The European Zoological Journal

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tizo21

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To cite this article: J. Krzystolik, A. Tański, R. Piesiewicz, A. Korzelecka-Orkisz & K. Formicki (2024) Effect of an electromagnetic field generated by power infrastructure on the spatial orientation of developing sea trout embryos *Salmo trutta* Linnaeus, 1758, The European Zoological Journal, 91:1, 366-377, DOI: 10.1080/24750263.2024.2340471

To link to this article: https://doi.org/10.1080/24750263.2024.2340471

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Published online: 25 Apr 2024.

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The European Zoological Journal, 2024, 366–377
Vol. 91, No. 1, https://doi.org/10.1080/24750263.2024.2340471

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Effect of an electromagnetic field generated by power infrastructure on the spatial orientation of developing sea trout embryos *Salmo trutta* Linnaeus, 1758

J. KRZYSTOLIK, A. TAŃSKI*, R. PIESIEWICZ, A. KORZELECKA-ORKISZ, & K. FORMICKI

Department of Hydrobiology, Ichthyology and Biotechnology of Animal Reproduction, West Pomeranian University of Technology, Szczecin, Poland

(Received 23 August 2023; accepted 7 March 2024)

Abstract

In recent decades, rapid technological advancements have led to a growing influence of anthropogenic electromagnetic fields on aquatic ecosystems. These fields predominantly stem from energy infrastructure facilities such as wind farms, high-voltage lines, underwater transmission cables, and power plants. As a result, there has been increasing interest in understanding the effects of heightened electromagnetic fields on aquatic ecosystems and their inhabitants, including developing fertilized eggs. This study focused on examining the effects of electromagnetic fields generated by high-voltage lines and power transformers, which are integral to transmission nodes and power plants, on the directional axis of symmetry in sea trout *Salmo trutta* (Linnaeus, 1758) embryos and their survival rates. The research was carried out at "PGE Dolna Odra in Nowy Czarnów", one of Poland's largest power plants (53°12′34″ N, 014°28′16″ E). Two experimental sites were selected, with electromagnetic field values ranging from 1.36 to 5.28 μT at the first site and 8.97 to 14.18 μT at the second site. A control sample was also established in an area unaffected by anthropogenic electromagnetic fields. The study findings revealed that electromagnetic fields originating from energy infrastructure facilities significantly affect the spatial orientation of sea trout embryos. The embryos' response was influenced to be influenced by both the strength and direction of the electromagnetic fields. At the first test site, lower field values caused deviations from the natural alignment axis in the geomagnetic field (north-south), resulting in a shift towards the primary field source. In contrast, the second test site, with higher electromagnetic field values, showed no significant spatial orientation in embryo alignment. Additionally, the study highlighted that higher electromagnetic field values accelerated the rate of embryogenesis but also led to an increased mortality rate among sea trout embryos.

Keywords: *Electromagnetic fields*, *anthropogenic impact*, *fish embryogenesis*, *power plant*

*Correspondence: A. Tański, Department of Hydrobiology, Ichthyology and Biotechnology of Animal Reproduction, West Pomeranian University of Technology, Szczecin, Poland. Email: adam.tanski@zut.edu.pl

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1. Introduction

All organisms on Earth live within the natural geomagnetic field, which is generated in the fluid part of the Earth's core and typically ranges from 30 to 70 μT (Hulot et al. 2010). The strength of this field varies depending on the distance from the Earth's magnetic poles (Jursa 1985; Skiles 1985; Finlay et al. 2010). While the geomagnetic field experiences gradual changes over centuries, primarily due to the shifting of the poles (Panovska et al. 2019), these alterations are insignificant and nearly imperceptible in the short term. Small periodic changes in geomagnetic field strength can occur due to anomalies caused by solar wind (Akasofu & Chapman 1974; Panovska et al. 2019). There are also diurnal fluctuations in magnetic field induction, of the order of tens of nanotesla (nT) (Yamazaki & Maute 2017).

Some animals, including fish, have evolved the ability of magnetoreception, that is, sensing magnetic fields in the surrounding environment and changes in their properties, such as field direction, intensity, and gradient, and responding to changes in these parameters. This is used by some fish species, especially those making long migrations such as salmon and eels, to determine the direction of migration (Tesch 1974; Mann et al. 1988; Tesch et al. 1992; Formicki 2008).

However, not only fish that make long migrations are able to sense and respond to the Earth's magnetic field; directional responses have been observed in carp, among others (Hart et al. 2012). In addition, it has been confirmed that both increases and decreases in magnetic fields can condition feeding in certain fish species, including Prussian carp *Carassius auratus gibelio* (Bloch, 1782) and southern stingray *Dasyatis americana* (Hildebrand & Schroeder, 1928) (O'Connell et al. 2010; Kuz'mina et al. 2022). The impact of magnetic fields affects not only adults, but all developmental stages, having a significant impact also on gametes, embryonic development, larvae, or fry (Formicki et al. 2021).

Research on the influence of artificial magnetic fields on organisms focuses on two types of fields: static and electromagnetic. Static fields are ones produced by ferrite magnets, and electromagnetic fields are those generated by movement of electrically charged particles, such as in sources like the energy infrastructure objects discussed in this article. Both fields differ in their interaction characteristics, yet their impact on biological structures is often similar, suggesting a comparable mechanism of response in living organisms to both interactions. This was shown in studies employing both types of magnetic fields, demonstrating that both static magnetic fields and electromagnetic fields showed a similar trend of action (Stolfa et al. 2007; Hashish et al. 2008). Comparisons of available studies primarily focusing on one of the aforementioned types of magnetic interaction also indicate that the influence of both types of fields on organisms is similar, although lower values of electromagnetic fields often induced effects comparable to those achieved with significantly higher values of static magnetic fields (Formicki et al. 2021). Considering those similarities, examples of reactions of living organisms to both types of magnetic fields are provided in the following sections of this article. However the research presented herein will focus solely on the influence of electromagnetic fields.

Magnetic fields can impact embryos from the very early stages. A short exposure of roach (*Rutilus rutilus*) fertilized eggs to a strong magnetic storm during cleavage with embryonic cells at the blastula stage resulted in an increase in the number of cells in the anaphase and telophase compared with the cells in the prophase and metaphase (Formicki et al. 2021). Additionally, it was revealed that exposure to a magnetic storms during the initial stages of development induces changes in the length, weight, and other morphological characteristics of hatchlings, including the number of rays in the ventral and anal fins, as well as the number of vertebrae (Krylov et al. 2010). Formicki and Winnicki (1998) further confirmed that hatchlings hatched from fertilized eggs exposed to an elevated static magnetic field during incubation tend to be longer and heavier, and this exposure also shortens the incubation time of fertilized eggs.

Manipulating the value of a static magnetic field through magnet application during embryonic development affects the motility of embryonic movements. During the early phases of development, it influences the movement of ectoplasm in the fertilized eggs (Korzelecka 1999). Subsequently, it impacts the motility of the heart muscle, resulting in an increased number of heartbeats per minute after the field's value is increased (Korzelecka-Orkisz 2015). Interestingly, acceleration of the heart rate was also observed in hypomagnetic fields, characterized by values lower than the natural geomagnetic field (Krylov et al. 2022).

A static magnetic field can delay the time of emergence and increase the density of melanophores in the developing embryo (Brysiewicz & Formicki 2019). In contrast, it can also accelerate the time of embryonic development and the rate of yolk sac resorption (Fey et al. 2019). A reduction in the value of the fields below the value of the natural

geomagnetic field (hypomagnetic fields), can impact the developing embryos by increasing their mortality and affecting the size and development of the hatchlings (Krylov et al. 2021).

Currently, the environment, including aquatic ecosystems, faces not only the influence of the natural geomagnetic field but also the increasing impact of magnetic and electromagnetic fields originating from human activities. Technological advancements in recent decades have led to the proliferation of facilities generating and transmitting electricity, such as wind farms, power plants, high-voltage power lines, and underwater transmission cables in seas and reservoirs. Consequently, these man-made structures locally alter the magnetic field in aquatic environments, thereby affecting the organisms that inhabit and develop within them (Andrulewicz et al. 2003; Öhman et al. 2007; Gill et al. 2012; Fey et al. 2019). Even slight changes in magnetic field values can have significant repercussions on aquatic ecosystems. Anthropogenic disturbances to the magnetic field primarily impact specific areas, potentially exerting considerable effects on aquatic ecosystems and ichthyofauna. This, in turn, may influence critical fish reproduction areas and the development of fish embryos.

The impact of anthropogenic electromagnetic fields on aquatic organisms remains an area of limited understanding (Gill & Desender 2020; Hutchison et al. 2020). Current research indicates that these fields can have noticeable effects on aquatic life, although such impacts are often subtle (Andrulewicz et al. 2003; Bochert & Zettler 2004; Gill et al. 2012; Scott et al. 2021).

Studies examining the effects of magnetic field disturbances on ichthyofauna primarily focus on adult fish and reveal their ability to respond directionally to new field sources (Öhman et al. 2007; Cada et al. 2011; Bevelhimer et al. 2013). This responsiveness can manifest in changes to migration routes and fish spawning grounds. Consequently, the fertilized eggs developing in these areas may also be exposed to artificial electromagnetic fields originating from human activities. Laboratory-based investigations demonstrate that electromagnetic fields can influence the process of embryogenesis (Formicki et al. 2021). However, there is a dearth of research transferring laboratory findings to field conditions to assess the actual impact of electromagnetic field-generating objects on incubating fertilized eggs.

The early stages of ontogenesis, particularly embryogenesis, have been found to be highly susceptible to the effects of electromagnetic fields. Numerous laboratory studies have demonstrated that magnetic and electromagnetic fields influence the directional alignment along the axis of symmetry in fish embryos concerning magnetic field lines (Formicki et al. 1997; Formicki & Winnicki 1998; Tański 2002; Tanski et al. 2005).

The mechanisms underlying fish responses to magnetic and electromagnetic fields remain poorly understood. Changes in the alignment of embryonic bodies under the influence of magnetic fields are likely explained by hypotheses concerning the perception of magnetic fields in fish. One such hypothesis involves the repositioning of magnetite particles (Fe_3O_4) to convert magnetic field signals into mechanical signals that the nervous system can perceive (Kirschvink & Gould 1981; Kirschvink et al. 1985). These magnetite particles have been found in fish bodies, particularly in migratory species, and are thought to assist in indicating the direction of migrations (Phillips 1986; Moore et al. 1990; Ogura et al. 1992; Phillips et al. 2002; Diego-Rasilla & Phillips 2021). Magnetite is synthesized in fish bodies throughout their entire lives and is accumulated mainly in the occipital regions (Kirschvink et al. 1985; Chew & Brown 1989). However, this explanation might not account for the directional response in fish embryo alignment since magnetite synthesis at early embryonic stages is limited, and the embryos do not exhibit active movements or have a developed nervous system during this time.

Alternatively, the changes in embryo orientation may be attributed to quasi-peristaltic movements, which involve ectoplasm movements during early embryonic development, with meridional and latitudinal waves of protoplasm across the yolk sphere (Korzelecka 1999; Korzelecka-Orkisz et al. 2010). Research suggests that both static and variable electromagnetic fields, similar to those generated by energy infrastructure facilities, can influence these quasi-peristaltic movements (Korzelecka 1999), which, in turn, may influence the directional alignment of the embryos within the developing fertilized eggs.

Another possibility is that changes at the cellular level resulting from the influence of magnetic fields could explain the shifts in embryo orientation. Magnetic fields have been shown to affect the pH and redox potential of cells, altering the solubility of salts and acids and impacting chemical reactions within the cell (Zablodskiy et al. 2018). Magnetic fields also influence the rate of reactions and electrolytic dissociation within cells (Savchenko et al. 2020). Since cell membranes are dipoles, magnetic fields can deform them (Sidortsov et al. 2006). These fields accelerate the diffusion process, leading to increased oxygen flow and water transport into

the cell (Savchenko et al. 2020). Additionally, at the cellular level, external magnetic fields may affect the position of magnetosomes (chains of single-domain biogenic magnetite surrounded by a membrane) and exert forces on the fibers closing or opening ion channels, thus altering the cell membrane potential (Walker et al. 2002; Solov'yov & Greiner 2007).

In this study, we sought to assess how the direction of embryo symmetry axis and mortality is affected by electromagnetic fields generated by high-voltage lines and current transformers – prevalent infrastructure in transmission nodes and power plants.

High-voltage lines and current transformers were chosen for investigation as they are commonly located near or even above bodies of water, and power plants are often situated close to water bodies, especially those employing open-circuit water for cooling. For this study, the sea trout *Salmo trutta* (Linnaeus, 1758), an anadromous migratory fish belonging to the Salmonidae family, was selected. This choice was further justified by previous confirmation of the Salmonidae family's susceptibility to the influence of magnetic fields (Quinn 1980; Dittman & Quinn 1996; Formicki et al. 2004; Lohmann et al. 2008). Moreover, the decline in the population of sea trout in the Baltic Sea catchment in recent decades (Amosova et al. 2021) underscores the importance of understanding and considering anthropogenic factors, including the impact of electromagnetic fields, on this migratory species, especially as it frequently traverses regions close to power grids in both marine and freshwater environments.

2. Methods

The study used fertilized sea trout eggs collected from fish in the Rega River, specifically from the egg collection point for stocking purposes (belonging to the Polish Angling Association in Szczecin) in the town of Trzebiatów (54°02′55″ N, 15°16′17″ E). The eggs were collected from 5 females using a pneumatic method known for collecting high-quality gametes (Kowalski et al. 2018). Milt was obtained from 11 males through abdominal compression. After spawning, all fish were released back into the water.

Eggs from individual females were transported separately in 0.75 dm^3 thermoses, while milt from individual males was placed in glass tubes. Both were transported in thermoses or portable refrigerators, maintaining a constant temperature of 4 ± 0.5°C. Upon arrival at the laboratory, the eggs were qualitatively assessed for any contamination or traces of ovarian tissue. The milt quality was also evaluated using CASA computerized sperm movement analysis (Alavi & Cosson 2006; Bonisławska et al. 2015; Dziewulska & Pilarska 2023). The eggs from all 5 females were then fertilized with sperm from 9 males using the "dry method", selecting the milt with the highest motility. Fertilized eggs were subsequently transported in thermoses to the test sites. The fertilization efficiency was assessed by microscopic observation of a sample of 100 eggs.

For the experiments, the site of the Polish Energy Group's Dolna Odra power plant in Nowy Czarnów (53°12′34″ N, 014°28′16″ E) was chosen due to its numerous anthropogenic sources of disturbance to the natural geomagnetic field and its proximity to watercourses. The power plant, operating since the 1970s, has four units with a total installed electrical capacity of 908 MWe and a thermal capacity of 91.15 MWt. It operates in a continuous system as it serves as a "must run" unit, meaning that its operation is enforced by grid security considerations.

Two research sites were designated on the power plant's premises. The first site was located 10 meters from the 220 kW/110 kW autotransformer directly under the high-voltage line with a current power of 220 kW. The autotransformer was positioned northwest of the egg incubator, and the high-voltage line served as an additional source disturbing the natural geomagnetic field from above (Figure 1). The second site, situated a few hundred meters from the first one, was positioned directly under

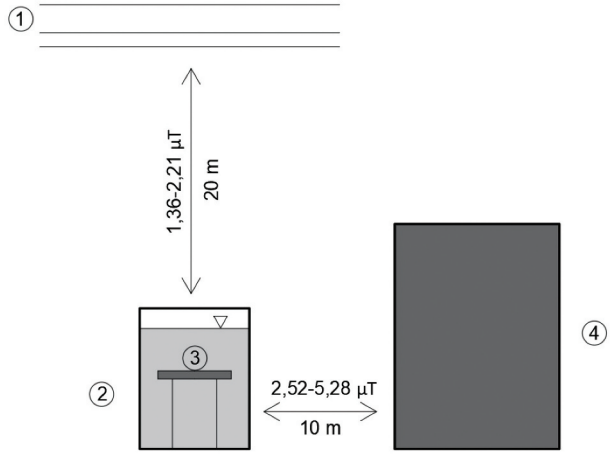

Figure 1. Diagram of test site 1 with marked distance from sources of electromagnetic fields and intensity of those fields, where:1- high voltage line; 2- water tank; 3- glass column with three circular orientation arenas; 4–220 kW/110 kW autotransformer.

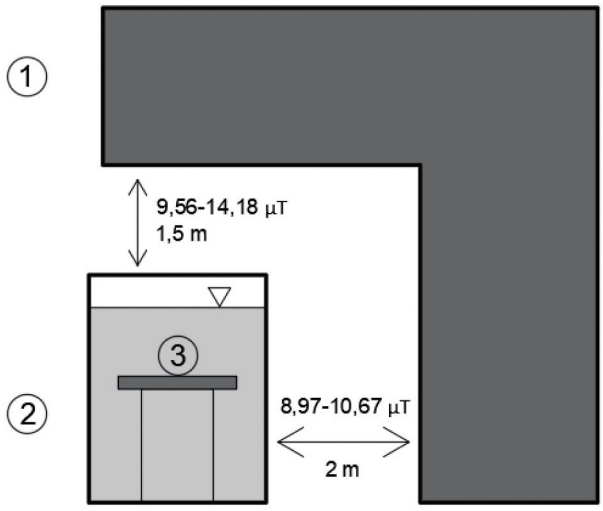

Figure 2. Diagram of test site 2 with marked distance from sources of electromagnetic fields and intensity of those fields, where: 1–220 kW multi-tap transformer; 2- water tank; 3- glass column with three circular orientation arenas.

the transformer in such a way that the electromagnetic fields generated by it affected the incubating fertilized eggs both from the northwest and from above (Figure 2). The intensity of the electromagnetic field affecting the developing embryos depended on the current load of the transformer or high-voltage line, wire configuration, and distance from the source. As the current load varied over time, the measured values of electromagnetic fields at each site differed depending on the time of measurement (Table I). The control sample was located in fields near the village of Babinek, away from any buildings and high-voltage lines, to eliminate any anthropogenic magnetic fields of anthropogenic origin (53°08′32″ N, 014°34′52″ E).

The experiment began on November 27, 2021. Portable egg incubation kits were used to incubate sea trout fertilized eggs at selected test sites, which included oval tanks with a volume of 200 dm^3 with walls impervious to light. Inside the tanks, glass columns were set up with three circular orientation arenas with a volume of 3 dm^3 on which nets with mesh sides adjusted to the size of the eggs were stretched, so that each egg stuck still during incubation. The large volume of water guaranteed thermal stability and ensured adequate oxygen requirements during the initial stage of embryonic development. In addition, the installation was shielded by a layer of thermal insulation so that the incubation kit was not affected by solar radiation and prevented temperature drops at night.

Readings of the positioning of developing embryos were taken after the closure of the blastopore, that is, when the body of the embryo is already visible, but still does not make movements. In the case of sea trout, this usually occurs at 120 D^o (degree-day)

In order to capture the right moment, the water temperature in all incubators was continuously monitored, and individual developing fertilized eggs were carefully pulled out and observed under a microscope to assess the advancement of embryogenesis. Thus, the moment was determined when blastopore closure occurred in all developing embryos (Figure 3), which occurred on January 11, 2022, which is 129 D^o of development. A reading at a later stage of embryonic

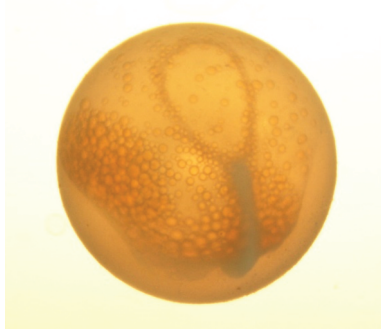

Figure 3. Sea trout embryo after blastopore closure.

Table I. Characteristics of the study sites.

Variant	Main source of electromagnetic field interference	Distance to the nearest source of electromagnetic fields [m]	Intensity of electromagnetic fields [µT]	Direction to the source of electromagnetic fields
Control sample	no	>1000	no	no
Test stand 1	220 kW/110 kW autotransformer	10	2.52–5.28	northwest
	high voltage line	20	1.36–2.21	from the top
Test stand 2	220 kW multi-tap transformer	2	8.97–10.67	northwest
	220 kW multi-tap transformer	1,5	9.56–14.18	from the top

development, when motility is already occurring, could falsify the results. The reading was taken after the water level in the incubator was lowered and acetic acid was added dropwise to the water in the "orientation arenas", which caused the protein to denature and the outline of the embryo's body to become visible, allowing it to be observed more easily. The position of the embryos in relation to the cardinal directions was determined in situ using a compass rose. Circular statistics were used to determine the direction and planes of the trout embryos. The results in terms of statistics were analyzed using the Rayleigh test (Batschelet et al. 1981). In addition, the percentage of embryos survival until blastopore closure was evaluated using the formula:

$$Ps = \frac{a}{n \times Pf} \times 100\%$$

where:

Ps - survival rate;

a - number of embryos *that survived until blastopore closure;*

n - initial number of eggs placed in incubators at a single test site (n = 360);

Pf – percentage of fertilization.

Survival results were statistically analyzed using the chi-square test.

At each of the stations, 360 eggs were placed in incubators, at the end of the experiment taking into account mortality and unfertilized eggs, the following number of properly developing fertilized eggs were obtained, from which the direction of embryo alignment could be read: in the control sample 217 pieces, test station 1 (autotransformer 220 kW/110 kW and high-voltage line) 214 pieces, test station 2 (multi-tap transformer 220 kW) 187 pieces.

3. Results

The results of the spatial orientation of developing embryos from individual research sites are presented below (Table II). The bodies of sea trout embryos incubated without magnetic field interference (control sample) showed a dominant north-south alignment, and there was a significant percentage of embryos aligned in the east-west plane (Figure 4) (Rayleigh test $r = 0.1821$, $p = 0.0007$). At the first test site, where fertilized eggs incubated under the interference of the autotransformer and the high-voltage line, embryo bodies aligned in a significant percentage in two perpendicular axes in the northwest-southeast axis and in the northeast-southwest axis (Figure 5) (Rayleigh test $r = 0.0720$, $p = 0.3302$). The fertilized eggs incubated under the multi-tap transformer showed a clear tendency for the embryos to be arranged in four planes: west-east, northwest-southeast, northeast-southwest, and north-south (Figure 6) (Rayleigh test $r = 0.0440$, $p = 0.6968$).

The fertilization efficiency was 84%. The survival rate of fertilized eggs until blastopore closure was 71.85% in the absence of additional sources of electromagnetic fields, 70.86% ($X^2 = 0.73$; $p > 0.05$) at test site 1 located near the autotransformer and high voltage line, and 61.92% ($X^2 = 6.73$; $p \leq 0.05$) at test site 2 located near the multi-tap transformer, respectively. Comparing by chi-

Table II. Spatial orientation of sea trout embryos.

	Control sample		Test stand 1		Test stand 2	
Direction	Quantity [pcs.]	Percentage [%]	Quantity [pcs.]	Percentage [%]	Quantity [pcs.]	Percentage [%]
N	21	9.68%	8	3.74%	18	9.63%
NNE	16	7.37%	13	6.07%	4	2.14%
NE	7	3.23%	21	9.81%	20	10.70%
ENE	7	3.23%	8	3.74%	4	2.14%
E	19	8.76%	16	7.48%	10	5.35%
ESE	7	3.23%	14	6.54%	4	2.14%
SE	9	4.15%	31	14.49%	14	7.49%
SEZ	20	9.22%	15	7.01%	10	5.35%
S	31	14.29%	13	6.07%	16	8.56%
SSW	11	5.07%	10	4.67%	10	5.35%
SW	12	5.53%	17	7.94%	16	8.56%
WSW	13	5.99%	6	2.80%	3	1.60%
W	14	6.45%	10	4.67%	26	13.90%
WNW	6	2.76%	6	2.80%	4	2.14%
NW	9	4.15%	15	7.01%	22	11.76%
NNW	15	6.91%	11	5.14%	6	3.21%

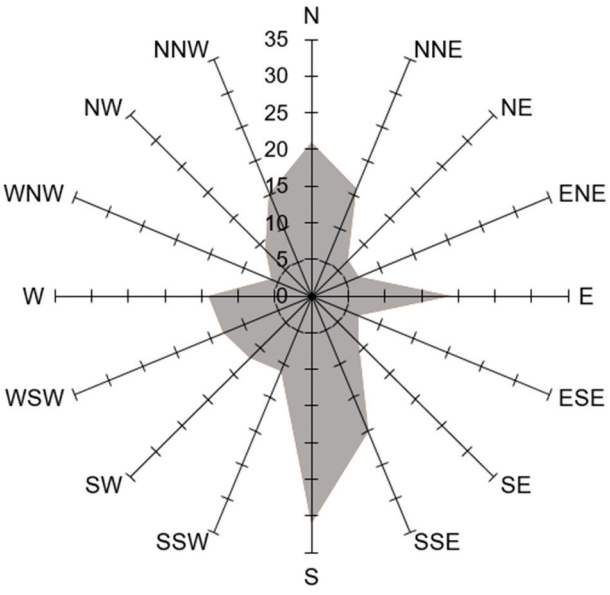

Figure 4. The spatial orientation of sea trout embryos – control sample only with natural geomagnetic field.

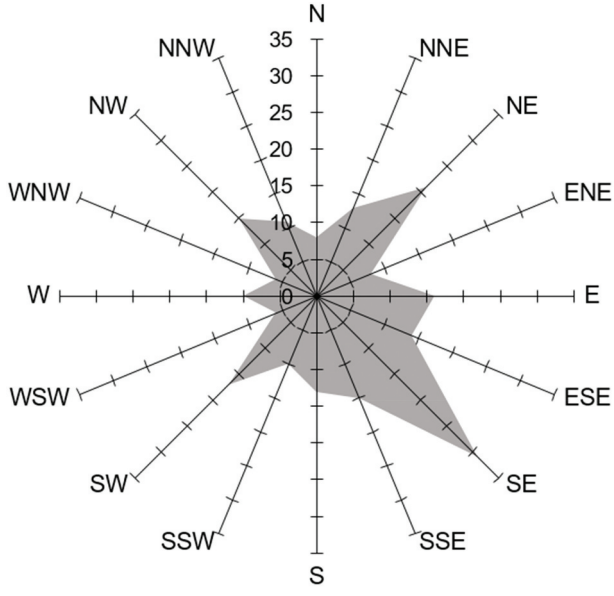

Figure 5. The spatial orientation of sea trout embryos – test site 1, with the source of electromagnetic fields in the NW direction (2.52–5.28 μT); a weaker field also interacted in the vertical plane (1.36–2.21 μT).

square test the control sample with the first test site, we see no significant difference in embryos survival, but at the site where the fertilized eggs were incubated in the strongest electromagnetic field (site 2), it can be concluded that electromagnetic fields had an impact on the increase in embryos mortality.

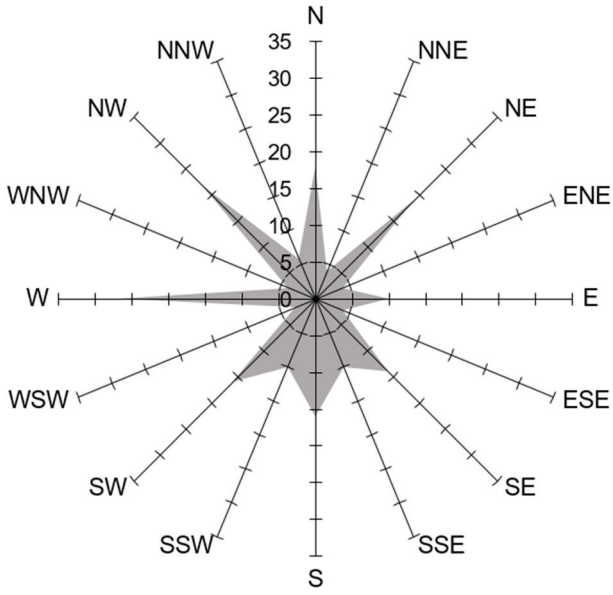

Figure 6. The spatial orientation of sea trout embryos – test site 2, with the source of electromagnetic fields in the NW direction (8.97–10.67 μT); a stronger field also interacted in the vertical plane (9.56–14.18 μT).

It was also observed that the fertilized eggs incubated at the site subjected to the strongest magnetic fields (test site 2) were at a more advanced stage of development, with identical water temperatures at all sites (±0.1°C). Microscopic observations allowed us to conclude that at the end of the experiment, the developmental stage of the embryos in the control sample and at test site 1 was assessed at the moment of blastopore closure, while at site 2 the incubated fertilized eggs were at a more advanced stage of embryogenesis after blastopore closure, at the early stages of organogenesis.

4. Discussion

4.1. The effects on orientation

The conducted experiment expands our understanding of the impact of anthropogenic electromagnetic fields on the early stages of fish ontogenesis. Specifically, it sheds light on how power infrastructure facilities, such as transformers and high-voltage power lines, can influence the orientation of embryo body axes during sea trout fertilized egg incubation. Comparisons were made between samples incubated in the Earth's natural magnetic field (geomagnetic field) and those exposed to electromagnetic fields generated by the autotransformer and high-voltage lines.

In the geomagnetic field (Figure 4), the primary axis of embryo body was along the north-south (N-S) axis, with an additional contribution from the west-east (W-E) axis, which confirmed findings from previous studies on salmonid embryos in the Earth's natural field (Tanski et al. 2005). In contrast, at the site where embryos were exposed to electromagnetic fields with measured values between 2.52 and 5.28 μT generated by the autotransformer and high-voltage lines (Figure 5), a different trend emerged. The embryos showed a tendency to align along the northwest-southeast (NW-SE) axis and the southwest-northeast (SW-NE) axis perpendicular to it. Compared to the control sample, there was a shift of two positions to the left on the compass rose for the main axes of the embryoid body. Notably, the dominant NW-SE axis coincided with the location of the main source of electromagnetic fields, which was the autotransformer (Figures 4 and 5), positioned to the northwest relative to the egg incubator.

These findings suggest a preference for the embryos to align along an axis consistent with the direction of the electromagnetic fields. This observation gains further support from a laboratory experiment using ferrite magnets to generate permanent fields ranging from 0.5 to 4.0 mT, despite the different nature and higher values of these fields (Tanski et al. 2005). That study similarly indicated that fish embryos tend to arrange themselves along artificially generated magnetic field lines.

At the second incubation site with the highest measured values of electromagnetic fields generated by the hitch transformer (Table I), the dominant axis in the direction of embryo stacking cannot be clearly identified (Figure 6). It is likely that this particular alignment of the embryoid bodies occurred as a result of higher values of electromagnetic fields than in the other test sites. Alternatively, the inability to indicate one or two dominant axes could as well be attributed to the fact that the strongest effects of electromagnetic fields exerted on the developing embryos came not only in the horizontal, but mainly in the vertical plane. In case of vertical interaction it could be possible that embryo's axis also aligned vertically. Such hypothetical effects could not be observed due to experiments two dimensional design. The tendency for the orientation of embryo bodies along artificially generated electromagnetic or magnetic field lines, as demonstrated in the first experimental variant and by (Tanski et al. 2005), was not observed on site two. This phenomenon of embryo's axis alignment was previously only observed when the main field source interacted with the fertilized eggs in a horizontal plane and could be described on the wind rose. Thus, the higher values of electromagnetical fields on site two and their vertical plane are two possible explanations of the lack of observed directional orientation.

4.2. *The effects on embryos mortality*

Based on the results obtained, it can be concluded that higher-intensity electromagnetic fields influenced increased embryos mortality by nearly 10%. However, it is essential to acknowledge that embryos survival may depend on other factors not studied in this experiment, such as the development of pathogenic fungi and bacteria, which could have contributed to the increased mortality unrelated to the electromagnetic fields' impact. Previous research on the embryos of rainbow trout *Oncorhynchus mykiss* (Walbaum, 1792) and pike *Esox lucius* (Linnaeus, 1758) showed no significant effects on survival due to static magnetic and electromagnetic fields (Fey et al. 2019, 2019). However, other studies have shown that certain magnetic field strengths (1.4–1.6 μT) could double losses compared to control samples (Krylov et al. 2016), and increased embryos mortality was observed in hypomagnetic fields (Krylov et al. 2021).

Further research is necessary to firmly establish the effect of anthropogenic electromagnetic fields on salmonid embryos survival. Additionally, it is essential to note that in this experiment, embryos survival was evaluated at the moment of blastopore closure (120 D^{o}), which is before half of the typical embryogenesis duration of sea trout, where hatching usually occurs between 380 and 440 D^{o} (Bonisławska & Winnicki 2000; Bonisławska 2009; Jakubowska et al. 2020). Survival rate assessments in salmonid embryos studies typically choose the time between oviposition and hatching as the moment of evaluation (Tański et al. 2009; Krzystolik et al. 2021; Skoglund et al. 2023). Extending the incubation time may yield different results as it would significantly increase the exposure time of the embryos to electromagnetic fields.

In this study, the lower survival rate observed at the site with the highest electromagnetic field values (site 2) could potentially be explained by the accelerated development of embryos incubating in such conditions. Previous studies have discussed how accelerated embryogenesis can lead to greater embryos losses, as demonstrated in the ruffe *Gymnocephalus cernua* (Linnaeus, 1758) by Bonisławska et al. (2004). The fact that artificially

generated electromagnetic fields similar to those from energy infrastructure facilities can influence the time of embryonic development has been confirmed in research on the embryos of roach *Rutilus rutilus* (Linnaeus, 1758), and northern pike *Esox lucius* (Linnaeus, 1758) (Chebotareva et al. 2009; Fey et al. 2019). However, it should be noted that studies on tropical fish species such as the zebrafish *Danio rerio* (Hamilton, 1822) and the Japanese rice fish *Oryzias latipes* (Temminck & Schlegel, 1846) indicate that electromagnetic fields can slow down embryogenesis (Cameron et al. 1985; Li et al. 2014). The fact that studies regarding the impact of electromagnetic fields on both survival and the rate of embryogenesis present different results and conclusions from each other can be tried to explain by the variation in the course of embryogenesis in different fish species (Korwin-Kossakowski 2012). Therefore, it is possible that electromagnetic fields affect the course of embryogenesis differently depending on the fish species under consideration, as well as on the intensity and type of fields applied.

5. Conclusions

Our experiment demonstrated that anthropogenic electromagnetic fields generated by energy infrastructure facilities can influence the spatial orientation of sea trout embryos. At lower field values, they caused deviations from the natural axis of embryo alignment in the geomagnetic field (N-S), leading to a shift towards the main field source or a lack of significant spatial orientation in embryo alignment at higher field values and stronger field influence from above. Additionally, higher values of electromagnetic fields may accelerate the rate of embryogenesis and negatively impact the survival rate of sea trout embryos.

Despite an increasing number of studies exploring the effects of anthropogenic electromagnetic fields on aquatic animals, including fish (Otremba et al. 2019; Albert et al. 2020; Nyqvist et al. 2020; Copping et al. 2021; Huang et al. 2022; Durif et al. 2023), the responses of organisms and the underlying mechanisms are still not fully understood. Given the significant rise in anthropogenic sources of electromagnetic fields affecting the aquatic environment in recent decades (Gill et al. 2014) and the projections of continued growth in such facilities, it is crucial to continually expand our knowledge of how electromagnetic fields affect the aquatic environment and the organisms living within it.

Author contributions

JK and AT conceived and designed the research. JK and RP performed research and collected the data. All authors contributed to the interpretations of the results and the discussion. JK and AT performed statistical analyses and wrote the manuscript. All authors read and approved the final manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data generated and analysed during the current study are available from the corresponding author upon reasonable request.

Ethics approval statement

Not required. The research was conducted on non-mammal vertebrate embryos in the first half of embryogenesis.

Funding

Financed from funds for statutory activities of the Department of Hydrobiology, Ichthyology and Biotechnology of Animal Reproduction, West Pomeranian University of Technology, Szczecin, Poland.

ORCID

J. Krzystolik http://orcid.org/0000-0001-8415-8443
A. Tański http://orcid.org/0000-0002-3537-4198
R. Piesiewicz http://orcid.org/0000-0001-6948-4240
A. Korzelecka-Orkisz http://orcid.org/0000-0002-8384-2355
K. Formicki http://orcid.org/0000-0003-0068-4011

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