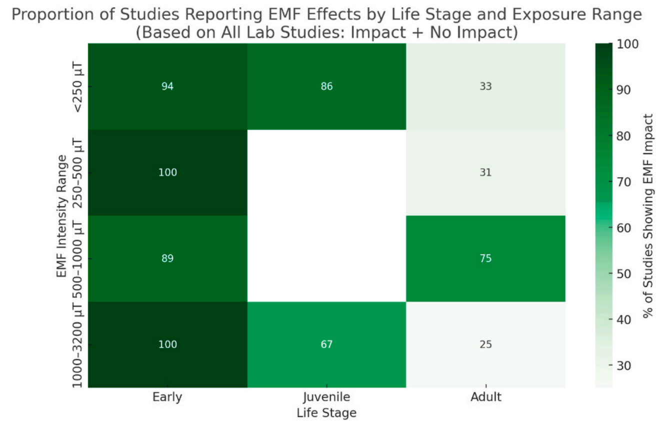

Fig. 5. EMF sensitivity heatmap by life stage and exposure range (lab studies).

Table 3
Summary of key synthesis findings.

Key Factor	Pattern Observed	Implications/Risks
Life stage	Early stages = most sensitive	Risk to recruitment/population growth
EMF type	DC > AC for physiological changes	Design considerations for SPCs
Species group	Fish > crustacea > molluscs	Relative sensitivity across taxa for risk assessment
Environment	Lab > field impact reporting	Need for realistic in situ studies
Study design	Lack of standardisation	Method harmonization required
Sex-specific responses	Poorly studied	Gap in understanding differential sensitivity
EMF exposure strength	Significant impacts even at <500 μT	Effects occur at environmentally realistic exposure levels
Exposure duration	Mostly short-term experiments	Lack of knowledge on chronic and cumulative effects
Long-term monitoring	Extremely limited	Need for multi seasonal, long-term studies
Magneto-/electrosensitive species	Highly vulnerable to anthropogenic EMFs	Potential for altered movement and habitat use
Scale of SPCs Global Impact by 2050	Estimated less than 0.1% of the world's continental shelf	Risk of ecological significant localised effects, especially in sensitive or migration critical areas

4. Discussion

This systematic review demonstrates that biological responses to EMFs generated by SPCs are consistently reported across multiple aquatic taxa, with early life stages displaying heightened sensitivity. The majority of embryo and larval studies reported significant effects, including at intensities below 250 μT (Cresci et al., 2023; Harsanyi et al., 2022; Scott et al., 2021), supporting the hypothesis that development represents a critical window of biological sensitivity. Fish and crustaceans were the most frequently studied groups and showed the highest prevalence of reported effects, whereas molluscs and other invertebrates displayed more variable outcomes (Albert et al., 2020; Hutchison et al., 2020a,b). Sensitivity therefore appears structured by both ontogeny and taxon; although mechanistic understanding remains incomplete.

Behavioural and physiological responses were both documented, but they differ in inferential strength. Behavioural endpoints such as altered swimming speed, attraction or avoidance, and habitat use were frequently affected (Hermans et al., 2024; Hutchison et al., 2020a,b), yet responses were often context dependent, reflecting species-specific sensory ecology and methodological heterogeneity. Physiological studies, although fewer, more consistently reported effects, including altered metabolic regulation and immune responses, and cardiovascular anomalies during development (Harsanyi et al., 2022; Krylov et al., 2022; Scott et al., 2021). Behavioural responses may therefore act as sensitive early indicators, while physiological endpoints provide stronger mechanistic insight.

A key limitation of the evidence base is the imbalance between laboratory and field studies. Laboratory experiments provide controlled exposure and statistical power but often generate spatially uniform fields that differ from the heterogeneous gradients produced by operational SPCs (Albert et al., 2020; Taormina et al., 2020). This likely contributes to the higher proportion of significant outcomes in laboratory settings. Field studies offer ecological realism but are typically short term, rarely quantify exposure gradients, and seldom stratify by life stage or sex (Hutchison et al., 2020a,b; Klimley et al., 2021). Paired laboratory and field approaches incorporating exposure validation and standardised endpoints will be essential to improve ecological inference.

4.1. Keystone evidence and strength of inference

Although the broader literature is methodologically heterogeneous, a small number of the keystone studies provide particularly strong inferential value by combining well-characterised EMF exposures with ecologically meaningful endpoints. Controlled laboratory experiments on Atlantic cod and haddock larvae demonstrate consistent reductions in swimming activity at environmentally realistic field strengths, indicating direct interference with early life-stage locomotion and orientation (Cresci et al., 2023; Cresci, Perrichon, et al. 2022). Developmental sensitivity is further supported by physiological studies on European lobster and edible crab embryos, which revealed reduced larval size and altered egg metrics following chronic DC exposure (Harsanyi et al., 2022), and by zebrafish embryo studies linking EMF exposure to delayed hatching, cardiac disruption and gene expression change (Krylov et al., 2022; Li et al., 2014). At the juvenile and adult stages, laboratory experiments on *Cancer pagurus* demonstrate both attraction behaviour and metabolic disruption under SPC-relevant EMF conditions, providing mechanistic evidence of stress-related physiological change (Scott et al., 2018, 2021). These laboratory findings are complemented by field telemetry studies on skates and lobsters, which show increased exploratory behaviour and altered spatial use in the vicinity of operational cables (Hutchison et al., 2018, 2021). Collectively, these studies indicate that EMFs can act as behavioural cues, disrupt physiological homeostasis, and exert particularly strong effects during early development, although few studies have yet linked short-term responses to longer-term fitness or population level consequences.

Sex-specific responses represent a critical and largely overlooked dimension of EMF sensitivity. Most studies do not stratify by sex, despite well-established sex differences in physiology, behaviour, and reproductive investment across aquatic taxa (White et al., 2017). A recent laboratory study recorded that female shore crabs *(Carcinus maenas)* exhibit significantly greater attraction to SPC relevant EMFs than males (James et al., 2025), suggesting that EMFs may interact with sex-specific sensory ecology, movement behaviour, or reproductive strategies. This finding highlights the risk of obscuring biologically meaningful patterns when sexes are pooled and underscores the need to routinely incorporate sex as a biological variable in EMF research.

Another limitation is the strong focus on magnetic fields, with electric fields rarely tested independently despite their ecological relevance for electroreceptive taxa (Klimley et al., 2021). In addition, AC and DC outcomes are sometimes pooled, obscuring differences in waveform, frequency and biological interaction pathways (Cada et al., 2011; Hutchison et al., 2020a,b). Clearer reporting of field type, intensity, frequency, and spatial gradients is therefore essential for mechanistic understanding and enabling cross-study comparison.

At the global scale, SPC expansion is projected to represent a modest proportional footprint (<0.1% of the continental shelf by 2050), but this masks localised ecological risks. Cables are concentrated in nearshore habitats that are disproportionately productive and biodiverse, including nursery grounds and migratory corridors (Hermans et al., 2024; Schell et al., 2017; Taormina et al., 2018; Zhang et al., 2024). Consequently, cumulative exposure in cable dense regions warrants particular attention within environmental assessment and marine spatial planning.

4.2. Interpreting research priorities through feasibility and scalability

The research priorities identified in this review highlight the need to balance scientific ambition with practical feasibility and scalability. While Short term laboratory studies dominate the current literature, limiting inference on chronic, cumulative and multigenerational effects, several high-impact advances can be implemented immediately without substantial additional infrastructure. Conversely, many ecologically realistic research directions, particularly field-based, multi stressor and long-term studies remain constrained by logistical, regulatory and financial barriers.

Rather than ranking research topics by perceived urgency or importance, we adopt a feasibility informed framework that reflects the capacity of the wider research community to implement different study types under current conditions. This approach recognises that many research questions are equally important from an ecological and regulatory perspective, but differ substantially in the resources, coordination, and time horizons required to address them.

High feasibility priorities include methodological standardisation, harmonised exposure reporting, and routine consideration of sex and life stage as biological variables. These actions are low-cost, widely accessible, and can be implemented immediately across laboratory and field studies. Improving consistency in exposure characterisation, behavioural metrics, and metadata reporting would substantially enhance comparability across studies and strengthen the evidentiary base for environmental risk assessment.

Moderate feasibility priorities encompass coordinated laboratory experiments, extended chronic exposures, and comparative studies across taxa or life stages. While technically achievable, these approaches often require inter-laboratory collaboration, shared protocols, and moderate increases in infrastructure or personnel investment. Such studies represent a critical intermediate step between short-term laboratory experiments and large-scale field validation.

Low feasibility priorities represent long-horizon research agendas, including multi-generational exposure studies, multi-stressor field experiments, and population- or ecosystem-level assessments near operational submarine power cables. These approaches require sustained funding, specialist equipment, long-term site access, and close coordination between researchers, industry, and regulators. Although challenging to implement, they remain essential for resolving uncertainties around cumulative and indirect ecological effects and should be supported through dedicated consortia and strategic research programmes.

By framing research priorities through feasibility and scalability rather than categorical ranking, this review emphasises the importance of sequencing research efforts while avoiding assumptions about relative ecological significance. This approach supports both immediate methodological improvements and the longer-term development of evidence needed to inform environmental management and policy decisions related to submarine power cable electromagnetic fields.

5. Conclusion

This systematic review applies PRISMA standards to deliver a transparent and structured synthesis of evidence on the biological effects of SPC EMFs. Across 67 peer reviewed laboratory and field studies, significant biological responses were reported in multiple taxa, with early developmental stages consistently exhibiting the greatest sensitivity (Cresci et al., 2022a; Harsanyi et al., 2022; Scott et al., 2021). Both behavioural and physiological endpoints were affected, although the consistency of the responses varied among metrics, and effects were detected at field intensities comparable to those generated by operational cables (<250 μT).

Across taxa, sensitivity was shaped by both life stage and taxonomic group, with fishes and crustaceans generally more responsive than molluscs and other invertebrates. Early stages consistently emerged as critical exposure windows, suggesting potential consequences for recruitment and population resilience in marine ecosystems. Emerging evidence further indicates that sex-specific responses represent an important and previously under recognised dimension of EMF sensitivity, with recent work demonstrating significantly greater attraction of female shore crabs to SPC relevant EMFs ().

Despite this expanding evidence base, substantial uncertainties remain. Long-term and multigenerational impacts are poorly resolved, tropical and Southern Hemisphere marine ecosystems are under-represented, and methodological heterogeneity continues to constrain cross-study comparability. Addressing these limitations will require improved standardisation of exposure and reporting, coordinated laboratory to field validation, and routine inclusion of sex and life stage as biological variables in experimental design.

As offshore renewable energy expands globally, systematic consideration of EMF effects within environmental risk assessment, marine spatial planning, and biodiversity policy frameworks will become increasingly important (Taormina et al., 2018). By consolidating current evidence and articulating feasibility informed research agenda. This review supports the development of proportionate, evidence-based management strategies that enable SPC deployment to proceed in parallel with climate mitigation and marine biodiversity protection.

CRediT authorship contribution statement

Elizabeth James: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mojtaba Ghodsi:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Alex T. Ford:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Elizabeth James reports a relationship with Subsea 7 Limited that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This manuscript, "Electromagnetic Fields from Submarine Power Cables: A 35 Year Synthesis of Effects on Aquatic Biota", represents original research. The review protocol was registered in PROSPERO (ID: 1138188 – pending publication) during the conduct of this review. The author thanks Tjeerd Braun for his assistance in developing the schematic. No specific funding was received for this research.

Data availability

Data will be made available on request.

References

Albert, L., Deschamps, F., Jolivet, A., Olivier, F., Chauvaud, L., Chauvaud, S., 2020. A current synthesis on the effects of electric and magnetic fields emitted by submarine power cables on invertebrates. Mar. Environ. Res. 159, 104958. https://doi.org/10.1016/j.marenvres.2020.104958.

Albert, L., Maire, O., Olivier, F., Lambert, C., Romero-Ramirez, A., Jolivet, A., Chauvaud, L., Chauvaud, S., 2022a. 'Can Artificial Magnetic Fields Alter the Functional Role of the Blue Mussel, Mytilus edulis?'. Mar. Biol. 169 (6). https://doi.org/10.1007/s00227-022-04065-4.

Albert, L., Olivier, F., Jolivet, A., Chauvaud, L., Chauvaud, S., 2022b. Insights into the behavioural responses of juvenile thornback ray *Raja clavata* to alternating and direct current magnetic fields. J. Fish. Biol. 100 (3), 645–659. https://doi.org/10.1111/jfb.14978.

Albert, L., Olivier, F., Jolivet, A., Chauvaud, L., Chauvaud, S., 2023. Effects of anthropogenic magnetic fields on the behavior of a major predator of the intertidal and subtidal zones, the velvet crab *Necora puber*. Mar. Environ. Res. 190. https://doi.org/10.1016/j.marenvres.2023.106106.

Andrulewicz, E., Napierska, D., Otremba, Z., 2003. The environmental effects of the installation and functioning of the submarine SwePol link HVDC transmission line: a case study of the Polish marine area of the Baltic sea. J. Sea Res. 49, 337–345. https://doi.org/10.1016/S1385-1101(03)00020-0.

Bevelhimer, M.S., Cada, G.F., Fortner, A.M., Schweizer, P.E., Riemer, K., 2013. Behavioral responses of representative freshwater fish species to electromagnetic fields. Trans. Am. Fish. Soc. 142 (3), 802–813. https://doi.org/10.1080/00028487.2013.778901.

Bieszke, B., Namiotko, L., Namiotko, T., 2020. Life history traits of a temporary water ostracod *Heterocypris incongruens* (Crustacea, Ostracoda) are affected by power frequency (50 Hz) electromagnetic environmental pollution. European Zool. J. 87 (1), 148–155. https://doi.org/10.1080/24750263.2020.1736654.

Bochert, R., Zettler, M.L., 2004. Long-Term exposure of several marine benthic animals to static magnetic fields. Bioelectromagnetics 25 (7), 498–502. https://doi.org/10.1002/bem.20019.

Bochert, R., Zettler, M.L., 2006. Effect of electromagnetic fields on marine organisms. In: In Offshore Wind Energy. Springer, Berlin/Heidelberg, Germany, pp. 223–234. https://doi.org/10.1007/3-540-29201-1_17.

Brysiewicz, A., Formicki, K., Tański, A., Wesołowski, P., 2017. Magnetic field effect on melanophores of the European whitefish *Coregonus lavaretus* (Linnaeus, 1758) and Vendace *Coregonus albula* (Linnaeus, 1758) (Salmonidae) during early embryogenesis. European Zool. J. 84 (1), 49–60. https://doi.org/10.1080/11250003.2016.1272644.

Cada, G.F., Bevelhimer, M.S., Riemer, K.P., Turner, J.W., 2011. Effects on freshwater organisms of magnetic fields associated with hydrokinetic turbines. http://www.osti.gov/contact.html. (Accessed 15 December 2025).

Chapman, E.C.N., Rochas, C.M.V., Piper, A.J.R., Vad, J., Kazanidis, G., 2023. Effect of electromagnetic fields from renewable energy subsea power cables on righting reflex and physiological response of coastal invertebrates. Mar. Pollut. Bull. 193, 115250. https://doi.org/10.1016/j.marpolbul.2023.115250.

Charette, M.A., Smith, W.H.F., 2010. The volume of Earth's Ocean. Oceanography (Wash. D. C.) 23 (2), 112–114. https://doi.org/10.2307/24860721.

Chebotareva, Y.V., Izyumov, Y.G., Krylov, V.V., 2009. The effect of an alternating electromagnetic field upon early development in roach (*Rutilus rutilus: Cyprinidae, cypriniformes*). J. Ichthyol. 49 (5), 409–415. https://doi.org/10.1134/S0032945209050075.

Copping, A., 2016. Annex IV 2016 State of the science report: environmental effects of marine renewable energy development around the world. http://tethys.pnnl.gov. (Accessed 15 December 2025).

Corte Rosaria, J., Martin, E.R., 2010. Behavioral changes in freshwater crab, *Barytelphusa cunicularis* after exposure to low frequency electromagnetic fields. World J. Fish Mar. Sci. 2 (6), 487–494. https://www.researchgate.net/publication/228343260. (Accessed 15 December 2025).

Cresci, A., Perrichon, P., Durif, C.M.F., Sørhus, E., Johnsen, E., Bjelland, R., Larsen, T., Skiftesvik, A.B., Browman, H.I., 2022a. Magnetic fields generated by the DC cables of offshore wind farms have no effect on spatial distribution or swimming behavior of lesser sandeel Larvae (*Ammodytes marinus*). Mar. Environ. Res. 176, 105609. https://doi.org/10.1016/j.marenvres.2022.105609.

Cresci, A., Durif, C.M.F., Larsen, T., Bjelland, R., Skiftesvik, A.B., Browman, H.I., 2022b. Magnetic fields produced by subsea high-voltage direct current cables reduce swimming activity of haddock larvae (*Melanogrammus aeglefinus)*. PNAS Nexus 1 (4). https://doi.org/10.1093/pnasnexus/pgac175 pgac175.

Cresci, A., Durif, C.M.F., Larsen, T., Bjelland, R., Skiftesvik, A.B., Browman, H.I., 2023. Static magnetic fields reduce swimming activity of Atlantic cod (*Gadus morhua*) and haddock *(Melanogrammus aeglefinus)* Larvae. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. https://doi.org/10.1093/icesjms/fsad205.

Degraer, S., Carey, D.A., Coolen, J.W.P., Hutchison, Z.L., Kerckhof, F., Rumes, B., Vanaverbeke, J., 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning. Oceanography (Wash. D. C.) 33 (4), 48–57. https://doi.org/10.2307/26965749.

Durif, C.M.F., Nyqvist, D., Taormina, B., Shema, S.D., Skiftesvik, A.B., Freytet, F., Browman, H.I., 2023. Magnetic fields generated by submarine power cables have a negligible effect on the swimming behavior of Atlantic lumpfish *(Cyclopterus lumpus)* juveniles. PeerJ 11, e14745. https://doi.org/10.7717/peerj.14745.

Elvidge, C.K., Bihun, C.J., Davis, C., Ulhaq, S., Fung, D.T., Vermaire, J.C., Cooke, S.J., 2022. No evidence for collateral effects of electromagnetic fields used to increase dissolved oxygen levels on the behavior and physiology of freshwater fishes. Water Environ. Res. 94 (6). https://doi.org/10.1002/wer.10747.

Fey, D.P., Jakubowska, M., Greszkiewicz, M., Andrulewicz, E., Otremba, Z., Urban-Malinga, B., 2019. Are magnetic and electromagnetic fields of anthropogenic origin potential threats to early life stages of fish? Aquat. Toxicol. 209, 150–158. https://doi.org/10.1016/j.aquatox.2019.01.023.

Fey, D.P., Greszkiewicz, M., Jakubowska, M., Lejk, A.M., Otremba, Z., Andrulewicz, E., Urban-Malinga, B., 2020. Otolith fluctuating asymmetry in larval trout, *Oncorhynchus mykiss walbaum,* as an indication of organism bilateral instability affected by static and alternating magnetic fields. Sci. Total Environ. 707, 135489. https://doi.org/10.1016/j.scitotenv.2019.135489.

Formicki, K., Winnicki, A., 1998. Reactions of fish embryos and larvae to constant magnetic fields. Ital. J. Zool. 65, 479–482. https://doi.org/10.1080/11250009809386870.

Gandini, M., Trolli, A., Karnezis, P., Pietribiasi, D., Rochat, E., Consonni, E., Siripurapu, S., 2024. Submarine power connections: a key element in unlocking the energy transition to a more sustainable future. IEEE Power Energy Mag. 22 (5), 100–110. https://doi.org/10.1109/MPE.2024.3402182.

Gill, A.B., 2005. Offshore Renewable Energy: Ecological Implications of Generating Electricity in the Coastal Zone, 42. https://www.jstor.org/stable/3505894?seq=1&cid=pdf. (Accessed 15 December 2025).

Harsanyi, P., Scott, K., Easton, B.A.A., de la Cruz Ortiz, G., Chapman, E.C.N., Piper, A.J.R., Rochas, C.M.V., Lyndon, A.R., 2022. The effects of anthropogenic electromagnetic fields (EMF) on the early development of two commercially important crustaceans, European lobster, *homarus gammarus (L.)* and edible crab, *cancer pagurus (L.)*. J. Mar. Sci. Eng. 10 (5), 564. https://doi.org/10.3390/jmse10050564.

Hermans, A., Winter, H.V., Gill, A.B., Murk, A.J., 2024. Do electromagnetic fields from subsea power cables effect benthic elasmobranch behaviour? A risk-based approach for the Dutch Continental Shelf. Environ. Pollut. 346, 123570. https://doi.org/10.1016/j.envpol.2024.123570.

Hutchison, Z.L., Sigray, P., He, H., Gill, A.B., King, J.W., Gibson, C., 2018. Electromagnetic field (EMF) impacts on elasmobranch (Shark, rays, and skates) and American lobster movement and migration from direct Current cables. https://www.boem.gov/environment/environmental-studies/(accessed2025-12-15.

Hutchison, Z.L., Gill, A.B., Sigray, P., He, H., King, J.W., 2020a. Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. Sci. Rep. 10, 4219. https://doi.org/10.1038/s41598-020-60793-x.

Hutchison, Z.L., Secor, D.H., Gill, A.B., 2020b. The interaction between resource species and electromagnetic fields associated with electricity production by offshore wind farms. Oceanography (Wash. D. C.) 33 (4), 96–107. https://doi.org/10.2307/26965753. Special issue: Understanding the effects of offshore wind energy development on fisheries.

Hutchison, Z.L., Gill, A.B., Sigray, P., He, H., King, J.W., 2021. A modelling evaluation of electromagnetic fields emitted by buried subsea power cables and encountered by marine animals: considerations for marine renewable energy development. Renew. Energy 177, 72–81. https://doi.org/10.1016/j.renene.2021.05.041.

Isaksson, N., Scott, B.E., Hunt, G.L., Benninghaus, E., Declerck, M., Gormley, K., Harris, C., Sjöstrand, S., Trifonova, N.I., Waggitt, J.J., Wihsgott, J.U., Williams, C., Zampollo, A., Williamson, B.J., 2023. A paradigm for understanding whole ecosystem effects of offshore wind farms in Shelf Seas. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. https://doi.org/10.1093/icesjms/fsad194.

Jakubowska, M., Urban-Malinga, B., Otremba, Z., Andrulewicz, E., 2019. Effect of low frequency electromagnetic field on the behavior and bioenergetics of the polychaete *Hediste diversicolor*. Mar. Environ. Res. 150, 104766. https://doi.org/10.1016/j.marenvres.2019.104766.

James, E., Ghodsi, M., Ford, A.T., 2025. Female crabs are more sensitive to environmentally relevant electromagnetic fields from submarine power cables. Environ. Sci. Technol. Lett. https://doi.org/10.1021/acs.estlett.5c00862.

Katovich, E., 2024. Quantifying the effects of energy infrastructure on bird populations and biodiversity. Environ. Sci. Technol. 58 (1), 323–332. https://doi.org/10.1021/acs.est.3c03899.

Kavet, R., Wyman, M.T., Klimley, A.P., 2016. Modeling magnetic fields from a DC power cable buried beneath San Francisco Bay based on empirical measurements. PLoS One 11 (2). https://doi.org/10.1371/journal.pone.0148543.

Khoshroo, M.M.Z., Mehrjan, M.S., Samiee, F., Soltani, M., Shekarabi, S.P.H., 2018. Some immunological responses of common carp *(Cyprinus Carpio)* fingerling to acute extremely low-frequency electromagnetic fields (50 hz). Fish Physiol. Biochem. 44 (1), 235–243. https://doi.org/10.1007/s10695-017-0429-1.

Kilfoyle, A.K., Jermain, R.F., Dhanak, M.R., Huston, J.P., Spieler, R.E., 2018. Effects of EMF emissions from undersea electric cables on coral reef fish. Bioelectromagnetics 39 (1), 35–52. https://doi.org/10.1002/bem.22092.

Klimley, A.P., Wyman, M.T., Kavet, R., 2017. Chinook salmon and green sturgeon migrate through San Francisco Estuary despite large distortions in the local magnetic field produced by bridges. PLoS One 12 (6). https://doi.org/10.1371/journal.pone.0169031.

Klimley, A.P., Putman, N.F., Keller, B.A., Noakes, D., 2021. A call to assess the impacts of electromagnetic fields from subsea cables on the movement ecology of marine migrants. Conser. Sci. Practice 3 (7), e436. https://doi.org/10.1111/csp2.436.

Krylov, V.V., 2008. Impact of alternating electromagnetic field of ultralow and low frequencies upon survival, development, and production parameters in Daphnia *Magna straus* (Crustacea, cladocera). Inland Water Biol. 1 (2), 134–140. https://doi.org/10.1134/s1995082908020053.

Krylov, V.V., 2010. Effects of electromagnetic fields on parthenogenic eggs of Daphnia *Magna Straus*. Ecotoxicol. Environ. Saf. 73, 62–66. https://doi.org/10.1016/j.ecoenv.2009.03.005.

Krylov, V., Machikhin, A., Sizov, D., Guryleva, A., Sizova, A., Zhdanova, S., Tchougounov, V., Burlakov, A., 2022. Influence of hypomagnetic field on the heartbeat in zebrafish embryos. Front. Physiol. 13, 1040083. https://doi.org/10.3389/fphys.2022.1040083.

Kuhnz, L.A., Buck, K., Lovera, C., Litvin, S., Whaling, P.J., Barry, J.P., 2008. Potential impacts of the MARS cable on the seabed and benthic faunal assemblages (report). https://www.researchgate.net/publication/268374310_Potential_impacts_of_the_MARS_Cable_on_the_seabed_and_benthic_faunal_assemblages. (Accessed 15 December 2025).

Laruelle, G.G., Cai, W.-J., Hu, X., Gruber, N., Mackenzie, F.T., Regnier, P., 2018. Continental shelves as a variable but increasing global sink for atmospheric carbon dioxide. Nat. Commun. 9, 454. https://doi.org/10.1038/s41467-017-02738-z.

Lee, W., Yang, K.L., 2014. Using Medaka embryos as a model System to Study biological effects of the electromagnetic fields on development and behavior. Ecotoxicol. Environ. Saf. 108, 187–194. https://doi.org/10.1016/j.ecoenv.2014.06.035.

Lerchl, A., Zachmann, A., Ali, M.A., Reiter, R.J., 1998. The effects of pulsing magnetic fields on pineal melatonin synthesis in a teleost fish (Brook trout, *Salvelinus fontinalis*)'. Neurosci. Lett. 256 (2), 113–116. https://doi.org/10.1016/S0304-3940(98)00760-3.

Li, Y., Liu, X., Liu, K., Miao, W., Zhou, C., Li, Y., Wu, H., 2014. Extremely low-frequency magnetic fields induce developmental toxicity and apoptosis in zebrafish (*Danio rerio*) Embryos. Biol. Trace Elem. Res. 162 (1–3), 324–332. https://doi.org/10.1007/s12011-014-0130-5.

Li, Y., Ru, B., Liu, X., Miao, W., Zhang, K., Han, L., Ni, H., Wu, H., 2015. Effects of extremely low frequency alternating-current magnetic fields on the growth performance and digestive enzyme activity of Tilapia *Oreochromis Niloticus*. Environ. Biol. Fish. 98 (1), 337–343. https://doi.org/10.1007/s10641-014-0263-6.

Li, C., Mogollón, J.M., Tukker, A., Steubing, B., 2022. Environmental impacts of global offshore wind energy development until 2040. Environ. Sci. Technol. 56 (16), 11567–11577. https://doi.org/10.1021/acs.est.2c02183.

Li, C., Coolen, J.W.P., Scherer, L., Mogollón, J.M., Braeckman, U., Vanaverbeke, J., Tukker, A., Steubing, B., 2023. Offshore wind energy and marine biodiversity in the North Sea: life cycle impact assessment for benthic communities. Environ. Sci. Technol. 57 (16), 6455–6464. https://doi.org/10.1021/acs.est.2c07797.

Loghmannia, J., Heidari, B., Rozati, S.A., Kazemi, S., 2015. The physiological responses of the caspian Kutum (*rutilus frisii Kutum*) fry to the static magnetic fields with different intensities during acute and subacute exposures. Ecotoxicol. Environ. Saf. 111, 215–219. https://doi.org/10.1016/j.ecoenv.2014.10.020.

Lohmann, K.J., Pentcheff, N.D., Nevitt, G.A., Stetten, G.D., Zimmer-Faust, R.K., Jarrard, H.E., Boles, L., 1995. Magnetic orientation of spiny lobsters in the Ocean: experiments with undersea coil systems. J. Exp. Biol. 198 (10), 2041–2048. https://doi.org/10.1242/jeb.198.10.2041.

Love, M.S., Nishimoto, M.M., Bull, A.S., 2015. 'Identical response of caged rock crabs (Genera *metacarcinus* and *Cancer productus*) to energized and unenergized undersea power cables in Southern California, USA'. Report to the Pacific fishery management council. http://www.pcouncil.org/wp-content/uploads/Cmt_Reedsport. (Accessed 15 December 2025).

Love, M.S., Nishimoto, M.M., Clark, S., Bull, A.S., 2016. Renewable energy in situ power cable observation. In: U.S. Department of the Interior, Bureau of Ocean Energy Management, Pacific OCS Region. OCS Study BOEM 2016-041, p. 86. https://espis.boem.gov/final%20reports/BOEM_2016-041.pdf.

Love, M.S., Nishimoto, M.M., Clark, S., McCrea, M., Bull, A.S., 2017a. The responses of caged rock crabs (Genera Metacarcinus and Cancer) to energized and unenergized undersea power cables in Southern California, USA. Bull. South Calif. Acad. Sci. 116 (2), 61–69. https://doi.org/10.3160/0038-3872-116.2.61.

Love, M.S., Nishimoto, M.M., Clark, S., McCrea, M., Bull, A.S., 2017b. Assessing potential impacts of energized submarine power cables on crab harvests. Cont. Shelf Res. 151, 23–29. https://doi.org/10.1016/j.csr.2017.10.002.

Love, M.S., Nishimoto, M.M., Schroeder, D.M., Snook, L., Bull, A.S., 2017c. A comparison of fishes and invertebrates living in the vicinity of energized and unenergized submarine power cables and natural Sea floor off Southern California, USA. J. Renewable Energy 2017, 8727164. https://doi.org/10.1155/2017/8727164.

Malagoli, D., Gobba, F., Ottaviani, E., 2003. Effects of 50-Hz magnetic fields on the signalling pathways of FMLP-induced shape changes in invertebrate immunocytes: the activation of an alternative "Stress Pathway". Biochim. Biophys. Acta Gen. Subj. 1620 (1–3), 185–190. https://doi.org/10.1016/S0304-4165(02)00531-7.

Malagoli, D., Gobba, F., Ottaviani, E., 2006. 50 Hz magnetic fields of constant or fluctuating intensity: effects on immunocyte Hsp70 in the mussel Mytilus galloprovincialis. Bioelectromagnetics 27 (5), 427–429. https://doi.org/10.1002/bem.20241.

Newton, K.C., 2024. The Effects of Anthropogenic Electromagnetic Fields on the Behavior of Geomagnetically Displaced Skates' https://doi.org/10.1101/2024.04.23.590834.

Nofouzi, K., Sheikhzadeh, N., Mohamad-Zadeh Jassur, D., Ashrafi-Helan, J., Shabazfar, A.A., Tukmechi, A., Nagshara, H., Baradaran, B., Mahmoudi, R., 2017. Effects of low frequency electromagnetic fields on growth. Total Antioxidant Activity Morpho. Intest. Rainbow Trout (Oncorhynchus mykiss). https://doi.org/10.22067/veterinary.v8i1.51865.

Oliva, M., De Marchi, L., Cuccaro, A., Fumagalli, G., Freitas, R., Fontana, N., Raugi, M., Barmada, S., Pretti, C., 2023. Introducing energy into marine environments: a lab-scale static magnetic field submarine cable simulation and its effects on sperm and larval development on a reef *forming serpulid*. Environ. Pollut. 328, 121625. https://doi.org/10.1016/j.envpol.2023.121625.

Ottaviani, E., Malagoli, D., Ferrari, A., Tagilazucchi, D., Conte, A., Gobba, F.M., 2002. 50 Hz magnetic fields of varying flux intensity affect cell shape changes in invertebrate immunocytes: the role of potassium ion channels. Bioelectromagnetics 23 (4), 292–297. https://doi.org/10.1002/bem.10021.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., et al., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Syst. Rev. 10, 89. https://doi.org/10.1186/s13643-021-01626-4.

Preziosi, D., Dawson, D., Flanary, C., Raghukumar, K., Eikenbary, S., Hull, D., Schultz, C., 2024. Using Ecological Risk Assessment to Assess EMF Impacts to Marine Life from Offshore Wind Infrastructure. Society of Petroleum Engineers (SPE) conference paper. (Accessed 15 December 2025).

Rebecchi, F., Lattanzi, D., Abramovich, S., Ambrogini, P., Ciacci, C., Betti, M., Frontalini, F., 2023. Evaluation of the effects of electrical stimulation: a pilot experiment on the marine benthic foraminiferal species *Amphistegina lessonii*. Life 13 (4), 862. https://doi.org/10.3390/life13040862.

Rijkswaterstaat, 2020. Potential effects of electromagnetic fields in the Dutch north Sea: phase 2 – pilot field study. Rijkswaterstaat, Minist. Infrastruct. Water Manag. The Netherlands. https://www.noordzeeloket.nl/publish/pages/173407/potential_effects_of_electromagnetic_fields_in_the_dutch_north_sea_-_phase_12pilot_study_rws_wvl.pdf. (Accessed 15 December 2025).

Sadowski, M., Winnicki, A., Formicki, K., Sobociński, A., Tański, A., 2007. The effect of magnetic field on permeability of egg shells of salmonid fishes. Acta chthyologica et Piscatoria 37 (2), 129–135. https://doi.org/10.3750/AIP2007.37.2.10.

Schell, K.R., Claro, J., Guikema, S.D., 2017. Probabilistic cost prediction for submarine power cable projects. Int. J. Electr. Power Energy Syst. 90, 1–9. https://doi.org/10.1016/j.ijepes.2017.01.017.

Scott, K., Harsanyi, P., Lyndon, A.R., 2018. Understanding the effects of electromagnetic field emissions from marine renewable energy devices (MREDs) on the commercially important edible crab, *cancer pagurus (L.)*. Mar. Pollut. Bull. 131, 580–588. https://doi.org/10.1016/j.marpolbul.2018.04.062.

Scott, K., Harsanyi, P., Easton, B.A.A., Piper, A.J.R., Rochas, C.M.V., Lyndon, A.R., 2021. Exposure to electromagnetic fields (EMF) from submarine power cables can trigger strength-dependent behavioural and physiological responses in edible crab, *cancer pagurus (L.)*. J. Mar. Sci. Eng. 9 (7), 776. https://doi.org/10.3390/jmse9070776.

Sherwood, J., Chidgey, S., Crockett, P., Gwyther, D., Ho, P., Stewart, S., Strong, D., Whitely, B., Williams, A., 2016. Installation and operational effects of a HVDC submarine cable in a Continental shelf setting: Bass Strait, Australia. J. Ocean Eng. Sci. 1 (4), 337–353. https://doi.org/10.1016/j.joes.2016.10.001.

Skauli, K.S., Reitan, J.B., Walther, B.T., 2000. Hatching in zebrafish (*Danio rerio)* embryos exposed to a 50 Hz magnetic field. Bioelectromagnetics 21 (5), 407–410. https://doi.org/10.1002/1521-186X(200007)21:5<407::AID-BEM10>3.0.CO;2-V.

Stankevičiūtė, M., Jakubowska, M., Pažusienė, J., et al., 2019. Genotoxic and cytotoxic effects of 50 Hz 1 MT electromagnetic field on larval Rainbow Trout (*Oncorhynchus Mykiss),* Baltic clam (*Limecola balthica)* and common ragworm *(Hediste diversicolor*). Aquat. Toxicol. 208, 109–117. https://doi.org/10.1016/j.aquatox.2018.12.023.

Tański, A., Formicki, K., Śmietana, P., Sadowski, M., Winnicki, A., 2005. Sheltering behaviour of spinycheek crayfish (*Orconectes cimosus*) in the presence of an artificial magnetic field. BFPP Bull. Fr. Pêche Prot. Milieux Aquatiques 787–793. (Accessed 15 December 2025).

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., Carlier, A., 2018. A review of potential impacts of submarine power cables on the Marine environment: knowledge gaps, recommendations and future directions. Renew. Sustain. Energy Rev. 96, 380–391. https://doi.org/10.1016/j.rser.2018.07.026.

Taormina, B., Di Poi, C., Agnalt, A.L., Carlier, A., Desroy, N., Escobar-Lux, R.H., D'eu, J. F., Freytet, F., Durif, C.M.F., 2020. Impact of magnetic fields generated by AC/DC submarine power cables on the behavior of juvenile European lobster (*Homarus gammarus*). Aquat. Toxicol. 220, 105401. https://doi.org/10.1016/j.aquatox.2019.105401.

Tomanova, K., Vacha, M., 2016. The magnetic orientation of the antarctic amphipod *Gondogeneia Antarctica* is cancelled by very weak radiofrequency fields. J. Exp. Biol. 219 (11), 1717–1724. https://doi.org/10.1242/jeb.132878.

Ugolini, A., Pezzani, A., 1995. Magnetic compass and learning of the Y-axis (sea-land) direction in the marine isopod Idotea baltica basteri. Anim. Behav. 50 (2), 295–300. https://doi.org/10.1006/anbe.1995.0245.

Westerberg, H., Lagenfelt, I., 2008. Sub-Sea power cables and the migration behaviour of the European Eel. Fish. Manag. Ecol. 15, 369–375. https://doi.org/10.1111/j.1365-2400.2008.00630.x.

Whaley, P., Roth, N., 2022. How we promote rigour in systematic reviews and evidence maps at environment International. Environ. Int. 170, 107543. https://doi.org/10.1016/j.envint.2022.107543.

White, J.W., Cole, B.J., Cherr, G.N., Connon, R.E., Brander, S.M., 2017. Scaling up endocrine disruption effects from individuals to populations: outcomes depend on how many males a population needs. Environ. Sci. Technol. 51 (3), 1802–1810. https://doi.org/10.1021/acs.est.6b05276.

Williams, J.P., Jaco, E.M., Scholz, Z., Williams, C.M., Pondella, D.J., Rasser, M.K., Schroeder, D.M., 2023. Red rock crab *(Cancer Productus*) movement is not influenced by electromagnetic fields produced by a submarine power transmission cable. Cont. Shelf Res. 269, 105145. https://doi.org/10.1016/j.csr.2023.105145.

Woodruff, D.L., Cullinan, V.I., Copping, A.E., Marshall, K.E., 2013. *Effects of Electromagnetic Fields on Fish and Invertebrates Task 2.1.3: Effects on Aquatic Organisms Fiscal Year 2012 Progress Report. Environmental Effects of Marine and Hydrokinetic Energy'*. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy, Richland, WA, USA. https://tethys.pnnl.gov/publications/effects-electromagnetic-fields-fish-invertebrates-fy2012-progress-report. (Accessed 15 December 2025).

Wyman, M.T., Klimley, A.P., Battleson, R.D., Agosta, T.V., Chapman, E.D., Haverkamp, P.J., Pagel, M.D., Kavet, R., 2018. Behavioral responses by migrating juvenile salmonids to a subsea high-voltage DC power cable. Mar. Biol. 165 (8). https://doi.org/10.1007/s00227-018-3385-0.

Wyman, M.T., Kavet, R., Battleson, R.D., Agosta, T.V., Chapman, E.D., Haverkamp, P.J., Pagel, M.D., Klimley, A.P., 2023. Assessment of potential impact of magnetic fields from a subsea high-voltage DC power cable on migrating green sturgeon. Acipenser Medirost. Marine Biol. 170 (12). https://doi.org/10.1007/s00227-023-04302-4.

Zhang, Z., Kuang, J., Chen, G., Zeng, H., Huang, B., Liu, Z., 2024. Numerical study on trenching performances of the underwater jet flow for submarine cable laying. Appl. Ocean Res. 150, 104140. https://doi.org/10.1016/j.apor.2024.104140.

Zimmerman, S., Zimmerman, A.M., Winters, W.D., Cameron, I.L., 1990. Influence of 60-Hz magnetic fields on sea urchin development. J. Bioelectromagnetics Soc. 11 (1), 37–45. https://doi.org/10.1002/bem.2250110106, 11(1), 37–45.