

Limited effect of the electromagnetic field associated with submarine power cables on the growth of the Baltic macroalgae

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Abstract

Magnetic fields generated by submarine cables and marine renewable energy devices may negatively affect organisms living nearby. At the same time, the number of projects related to the strategic integration of low-trophic aquaculture within offshore wind farms is increasing. As there is a complete lack of information on the effects of magnetic fields on macroalgae, in our study, we investigated the effects of an electromagnetic field (EMF; 50 Hz, 1 mT) on the basic indicators of macroalgal functioning in two Baltic species of commercial value, *Fucus vesiculosus* and *Furcellaria lumbricalis*. EMF had a limited effect on the growth of both species. No changes were observed in nutrient uptake rates, water content, or organic matter content.

Keywords

Electromagnetic field; Submarine cables; Offshore wind farms; *Fucus vesiculosus*; *Furcellaria lumbricalis*; Ocean Multi-Use

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1. Introduction

Although macroalgae cultivation is still in its early stages in the Baltic Sea region (Weinberger et al., 2020), in recent years, there has been an increasing number of projects related to experimental aquaculture and the use of macroalgae biomass, such as FucoSan and Seafarm projects and few other initiatives (FucoSan 2020; Thomas et al., 2020; Boderskov et al., 2021; Adler et al., 2025). Among macroalgae species present in the Baltic Sea, including the southern part, two species have a commercial value – red alga *Furcellaria lumbricalis* and brown alga *Fucus vesiculosus*. *F. lumbricalis* is commercially exploited from natural populations, mainly for the purpose of obtaining its structural polysaccharide – furcellaran, which is widely used in the food and pharmaceutical industries as a gelling agent (Kersen et al., 2017). Currently, the commercial harvesting of this species is limited to Kassari Bay (Estonia). *F. vesiculosus* is a source of several valuable components used in medicine and the food industry such as fucoïdan, fucoxan-

thin, alginic acid and iodine, thus it is commercially harvested in some countries (Peteiro, 2018; Catarino et al., 2018), but not in the Baltic Sea area. In the 1960s and 1970s, *F. lumbricalis* (aegagropila – unattached form) and *F. vesiculosus* (benthopleustophytic ecotype – unattached form) were abundant in the Puck Bay (southern Baltic Sea, Poland) and were harvested and used for small-scale commercial processing and production of furcellaran and alginic acid (Trokowicz and Skrodzki, 1964; Ślesińska, 1973). Unfortunately, in the late 1970s and 1980s, the abundant populations of these species started to decline due to increased eutrophication and pollution (Pliński and Florczyk, 1984; Kruk-Dowgiało, 1991) and due to their overexploitation (Zgrundo and Złoch, 2022). In recent years, there have been positive changes in the structure of macroalgae in the waters of Puck Bay – after more than 40 years of absence, the reappearance of *F. lumbricalis* and *F. vesiculosus* in their unattached forms has been noted (Zgrundo and Złoch, 2022; Bałazy et al., 2024).

Recent model prediction indicates that the southern Baltic Sea exhibits high farming potential for *F. vesiculosus*

(Kotta et al., 2022). Additionally, experimental aquaculture of this species has been established in the region, providing helpful guidance for planning future commercial activities (Meichssner et al., 2020, 2021). A few pilot projects have also been initiated to develop cultivation techniques for the unattached form of *F. lumbricalis* (Kersen et al., 2017; Weinberger et al., 2020). However, the lack of tradition, experience, and dedicated technical solutions, as well as marine spatial planning conflicts, hamper the development of seaweed aquaculture in the region.

Aquaculture that can be strategically integrated within offshore wind farms (OWFs) is increasingly considered as a way of sustainable use of marine space (Billing et al., 2022; O'Shea et al., 2022). In recent years, a growing number of projects related to this topic have been observed, and even the first pilot farms are already being established (North Sea Farmers, 2025). Such solutions promote better use of marine space that is limited to shipping and fishing, and provide synergy in the use of space and infrastructure. The multi-use of offshore wind farms with low-trophic aquaculture could provide not only sustainable energy and seafood, but also restorative ecosystem services through the significant nutrient removal and carbon capture (Maar et al., 2023). In many regions, including the southern Baltic Sea, this may be the only available or the most realistic form of marine aquaculture (Armoškaite et al., 2021).

In connection with the above facts, it would be reasonable to assume that at least experimental or restorative cultivation sites of macroalgae will be established based on wind farm structures in the southern Baltic Sea in the near future. The main factors that may negatively affect organisms cultivated within offshore wind farms during operation include magnetic fields (MFs), especially because cultivation structures may be placed at varying depths and distances from turbines, devices, and cables. Direct current cables produce a static magnetic field (SMF), whereas cables that carry alternating current generate an alternating magnetic field (low-frequency electromagnetic field; EMF). Artificial MFs, especially low-frequency EMF, introduced to the environment are classified as a type of pollution (GESAMP Reports and Studies, 1991) and considered harmful to biological structures (Suzuki et al., 2006; EC, 2013). Recent experimental studies indicated that artificial MFs with induction values characteristic of the close proximity to submarine cables may negatively affect fish and invertebrates, causing behavioural, physiological, genotoxic, and developmental changes (e.g., Li et al., 2014; Lohmannia et al., 2015; Scott et al., 2018; Oliva et al., 2023), including organisms from the Baltic Sea (Jakubowska et al., 2019; Stankevičiūtė et al., 2019; Jakubowska-Lehrmann et al., 2022, 2025). Nonetheless, there is a lack of any recommendations regarding the technology used for underwater energy transmission and the potential implementation of available alleviation measures.

On the other hand, SMF and low-frequency EMF are considered growth-promoting factors for microalgae as they can increase the biomass production, content of carbohydrates, proteins, lipids, essential amino acids, trace elements and pigments, and enhance nutrient assimilation (e.g., Li et al., 2007; Small et al., 2011; Deamici et al., 2016a,b; Luo et al., 2020). However, these positive effects have been observed mainly after applying relatively high magnetic induction (10–400 mT), whereas scanty available data concerning exposure to lower values, similar to those noted in the vicinity of cables and devices (0.2–5 mT), indicate lack of effect or decreased growth of freshwater microalgae (Pazur and Scheer, 1992; Wang et al., 2008). In the case of terrestrial vascular plants, the effect of MFs is mainly positive and manifested in increased growth, faster accumulation of nutrients, or increased resistance to diseases, and thus exposure to this factor is considered a potential method for increasing productivity (Sarraf et al., 2020; Saletnik et al., 2022). It is therefore challenging to predict whether the presence of MFs will increase the biomass gain and potential to remove excess nutrients by macroalgae that are cultivated or naturally occurring in wind farm areas, or whether it will have a negative effect. Surprisingly, the information concerning the influence of magnetic fields on macroalgae is completely missing. In this regard the aim of the present study was to find out if exposure to electromagnetic field (50 Hz), of value typically recorded in the close vicinity of submarine cables (1 mT), affects the growth, nutrient uptake, water content, and organic matter content in *F. lumbricalis* and *E. vesiculosus* from Puck Bay.

2. Material and methods

2.1 The experimental setup

The experimental setup consisted of a magnetic field generator (designed by and constructed in Gdynia Maritime University), two identical aquaria ($V = 25$ L connected by a flow-through system to a conditioning tank ($V = 900$ L) equipped with a cooling system (Titan 4000, Aqua Medic, Bissendorf, Germany). The experimental aquarium was situated in EMF, while the reference one was positioned in a natural geomagnetic field (~ 0.05 mT). The generator consists of two identical Helmholtz coils (each for 200 turns, height – 47 cm, distance between the outer edges of the coils – 30 cm) and was powered by variable auto-transformer RAVISTAT 15 P-1 (Ravi Electricals Pvt. Ltd, India). A current of 1.3 A was maintained in the coils. The Helmholtz coils were cooled by circulating water from the cooling unit (Titan 2000; Aqua Medic; Bissendorf, Germany). The technical details of the generator and the distribution of the EMF in the experimental aquarium were previously described in detail (Fey et al., 2019). The generator produces an electromagnetic field of 50 Hz (EMF), which is nearly uniform throughout the entire volume of the exposure aquarium. The direction of the artificially

generated magnetic field (magnetic induction vector) was horizontal, while the direction of the geomagnetic field (approximately 60 μT) at the experimental site was inclined at 68 degrees to the horizontal. The experimental value (1 mT) was set and subsequently monitored at several-day intervals using a teslameter (13610-93, Phywe, Göttingen, Germany). It was calculated using an equation for a line conductor based on the Biot-Savart law, and it corresponds to the field at approximately 30 cm distance from the surface of a high-power submarine single-core cable carrying 1500 A. EMF was chosen as cables carrying alternating current (AC) are most commonly used in offshore wind farms (Soares-Ramos et al., 2020).

2.2 Macroalgae collection and maintenance

The experiments were conducted subsequently on two macroalgae species collected from the Puck Bay (Inner Gulf of Gdańsk, southern Baltic Sea) – *Furcellaria lumbricalis* and *Fucus vesiculosus*. Specimens and water for experiments were gathered from the station in the coastal zone (54.72839 N, 18.40152 E) at a depth of approximately 2 m by divers in September and October 2023. Only unattached macroalgae were collected, i.e., *F. lumbricalis* forma aegagropila and *F. vesiculosus* free living form. The plants used for the research were collected from the environment on the basis of the decision of the Regional Di-

rector for Environmental Protection, RDOS-Gd-WZG.6400.53.2023.SG2 permitting the collection and keeping of protected species for scientific research.

After transportation to the laboratory, algae were shortly immersed in deionised water (Sánchez-Saavedra et al., 2008) and any organisms attached to thalli were gently removed. Then algae were placed in large containers filled with aerated natural seawater. The temperature and salinity were similar to in situ conditions (16°C, 7 PSU).

2.3 Exposure to electromagnetic field

After approximately one week of acclimatization, algae of similar wet weights (no differences in weight between treatments (t-test, $p > 0.05$; $n = 12$ thalli per treatment) were placed individually in 400 ml transparent plastic containers filled with 350 ml of previously filtered (GFF filters, pore diameter 0.7 μm) natural seawater gathered from the algae collection site ($T = 16^\circ\text{C}$, $S = 7$ PSU) enriched with West and McBride’s Modified ES Medium (West and McBride, 1999). For each experiment, twelve containers with algae were placed in the exposure aquarium located in EMF, and another 12 in the reference aquarium located outside the range of the generator (in a natural geomagnetic field). Aquaria served as a water bath, keeping the temperature constant; water from containers did not mix with the water in the system. The light was provided by

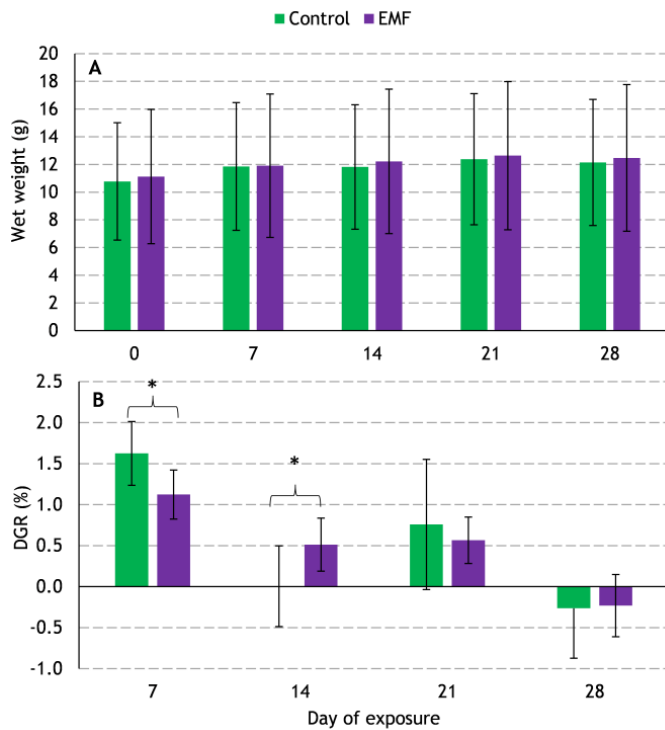


Figure 1. Wet weight (A) and DGR (B) of *Fucus vesiculosus* (mean \pm SD, $n = 12$) during the exposure to EMF of 1 mT and to control conditions. Asterisks (*) denote significant differences ($p < 0.05$).

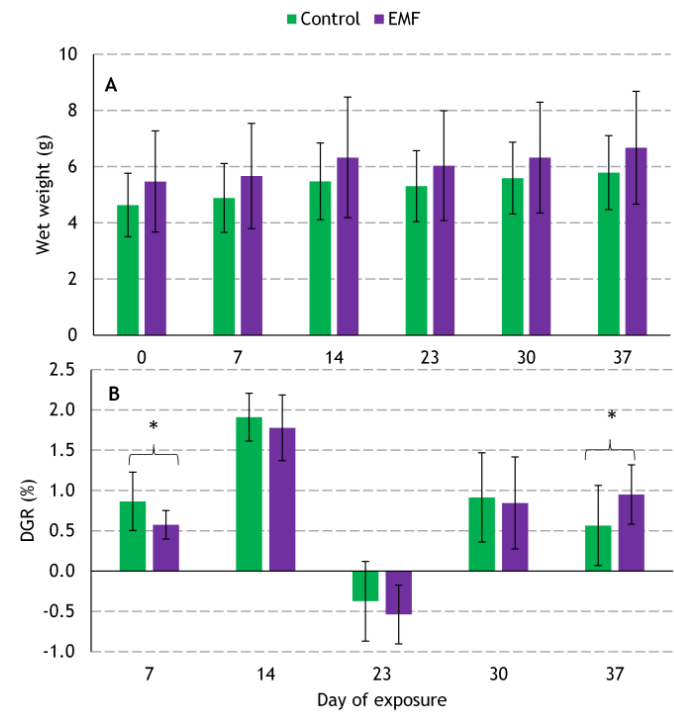


Figure 2. Wet weight (A) and DGR (B) of *Furcellaria lumbricalis* (mean \pm SD, $n = 12$) during the exposure to EMF of 1 mT and to control conditions. Asterisks (*) denote significant differences ($p < 0.05$).

two LED lamps (LED-A131-RB-230-03-GL, ELEKTROTECH, Poland) set above the aquaria. The value of the light intensity (photon flux density) used in both experiments was set at the level of $100 \pm 10 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ (photoperiod 12:12) using a photometer (Apogee MQ-510 Full Spectrum underwater PAR meter). The value of light saturation optimal for growth was chosen based on previous experiments (unpublished data) and literature data (Wallentinus, 1978; Bäck et al., 1992; Svahn et al., 2012). Water in each container was aerated by diaphragm compressor. Temperature in the experimental setup was monitored continuously by Hobo loggers UA-001-08 (Onset, USA). The exposure to EMF (1 mT, 50 Hz) lasted 37 (*F. vesiculosus*) or 28 days (*F. lumbricalis*).

2.4 Determination of growth rate

During the experiments, the wet weight of each alga was determined approximately on a weekly basis. For this purpose, the thalli were dried in a salad dryer (Meichssner et al., 2020) for 40 seconds and then weighed using an analytical balance ($\pm 0.01 \text{ g}$). After determining the wet mass of each thallus, the water in each container was exchanged

for newly collected and filtered seawater enriched with the medium. The daily growth rate (DGR) was calculated according to the formula:

$$\text{DGR (\%)} = [(\ln W_1 - \ln W_0)/(t - 1)] \times 100,$$

where t is the duration of the incubation period in days, W_0 and W_1 are the initial and the final wet weights of algae.

2.5 Determination of nutrient uptake rate

For each species, experimental water was collected from each container twice – after a week of exposure and at the end of the experiment – to analyse the concentrations of basic biogenic compounds, i.e., NO_3^- , NO_2^- , NH_4^+ , PO_4^{3-} , and Fe. To determine the initial nutrient concentrations, samples of the experimental water were collected before being poured into the experimental containers. The concentrations were assessed using a direct reading spectrophotometer (DR6000 UV-VIS, Hach Company, USA) and its standard test methods. To calculate the uptake of nutrients by each thallus, the decrease in their concentrations in experimental containers in relation to the culture medium after each week was measured according to the formula:

$$\text{nutrient uptake rate} = (N_0 - N_t) V m^{-1} t^{-1},$$

where N_0 is the initial concentration of nutrient, N_t is the concentration after one week, V is the volume of the culture medium, m is the wet weight of the thallus, and t is the time period.

The rate of nutrient uptake was expressed in micrograms per gram of wet weight per day ($\mu\text{g g}^{-1} \text{d}^{-1}$).

2.6 Determination of water content and the content of organic matter

After the exposure, each thallus was dried (60°C for 48 h), weighed, and the percentage water content was calculated. Then, the thalli were burned in the muffle furnace (450°C for 12 h; Gnaiger and Bitterlich, 1984) to determine the organic matter content.

2.7 Statistical analyses

The normal distribution of the data was examined using the Shapiro-Wilk test. For data characterised by a normal distribution, a parametric t-test was used to assess the significance of differences in wet weight, DGR, nutrient uptake rates, and water and organic matter contents between macroalgae exposed to EMF and the control treatment. For non-parametric data Mann-Whitney U test was applied. All analyses were performed using STATISTICA software (10.0 Software, Inc. PA, USA).

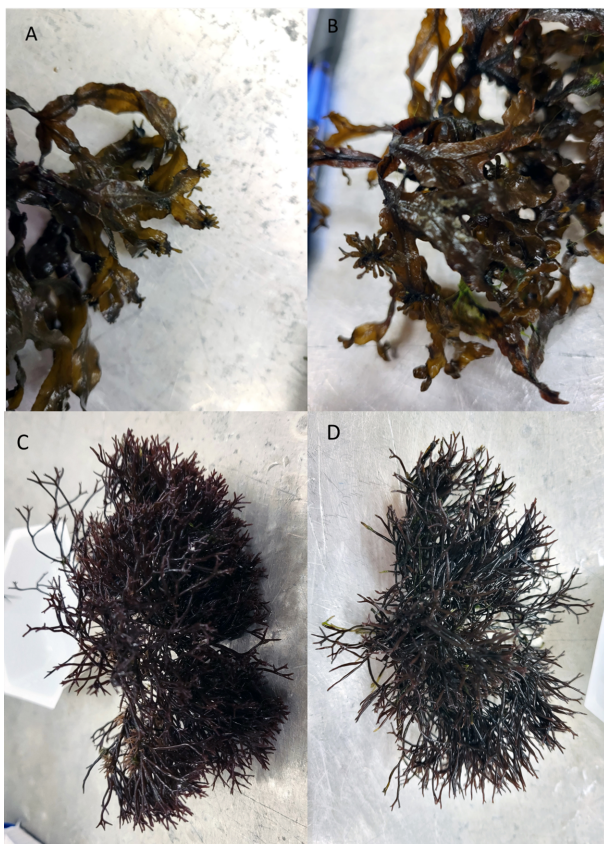


Figure 3. Examples of *Fucus vesiculosus* thalli and their visible growth after 30-day exposure to control conditions (A) and EMF of 1 mT (B) and *Furcellaria lumbricalis* after 14-day exposure to control conditions (C) and EMF of 1 mT (D).

3. Results

No influence of EMF was observed on the wet weights of *F. vesiculosus* thalli for any of the exposure days it was measured ($p > 0.05$; Figure 1A). After 7 days DGR of *F. vesiculosus* exposed to EMF was lower than that of the control

Table 1. The rates of nutrients nutrient uptake ($\mu\text{g g}^{-1} \text{d}^{-1}$; mean \pm SD, n = 12) of *Fucus vesiculosus* and *Furcellaria lumbricalis* after exposure to EMF of 1 mT and to control conditions.

		NO ₂ -N	NH ₄ ⁺ -N	NO ₃ ⁻ -N	EN	PO ₄ ³⁻ -P	Fe
<i>Fucus vesiculosus</i>							
1st week of exposure	Control	0.05 \pm 0.05	2.93 \pm 0.91	24.96 \pm 7.04	27.94 \pm 7.70	21.90 + 4.64	6.42 \pm 2.02
	EMF	0.06 \pm 0.05	2.61 \pm 0.94	22.23 \pm 10.09	24.9 \pm 10.64	18.30 + 7.64	5.87 \pm 2.22
Last (5th) week of exposure	Control	0.06 \pm 0.04	2.63 \pm 0.64	21.62 \pm 6.13	24.31 \pm 6.62	2.52 + 1.1	3.37 \pm 2.2
	EMF	0.07 \pm 0.04	2.3 \pm 0.98	18.47 \pm 6.30	20.84 \pm 6.80	2.78 + 1.65	2.84 \pm 2.08
<i>Furcellaria lumbricalis</i>							
1st week of exposure	Control	2.13 \pm 1.85	2.37 \pm 0.98	15.24 \pm 6.35	19.73 \pm 7.23	1.99 + 1.29	3.00 \pm 1.51
	EMF	3.17 \pm 1.19	2.44 \pm 1.1	12.91 \pm 5.08	18.52 \pm 7.19	2.05 + 1.45	3.67 \pm 1.69
Last (4th) week of exposure	Control	0.03 \pm 0.03	1.6 \pm 0.58	10.70 \pm 5.62	12.33 \pm 6.16	0.97 + 0.59	0.74 \pm 0.72
	EMF	0.02 \pm 0.02	1.63 \pm 0.78	9.82 \pm 3.61	11.47 \pm 4.30	0.81 + 0.38	1.18 \pm 0.74

algae (t-test, t = 2.49, p = 0.021; Figure 1B). After 14, 23 and 30 days, no significant effect of this factor was noted (p > 0.05), while after the last week of exposure, the thalli exposed to EMF showed a higher growth rate (t-test, t = -2.15, p = 0.042; Figure 2B). After 23 days of exposure, a slight decrease in the mass of the thalli instead of increase was noted compared to the previous week, both in the exposed and control plants.

Analogously to *F. vesiculosus*, the wet weights of *F. lumbricalis* thalli were not different from the weights of plants cultured in the control conditions during the whole experimental period (p > 0.05; Figure 2A). Also, similarly to *F. vesiculosus*, after 7 days, DGR was negatively affected by EMF (t-test, t = 3.54, p = 0.001; Figure 2B). After 14 days, the opposite situation to *F. vesiculosus* was observed – exposed *F. lumbricalis* thalli exhibited higher DGR than control plants (t-test, t = -2.98, p = 0.006; Figure 2B). In the following days of the experiment, no differences in growth rate were observed. At the end of the exposure, a slight decrease in the biomass of both exposed and non-exposed algae was noted.

Table 2. Percentage of water and organic matter (mean \pm SD, n = 12) in the thalli of *Fucus vesiculosus* and *Furcellaria lumbricalis* after exposure to EMF of 1 mT and to control conditions.

		Water content (%)	Organic matter content (%)
<i>Fucus vesiculosus</i>			
Control		78.93 \pm 1.72	80.15 \pm 2.41
EMF		79.79 \pm 2.32	78.51 \pm 6.64
<i>Furcellaria lumbricalis</i>			
Control		79.51 \pm 1.72	87.39 \pm 8.50
EMF		81.62 \pm 3.58	86.37 \pm 5.79

The thalli of both species were in good condition throughout the experiments, and their growth (branching) was clearly visible in both exposed and control algae, especially in *F. vesiculosus* (Figure 3).

The main results of the uptake of nutrients are presented in Table 1. The uptake rates of any of the studied parameters did not vary between EMF-exposed and control macroalgae, neither after a week of exposure nor after the longer period, in both species (p > 0.05). Uptake rates of nitrogen were higher than those of phosphorus. Among the nitrogen compounds, nitrates were taken up at the highest rate, followed by ammonium nitrogen. Nitrite uptake was, in most cases, at a low level. The uptake rates of phosphates were relatively high in *F. vesiculosus*, both exposed and control plants, during the first week of exposure, but the concentration in the culture medium was also high (> 2 mg l⁻¹) compared to the concentration in other periods investigated (\leq 0.6 mg l⁻¹). Neither the percentage of water nor the organic matter content in *F. vesiculosus* thalli differ significantly between macroalgae exposed to EMF and control ones (p > 0.05; Table 2). Similarly, exposure to EMF did not affect these parameters in *F. lumbricalis* (p > 0.05; Table 2).

4. Discussion

4.1 Growth rate

Low growth rates are typical for perennial species like *F. vesiculosus* and *F. lumbricalis*. The daily growth rate of *F. vesiculosus* in the present research, which ranged between 0.6 and 1.9%, was similar to that previously reported for this species reared in laboratory conditions under similar salinity, which was approximately 1.4% (Bäck et al., 1992), and slightly lower than in environmental culture, where it amounted to up to 3%, but at higher salinity (Kiel Fjord; Meichssner et al., 2020). Surprisingly, it was higher than observed for *F. vesiculosus* from the Puck Bay in laboratory experiments, which was up to 0.5% per day

(Kentzer et al., 1976). The growth rate of the unattached form of *F. lumbricalis* is lower than that of the attached form (Martin et al., 2006). Values of DGR obtained in the present study correspond with data for the unattached form from laboratory and environmental experiments, in which DGR ranged between 0.1 and 2%, depending on the environmental conditions (Kentzer et al., 1976; Rueness i Tananger, 1984; Haglund and Pedersen, 1998; Martin et al., 2006; Kotta et al., 2008; Paalme et al., 2013). In the present study, the negative DRG values were recorded for both species during some measurements, but were not reflected in a significant decrease of biomass. The degradation of older fronds is a rather typical phenomenon, especially in unattached *F. lumbricalis*, in which degeneration of the older parts followed by new branch initiation is part of the vegetative propagation strategy (Austin, 1960). Additionally, in aegagropila form, due to densely branched thalli, the self-shading occurs as well as reduced water movement and nutrient depletion, which may also cause degradation (Rueness and Tananger, 1984).

EMF affected DGR values both positively (37th day in *F. vesiculosus*, 14th day in *F. lumbricalis*) and negatively (7th day in both species), but during most of the exposure time it had no effect. However, the significant changes in DGR did not influence the total biomass of algae. Therefore, the effect on studied factor on the growth of both species was very limited. SMF of values ranging from 5 to 150 mT increased the growth rate and biomass of various microalgae (Small et al., 2012; Deamici et al., 2016a,b; Luo et al., 2020; Menestrino et al., 2020). Enhanced growth was also noted after applying lower values (0.5 mT), but the exposure was limited to 120 minutes per day (Asundi et al., 2024). In *Spirulina platensis* SMF of 5–40 mT increased the growth rate, while 70 mT caused growth inhibition (Hirano et al., 1998). Wang et al., (2008) observed higher growth rates of *Chlorella vulgaris* exposed to SMF of 10–35 mT, whereas algae cultured in 5, 45, and 50 mT were unaffected. Also, EMF of high induction values (100–550 mT, unknown frequency) had a positive effect on the growth rate of *S. platensis* (Li et al., 2007). On the other hand, EMF (7.8 Hz) as low as 0.02 mT had an inhibitory effect on the growth of three different microalgae, whereas a slightly higher value (0.2 mT) promoted their growth (Pazur and Scheer, 1992). MFs may interact with biological material in multiple ways. They can cause changes in the motion of electrons and ions, produce torques on ferromagnetic and paramagnetic materials, and alter the energy levels and orientations of electron spins, increasing the activity, concentration, and lifetimes of free radicals (Ghodbane et al., 2013; Santos et al., 2017). The most probable mechanism responsible for observed positive effects of microalgae growth is the formation of radical pairs associated with electron transmission changes in reaction centres of photosystem II, which facilitate the conversion of light energy to chemical energy (Font et al., 2023). The increase of pho-

tosynthetic efficiency by accelerating the light excitation of chlorophyll was manifested in the acceleration of O₂ production rates (Hirano et al., 1998; Tu et al., 2015). It is difficult to clearly state why such mechanisms and thus increased growth were not observed in the investigated macroalgae. It may be assumed that the mechanisms of MFs' action on unicellular organisms may be less effective for multicellular macroalgae due to their tissue thickness, thus lower photosynthetic efficiency of cells located deeper within the thallus and exhibiting lower carbon uptake and O₂ evolution. Moreover, the stimulation effect of MFs on microalgae growth occurs mainly in the exponential growth phase (Li et al., 2007; Wang et al., 2008), whereas macroalgae used in the present study are perennial, slow-growing species.

4.2 Nutrient uptake

MFs induce variations in the ionic equilibrium of cells and permeability of biological membranes, (Santini et al., 2005), what may increase the uptake of nutrients. Li et al., (2007) in addition to accelerated growth observed increased N and P content in *S. platensis* exposed to SMF (250 mT). In the present study the uptake rates of nutrients were not affected by EMF. N and P uptake varied with the time of exposure as they were lower in the last week of experiment than in the first in both species, especially the uptake of phosphates in *F. vesiculosus*. Contrary to fast-growing algae, the perennial species, including the investigated ones, may accumulate nitrates and phosphates to sustain growth during periods when fewer nutrients are available (Wallentinus, 1984; Indergaard and Knutsen, 1990; Lehvo et al., 2001). Therefore, the reduced PO₄³⁻-P assimilation in the last week of the experiment could have been the result of thalli saturation in the previous weeks. Moreover, nutrient uptake also increases with higher nutrient concentration. In our study, despite the same origin of experimental water and addition of the same culture media, PO₄³⁻-P concentrations were higher in the first week than in the last week of each experiment, especially in *F. vesiculosus*. The uptake rates of phosphates in *F. lumbricalis* (estimated on a dry weight basis ~ 0.2–0.5 μg g⁻¹ DW h⁻¹) were similar to those observed in similar temperatures by Wallentinus (1984), which ranged between 0.2 and 2.2 μg g⁻¹ DW h⁻¹. The uptake of PO₄³⁻-P of *F. vesiculosus* obtained by Wallentinus (1984) varied between 0.2 and 15 μg g⁻¹ DW h⁻¹ depending on the phosphate concentration in water, thallus parts (as in apical parts uptake is higher than in parts originating from previous years) and temperature, whereas in our experiment the mean uptake rates for whole thallus ranged from ~ 0.5 to 4.4 μg g⁻¹ DW h⁻¹. Contrary to findings of Wallentinus (1984) *F. vesiculosus* and *F. lumbricalis* in our study exhibited higher uptakes of NO₃-N than NH₄⁺-N. The mean uptake of NO₃-N and NH₄⁺-N ranged between 2 and 5, and 0.3–0.6 μg g⁻¹ DW h⁻¹, respectively, whereas Wallentinus

(1984) observed higher uptakes (1.6–90 for NH_4^+ -N and 0.50–50 $\mu\text{g g}^{-1} \text{DW h}^{-1}$ for NO_3 -N). Ammonium can be a preferable source of nitrogen for macroalgae, but ammonium concentrations in the environment are usually much lower than those of nitrates. Tissue nitrogen concentrations of *F. vesiculosus* are strongly correlated with ambient nitrate availability (Perini and Bracken 2014). Also, in culture media in the present experiment, the concentrations of nitrates were much higher than ammonia, which was usually completely used after a week of exposure. The uptake rate of iron, which in macroalgae is involved in photosynthesis, respiration, and nitrogen assimilation (Jing-wen et al., 2002), was high and not influenced by EMF.

4.3 The content of water and organic matter

The content of water in investigated algae was typical for these species, as for *F. vesiculosus* it ranges between 71% and 84% (Greenwell et al., 1984; Catarino et al., 2018), and for *F. lumbricalis* 78–83% (Greenwell et al., 1984; Indergaard and Knutsen, 1990). Even though magnetic fields may affect the permeability of biological membranes, cause disturbances in ion transport and water absorption, the water content of the investigated algae was unaffected by EMF. High content of organic matter in macroalgae is usually correlated with the high concentrations of polysaccharides, proteins, lipids, and pigments, as well as with high energetic and nutritional value (Garcia-Oliveira et al., 2020). In the present study, the content of organic matter in both species was high and was within the range given in the literature: 73 to 85% for *F. vesiculosus* (Bojanowski 1973; Greenwell et al., 1984) and 65–88 for *F. lumbricalis* (Bojanowski 1973; Greenwell et al., 1984; Indergaard and Knutsen, 1990), which may indicate that algae grew in optimal conditions. Exposure to EMF did not affect the content of organic matter; it might be thus presumed that the content of valuable compounds and nutritional value was also not influenced, neither positively nor negatively. After exposure to SMF, the increase in carbohydrates, lipids, proteins, and pigments was noted in microalgae (Li et al., 2007; Small et al 2012; Deamici et al., 2016b; Menestrino et al., 2020).

4.4 Conclusion and future perspectives

The present study demonstrated that EMF had a limited effect on the growth of *F. vesiculosus* and *F. lumbricalis*. Despite higher or lower growth rates of both species exposed to EMF in individual weeks of the experiment compared to the control conditions, the biomass of exposed thalli was not significantly reduced or increased. The lack of changes in the uptake rates of nutrients, as well as in the water and organic matter content, indicates that the applied EMF value does not pose a significant threat to macroalgae cultivated in such conditions, at least during the experimental period (28/37 days).

Unattached forms of *F. vesiculosus* and *F. lumbricalis*, despite many barriers for the development of seaweed

aquaculture in the Baltic Sea region, exhibit potential for experimental and commercial cultivation. The cultivation of sexual *Fucus* populations makes the potential yield much lower, as the change from germling to adult individuals that can be harvested can take even up to 2 years (Al Janabi, 2016). Moreover, it was revealed that the production and subsequent degeneration of reproductive organs significantly reduce the harvestable biomass (Meichsner et al., 2021). The unattached form of *F. lumbricalis* is also unable to develop generative organs and reproduces only vegetatively (Kentzer et al., 1976; Bird et al., 1991), which makes the potential cultivation easier than in the case of populations completing a complex full life cycle. The lack of observed negative effects of EMF on the growth of the investigated macroalgae indicates that the presence of cables and devices is not a barrier to cultivating seaweeds in the OWF area. In the context of spatial conflicts, lack of dedicated technology, and potentially high costs of cultivation and harvesting (Kulikowski et al., 2021), the seaweed aquaculture may benefit from synergies with OWFs. Also, the potential for providing ecosystem services may be an added value of the macroalgae aquaculture combined with OWFs. Based on the results from the FucoSan project, it is theoretically possible to obtain 50 tons of fresh mass from a hectare per year of asexual *F. vesiculosus* (FucoSan, 2020). Nutrients removed by harvesting 1 ton of fresh macroalgae, calculated based on their nitrogen and phosphorus content (Kornfeldt, 1982; Pedersen and Borum, 1996) may reach 5.5 kg N and 0.3 kg P for *F. lumbricalis* and 7.9 kg N and 1.9 kg P in the case of *F. vesiculosus*. It should be kept in mind, however, that although the nutrient content in red and brown algae is high, they are characterized by relatively low growth rates, thus their production would affect the nutrient content in the surrounding water to a lesser extent than the farming site's fast-growing species (Wallentinus, 1984). Nevertheless, their potential for combating eutrophication is not negligible.

Maximum value of magnetic induction in the close vicinity of the cable varies between a few and 8000 μT (Cada et al., 2011), depending mainly on the value of the electric current flowing in the cable core. Applying high magnetic induction in studies may be especially important in the case of red algae, as they can be cultured at a depth of over a dozen meters, potentially close to the cables. However, turbines in OWF areas are often connected by both vertical and horizontal cabling (Soares-Ramos et al., 2020), thus magnetic disturbances may also affect organisms in the water column, including algae cultivated in suspended cages and baskets. It should be highlighted that the present study investigated the effect of an artificial magnetic field on macroalgae for the first time. In future research, it would be thus reasonable to investigate the potential effects of different values of magnetic induction, ranging from a few μT to a few mT, on various species of macroalgae. It would also be important to assess the potential impact of MFs

directly on the content and quality of valuable compounds such as furcellaran, fucoidan, alginic acid, and pigments.

CRediT authorship contribution statement

Magdalena Jakubowska-Lehrmann – Conceptualization, Methodology, Investigation, Data curation, Formal Analysis, Resources, Visualization, Writing – original draft. Aleksandra Zgrundo: Methodology, Investigation, Resources, Writing – review & editing. Daniel Czmajdych: Investigation, Data curation, Writing – review & editing. Zbigniew Otremba: Methodology, Writing – review & editing.

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Conflict of interest

None declared.

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