

Limited effects of electromagnetic fields associated with submarine power cables on the growth of 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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Received: 6 October 2025; revised: 23 February 2026; accepted: 2 March 2026

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 (Trokwicz 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 probably 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 this 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) (multi-use) is increasingly considered as a way of sustainable use of marine space (Billing et al., 2022; O'Shea et al., 2022). In recent years, an increasing 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; Jakubowska-Lehrmann et al., 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 from 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 is powered by variable autotransformer RAVISTAT 15 P-1 (Ravi Electricals Pvt. Ltd, India). A current of 1.3 A was maintained in the coils. The Helmholtz coils are 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

150 the exposure aquarium. The direction of the artificially
 151 generated magnetic field (magnetic induction vector) was
 152 horizontal, while the direction of the geomagnetic field (ap-
 153 proximately 60 μT) at the experimental site was inclined
 154 at 68 degrees to the horizontal. The experimental value
 155 (1 mT) was set and subsequently monitored at several-day
 156 intervals using a teslameter (13610-93, Phywe, Göttingen,
 157 Germany). It was calculated using an equation for a line
 158 conductor based on the Biot-Savart law, and it corresponds
 159 to the field at approx. 1 cm distance from the surface of
 160 a high-power submarine single-core cable of 1500 A. EMF
 161 was chosen as cables carrying alternating current (AC)
 162 are most commonly used in offshore wind farms (Soares-
 163 Ramos et al., 2020).

164 **2.2 Macroalgae collection and maintenance**

165 The experiments were conducted subsequently on two
 166 macroalgae species collected from the Puck Bay (Inner Gulf
 167 of Gdańsk, southern Baltic Sea) – *Furcellaria lumbricalis*
 168 and *Fucus vesiculosus*. Specimens and water for experi-
 169 ments were gathered from the station in the coastal zone
 170 (54.72839 N, 18.40152 E) at a depth of approximately 2 m
 171 by divers in September and October 2023. Only unattached
 172 macroalgae were collected, i.e., *F. lumbricalis* forma aega-
 173 gropila and *F. vesiculosus* free living (unattached) forms.
 174 The plants used for the research were collected from the

175 environment on the basis of the decision of the Regional Di-
 176 rector for Environmental Protection, RDOS-Gd-WZG.6400.
 177 53.2023.SG2 permitting the collection and keeping of pro-
 178 tected species for scientific research.

179 After transportation to the laboratory, algae were shortly
 180 immersed in deionised water (Sánchez-Saavedra et al.,
 181 2008) and any organisms attached to thalli were gently
 182 removed. Then algae were placed in large containers filled
 183 with aerated natural seawater. The temperature and salini-
 184 ty were similar to in situ conditions (16°C, 7 PSU).

185 **2.3 Exposure to electromagnetic field**

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

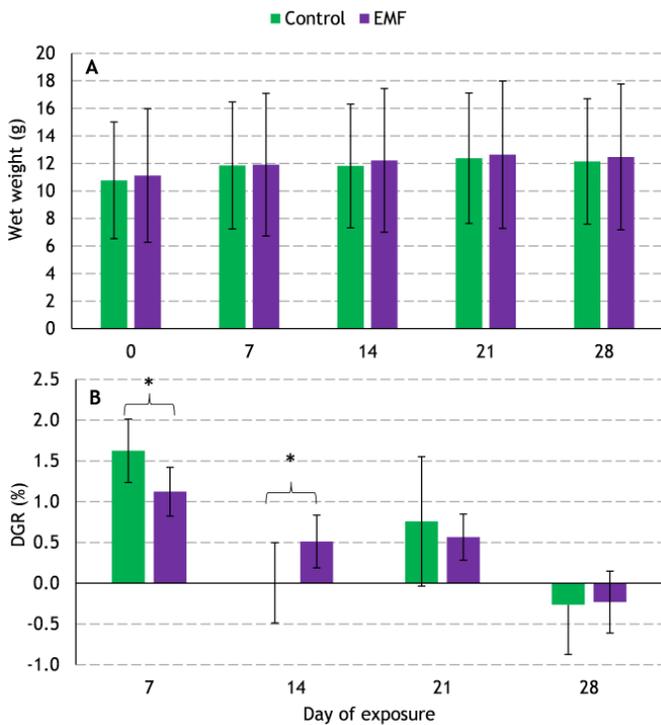


Figure 1. Wet weight (A) and DGR (B) of *Fucus vesiculosus* (mean \pm SD, $n = 12$) during the exposure to EMF of 1 mT and to control conditions. Asterisks (*) denote significant differences ($p < 0.05$).

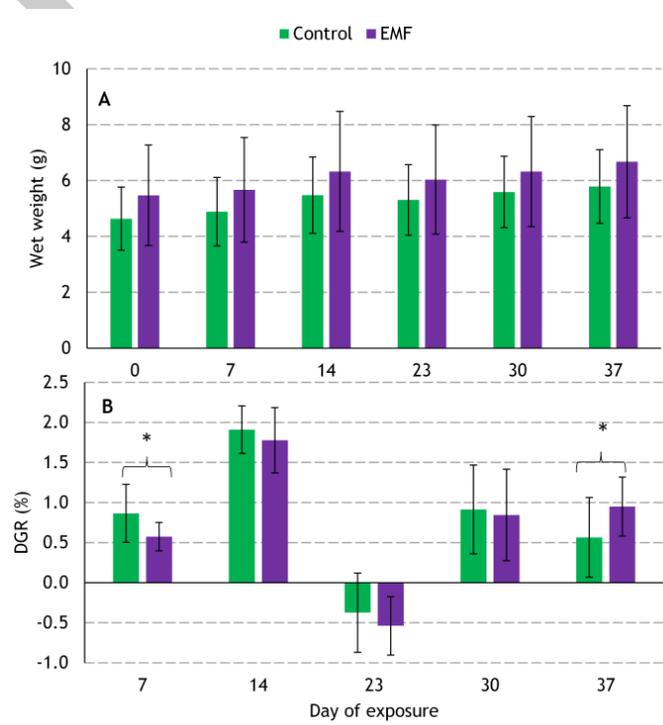


Figure 2. Wet weight (A) and DGR (B) of *Furcellaria lumbricalis* (mean \pm SD, $n = 12$) during the exposure to EMF of 1 mT and to control conditions. Asterisks (*) denote significant differences ($p < 0.05$).

with the water in the system. The light was provided by 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/sufficient 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:

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

where n 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).

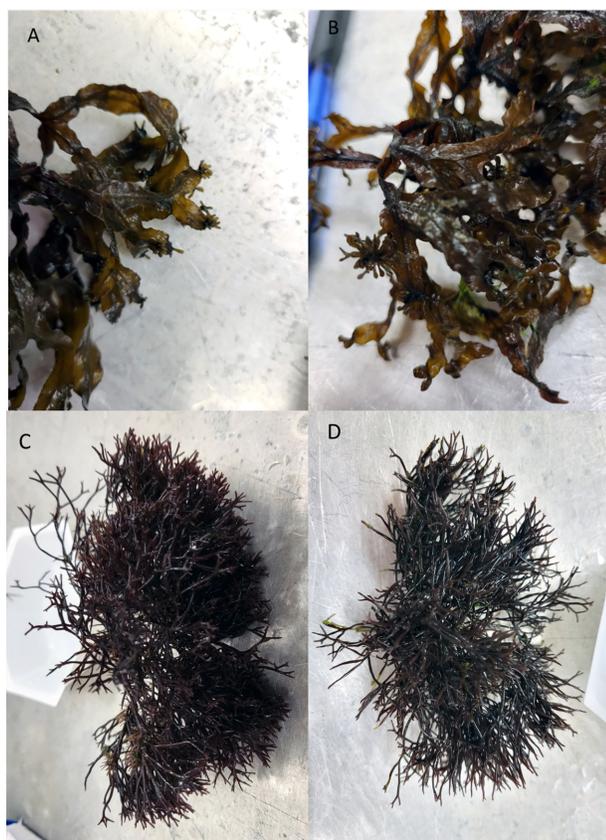


Figure 3. Examples of *Fucus vesiculosus* thalli and their visible growth after 30-day exposure to control conditions (A) and EMF of 1 mT (B) and *Furcellaria lumbricalis* after 14-day exposure to control conditions (C) and EMF of 1 mT (D).

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* (~ 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

435 NH_4^+ -N and $0.50\text{--}50 \mu\text{g g}^{-1} \text{ dw h}^{-1}$ for $\text{NO}_3\text{-N}$). 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

449 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

476 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).

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

489 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 that of the farming site's fast-growing species (Wallentinus, 1984). Nevertheless, their potential for combating eutrophication is not negligible.

526 Maximum value of magnetic induction in the close vicinity of the cable varies between a few and $8000 \mu\text{T}$ (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

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

546 CRediT authorship contribution statement

547 Magdalena Jakubowska-Lehrmann – Conceptualization,
548 Methodology, Investigation, Data curation, Formal Analy-
549 ses, Resources, Visualization, Writing – original draft. Alek-
550 sandra Zgrundo: Methodology, Investigation, Resources,
551 Writing – review & editing. Daniel Czmajdych: Investiga-
552 tion, Data curation, Writing – review & editing. Zbigniew
553 Otremba: Methodology, Writing – review & editing.

554 Acknowledgements

555 This research was funded by the statutory projects: DOT23/
556 GLONY conducted at the National Marine Fisheries Re-
557 search and DS. 531-0500-D717-23 conducted at the Uni-
558 versity of Gdańsk, financed by the Ministry of Science and
559 Higher Education in Poland.

560 Conflict of interest

561 None declared.

562 References

563 Adler, I., Martin, G., Kovalchuk, N., Orav-Kotta, H., Vene, K.,
564 Tuvikene, R., Kotta, J., 2025. *Exploring the cultivation*
565 *of Ulva intestinalis in low-salinity environments of the*
566 *Baltic Sea*. *Oceans* 6(2), 30.
567 <https://doi.org/10.3390/oceans6020030>
568 Al-Janabi, B., 2016. *The adaptive potential of early life stage*
569 *Fucus vesiculosus under multifactorial environmental*
570 *change*. Ph.D. thesis, Christian Albrecht's Univ., Kiel.
571 Armoškaitė, A., Bārda, I., Andersone, I., Bonnevie, I. M.,
572 Ikauniece, A., Kotta, J., Kõivupuu, A., Lees, L., Psuty, I.,
573 Stråke, S., Sprukta, S., Szymanek, L., von Thenen, M.,
574 Schroder, L., Hansen, H. S., 2021. *Considerations of*
575 *use-use interactions between macroalgae cultivation*
576 *and other maritime sectors: An eastern Baltic MSP case*
577 *study*. *Sustainability* 13(24), 13888.
578 <https://doi.org/10.3390/su132413888>
579 Asundi, S., Rout, S., Stephen, S., Khandual, S., Dutta, S., Ku-
580 mar, S., 2024. *Parametric study of the effect of increased*
581 *magnetic field exposure on microalgae Chlorella vul-*
582 *garis growth and bioactive compound production*. *Phy-*
583 *cology* 4(2), 314–329.
584 <https://doi.org/10.3390/phycolgy4020016>
585 Austin, A. P., 1960. *Observations on Furcellaria fastigiata*
586 *(L.) Lam. forma aegagropila Reinke in Danish waters*
587 *together with a note on other unattached algal forms*.
588 *Hydrobiologia* 14, 255–277.
589 Bäck, S., Collins, J. C., Russell, G., 1992. *Effects of salinity on*
590 *the growth of Baltic and Atlantic Fucus vesiculosus*. *Br.*
591 *Phycol. J.* 27(1), 39–47.

Balazy, P., Wiktor, J., Tatarek, A., Węśławski, J. M., 2024. *592*
Apparent return of free-living Fucus vesiculosus to the
Polish Baltic waters. *Oceanologia* 66(2), 424–428. *593*
<https://doi.org/10.1016/j.oceano.2024.02.004> *594*
595
Billing, S.-L., Charalambides, G., Tett, P., Giordano, M., Ruzzo,
C., Arena, F., Santoro, A., Lagasco, F., B rizzi, G., Collu, M.,
2022. *Combining wind power and farmed fish: Coastal*
community perceptions of multi-use offshore renewable
energy installations in Europe. *Energy Res. Soc. Sci.*
85, 102421. *596*
<https://doi.org/10.1016/j.erss.2021.102421> *597*
598
Bird, C. J., Saunders, G. W., McLachlan, J., 1991. *Biology of*
Furcellaria lumbricalis (Hudson) Lamouroux (Rhodophyta:
Gigartinales), a commercial carrageenophyte. *J. Appl.*
Phycol. 3, 61–82. *599*
600
Boderskov, T., Nielsen, M. M., Rasmussen, M. B., Balsby, T. J.
S., Macleod, A., Holdt, S. L., Sloth, J. J., Bruhn, A., 2021.
Effects of seeding method, timing and site selection on
the production and quality of sugar kelp, Saccharina
latissima: A Danish case study. *Algal Res.* 53, 102160.
<https://doi.org/10.1016/j.algal.2020.102160> *601*
602
Bojanowski, R., 1973. *The occurrence of major and minor*
chemical elements in the more common Baltic seaweed.
Oceanologia 2, 81–152. *603*
604
Cada, G. F., Bevelhimer, M. S., Riemer, K. P., Turner, J. W.,
2011. *Effects on freshwater organisms of magnetic*
fields associated with hydrokinetic turbines. ORNL/TM-
2011/244. Oak Ridge National Laboratory. *605*
<https://www.osti.gov/biblio/1025846> (accessed 9 *606*
July 2025) *607*
Catarino, M. D., Silva, A. M., Cardoso, S. M., 2018. *Phyco-*
chemical constituents and biological activities of Fucus
spp. *Mar. Drugs* 16(8), 249. *608*
<https://doi.org/10.3390/md16080249> *609*
610
Deamici, K. M., Cardias, B. B., Costa, J. A. V., Santos, L. O.,
2016. *Static magnetic fields in culture of Chlorella fusca:*
Bioeffects on growth and biomass composition. *Process.*
Biochem.y 51(7), 912–916. *611*
<https://doi.org/10.1016/j.procbio.2016.04.005> *612*
613
Deamici, K. M., Costa, J. A. V., Santos, L. O., 2016. *Magnetic*
fields as triggers of microalga growth: evaluation of its
effect on Spirulina sp., *Bioresour. Technol.* 220, 62–67.
<https://doi.org/10.1016/j.biortech.2016.08.038> *614*
615
EC, 2013. *The Minimum Health and Safety Requirements*
Regarding the Exposure of Workers to the Risks Arising
from Physical Agents (Electromagnetic Fields) and Re-
pealing Directive 2004/40/EC. European Parliament
and Council. *616*
617
Fey, D. P., Jakubowska, M., Greszkiewicz, M., Andrulowicz,
E., Otremba, Z., Urban-Malinga, B., 2019. *Are magnetic*
and electromagnetic fields of anthropogenic origin po-
tential threats to early life stages of fish? *Aquat. Toxicol.*
209, 150–158. *618*
<https://doi.org/10.1016/j.aquatox.2019.01.023> *619*
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645

- 646 Font, Y. S., Díaz, Y. O., Cuypers, A., Alemán, E. I., Vandamme,
647 D., 2023. *The effect of magnetic field treatment on the*
648 *cultivation of microalgae: An overview of involved mech-*
649 *anisms.* J. Appl. Phycol. 35(4), 1525–1536.
650 <https://doi.org/10.1007/s10811-023-02994-1>
- 651 FucoSan, 2020. *Algae sources, cultivation and collection.*
652 FucoSan project – Result Rep. [https://www.fucosan.](https://www.fucosan.eu/en/project/)
653 [eu/en/project/](https://www.fucosan.eu/en/project/) (Accessed 9 July 2025).
- 654 Garcia-Oliveira, P., Carreira-Casais, A., Caleja, C., Pereira, E.,
655 Calhelha, R. C., Sokovic, M., Simal-Gandara, J., Ferreira,
656 I. C. F. R., Prieto, M. A., Barros, L., 2020. *Macroalgae as*
657 *an alternative source of nutrients and compounds with*
658 *bioactive potential.* Proc. 70, 46.
659 https://doi.org/10.3390/foods_2020-07648
- 660 GESAMP, 1991. GESAMP Reports and Studies No. 47. Joint
661 Group of Experts on the Scientific Aspects of Marine
662 Environmental Protection.
- 663 Ghodbane, S., Lahbib, A., Sakly, M., Abdelmelek, H., 2013.
664 *Bioeffects of static magnetic fields: oxidative stress,*
665 *genotoxic effects, and cancer studies.* BioMed Res. Int.
666 2013, 602987.
667 <https://doi.org/10.1155/2013/602987>
- 668 Gnaiger, E., Bitterlich, G., 1984. *Proximate biochemical com-*
669 *position and caloric content calculated from elemental*
670 *CHN analysis: a stoichiometric concept.* Oecologia 62,
671 289–298.
- 672 Greenwell, M., Bird, C. J., McLachlan, J., 1984. *Depth-related*
673 *variation in gross chemical composition of several sea-*
674 *weeds.* Aquat. Bot. 20(3–4), 297–305.
- 675 Haglund, K., Pedersén, M., 1988. *Spray cultivation of sea-*
676 *weeds in recirculating brackish water.* Aquaculture
677 72(1–2), 181–189.
- 678 Hirano, M., Ohta, A., Abe, K., 1998. *Magnetic field effects on*
679 *photosynthesis and growth of the cyanobacterium* *Spir-*
680 *ulina platensis.* J. Ferment. Bioeng. 86(3), 313–316.
- 681 Indergaard, M., Knutsen, S. H. 1990. *Seasonal Differences*
682 *in Ash, Carbon, Fibre and Nitrogen Components of* *Fur-*
683 *cellaria lumbricalis (Gigartinales, Rhodophyceae), Nor-*
684 *way.* Bot. Mar. 33(4).
685 <https://doi.org/10.1515/botm.1990.33.4.327>
- 686 Jakubowska, M., Urban-Malinga, B., Otręmba, Z., Andrulowicz,
687 E., 2019. *Effect of low-frequency electromagnetic field*
688 *on the behavior and bioenergetics of the polychaete*
689 *Hediste diversicolor.* Mar. Environ. Res. 150, 104766.
690 <https://doi.org/10.1016/j.marenvres.2019.104766>
- 691 Jakubowska-Lehrmann, M., Białowas, M., Otręmba, Z., Hall-
692 mann, A., Śliwińska-Wilczewska, S., Urban-Malinga, B.,
693 2022. *Do magnetic fields related to submarine power*
694 *cables affect the functioning of a common bivalve?* Mar.
695 Environ. Res. 179, 105700.
696 <https://doi.org/10.1016/j.marenvres.2022.105700>
- 697 Jakubowska-Lehrmann, M., Makaras, T., Normant-Saremba,
698 M., Białowas, M., Otręmba, Z., 2025. *Exploring the im-*
699 *act of magnetic fields related to submarine power ca-*
700 *bles on the American mud crab* *Rhithropanopeus har-*
risii: A behavioural and physiological perspective. Mar.
Pollut. Bull. 212, 117492.
<https://doi.org/10.1016/j.marpolbul.2024.117492>
- Jing-wen, L., Shuang-lin, D., Xiao-yun, L., 2002. *Aspects*
of iron nutrition in macroalgae *Ulva pertusa (Chloro-*
phyta) under iron stress. Chin. J. Oceanol. Limnol.
20(2), 162–169.
- Kentzer, T., Borowczak, E., Szczepkowska, E., 1976. *Invest-*
igations on the growth intensity and its modification
due to impurities in certain Baltic algae. Stud. Mat.
Oceanol. 15, 169–186. (in Polish)
- Kersen, P., Paalme, T., Pajusalu, L., Martin, G., 2017. *Biotech-*
nological applications of the red alga *Furcellaria lum-*
bricalis and its cultivation potential in the Baltic Sea.
Bot. Mar. 60(2), 207–218.
<https://doi.org/10.1515/bot-2016-0062>
- Kornfeldt, R. A., 1982. *The relation between nitrogen and*
phosphorus content of macroalgae and the waters of
northern Öresund. Bot. Mar. 25(4), 197–291.
- Kotta, J., Paalme, T., Kersen, P., Martin, G., Herkul, K., Moller,
T., 2008. *Density dependent growth of the red algae*
Furcellaria lumbricalis and Coccotylus truncatus in the
West Estonian Archipelago Sea, Northern Baltic Sea.
Oceanologia 50(4), 577–585.
https://old.iopan.pl/oceanologia/50_4.html#A5
- Kotta, J., Raudsepp, U., Szava-Kovats, R., Aps, R., Armoskaite,
A., Barda, I., Bergström, P., Futter, M., Gröndahl, F.,
Hargrave, M., Jakubowska, M., Jänes, H., Kaasik, A.,
Kraufvelin, P., Kovaltchouk, N., Krost, P., Kulikowski, T.,
Kõivupuu, A., Kotta, I., Lees L., Loite S., Maljutenko I.,
Nylund G., Paalme T., Pavia H., Purina I., Rahikainen
M., Sandow V., Visch W., Yang B., Barboza, F. R., 2022.
Assessing the potential for sea-based macroalgae culti-
vation and its application for nutrient removal in the
Baltic Sea. Sci. Total Environ. 839, 156230.
<https://doi.org/10.1016/j.scitotenv.2022.156230>
- Kruk-Dowgiallo, L., 1991. *Long-term changes in the struc-*
ture of underwater meadows of the Puck Lagoon. Acta
Ichthyol. Piscat. 21 (Suppl.).
- Kulikowski, T., Jakubowska, M., Krupska, J., Psuty, I., Szulecka,
O., 2021. *Guide to macroalgae cultivation and use in*
the Baltic Sea Region. Nat. Marine Fisheries Res. Inst.,
Gdynia.
- Lehvo, A., Bäck, S., Kiirikki, M., 2001. *Growth of* *Fucus vesicu-*
losus L. (Phaeophyta) in the northern Baltic proper: En-
ergy and nitrogen storage in seasonal environment. Bot.
Mar. 44(4), 337–347.
<https://doi.org/10.1515/bot.2001.044>
- Li, Y., Liu, X., Liu, K., Miao, W., Zhou, C., Li, Y., Wu, H., 2014.
Extremely low-frequency magnetic fields induce devel-
opmental toxicity and apoptosis in zebrafish (Danio
rerio) embryos. Biol. Trace Elem. Res. 162, 324–332.
<https://doi.org/10.1007/s12011-014-0130-5>
- Li, Z. Y., Guo, S. Y., Li, L., Cai, M. Y., 2007. *Effects of electro-*
magnetic field on the batch cultivation and nutritional

- 756 composition of *Spirulina platensis* in an air-lift photo-
757 bioreactor. *Bioresour. Technol.* 98(3), 700–705.
758 <https://doi.org/10.1016/j.biortech.2006.01.024>
- 759 Loghmannia, J., Heidari, B., Rozati, S. A., Kazemi, S., 2015.
760 *The physiological responses of the Caspian kutum (Rut-*
761 *tilus frisii kutum) fry to static magnetic fields with dif-*
762 *ferent intensities during acute and subacute exposures.*
763 *Ecotoxicol. Environ. Saf.* 111, 215–219.
764 <https://doi.org/10.1016/j.ecoenv.2014.10.020>
- 765 Luo, X., Zhang, H., Li, Q., Zhang, J., 2020. *Effects of static*
766 *magnetic field on *Chlorella vulgaris*: growth and ex-*
767 *tracellular polysaccharide (EPS) production.* *J. Appl.*
768 *Phycol.* 32, 2819–2828.
769 <https://doi.org/10.1007/s10811-020-02164-7>
- 770 Maar, M., Holbach, A., Boderskov, T., Thomsen, M., Buck, B.
771 H., Kotta, J., Bruhn, A., 2023. *Multi-use of offshore wind*
772 *farms with low-trophic aquaculture can help achieve*
773 *global sustainability goals.* *Commun. Earth Environ.*
774 4(1), 447.
775 <https://doi.org/10.1038/s43247-023-01116-6>
- 776 Martin, G., Paalme, T., Torn, K., 2006. *Growth and produc-*
777 *tion rates of loose-lying and attached forms of the red*
778 *algae *Furcellaria lumbricalis* and *Coccotylus truncatus**
779 *in Kassari Bay, the West Estonian Archipelago Sea.* *Hy-*
780 *drobiologia* 554, 107–115.
781 <https://doi.org/10.1007/s10750-005-1010-y>
- 782 Meichssner, R., Krost, P., Schulz, R., 2021. *Experimental*
783 *testing of density- and season-dependent growth in veg-*
784 *etative *Fucus* aquaculture and modelling of growth over*
785 *one year for different cultivation scenarios.* *J. Appl. Phy-*
786 *col.* 33, 3939–3950.
787 <https://doi.org/10.1007/s10811-020-02274-2>
- 788 Meichssner, R., Stegmann, N., Cosin, A.-S., Sachs, D., Bres-
789 san, M., Marx, H., Krost, P., Schulz, R., 2020. *Control*
790 *of fouling in the aquaculture of *Fucus vesiculosus* and*
791 **Fucus serratus* by regular desiccation.* *J. Appl. Phycol.*
792 32, 4145–4158.
793 <https://doi.org/10.1007/s10811-020-02274-2>
- 794 Menestrino, B. D. C., Pintos, T. H. C., Sala, L., Costa, J. A. V.,
795 Santos, L. O., 2020. *Application of static magnetic fields*
796 *on the mixotrophic culture of *Chlorella minutissima* for*
797 *carbohydrate production.* *Appl. Biochem. Biotechnol.*
798 192(3), 822–830.
799 <https://doi.org/10.1007/s12010-020-03364-0>
- 800 North Sea Farmers, 2025. NORTH SEA FARM #1.
801 <https://www.northseafarmers.org/projects/nsf1>
802 (Accessed 9 July 2025)
- 803 Oliva, M., De Marchi, L., Cuccaro, A., Fumagalli, G., Freitas, R.,
804 Fontana, N., Raugi, M., Barmada, S., Pretti, C., 2023. *Int-*
805 *roducing energy into marine environments: A lab-scale*
806 *static magnetic field submarine cable simulation and*
807 *its effects on sperm and larval development on a reef-*
808 *forming serpulid.* *Environ. Pollut.* 328, 121625.
809 <https://doi.org/10.1016/j.envpol.2023.121625>
- O'Shea, R., Collins, A., Howe, C., 2022. *Offshore multi-use*
810 *setting: Introducing integrative assessment modelling*
811 *to alleviate uncertainty of developing seaweed aquacul-*
812 *ture inside wind farms.* *Environ. Challenges* 8, 100559.
813 <https://doi.org/10.1016/j.envc.2022.100559>
- 814 Paalme, T., Kotta, J., Kersen, P., 2013. *Does the growth rate*
815 *of drifting *Furcellaria lumbricalis* and *Coccotylus trun-**
816 *catus depend on their proportion and density?* *Proc.*
817 *Estonian Acad. Sci.* 62(2), 141–151.
818 <https://doi.org/10.3176/proc.2013.2.08>
- 819 Pazur, A., Scheer, H., 1992. *The growth of freshwater green*
820 *algae in weak alternating magnetic fields of 7.8 Hz fre-*
821 *quency.* *Z. Naturforsch. C* 47(9–10), 690–694.
822 <https://doi.org/10.1515/znc-1992-9-1009>
- 823 Pedersen, M., Borum, J., 1996. *Nutrient control of algal*
824 *growth in estuarine waters. Nutrient limitation and the*
825 *importance of nitrogen requirements and nitrogen stor-*
826 *age among phytoplankton and species of macroalgae.*
827 *Mar. Ecol. Prog. Ser.* 142, 261–272.
828 <https://doi.org/10.3354/meps142261>
- 829 Peteiro, C., 2017. *Alginate production from marine macroal-*
830 *gae, with emphasis on kelp farming.* [In:] *Alginates*
831 *and their biomedical applications*, Springer, Singapore,
832 27–66.
833 https://doi.org/10.1007/978-981-10-6910-9_2
- 834 Pliński, M., Florczyk, I., 1984. *Analysis of the composition*
835 *and vertical distribution of the macroalgae in the west-*
836 *ern part of the Gulf of Gdansk in 1979 and 1980.* *Oceanolo-*
837 *gia* 19, 101–116.
838 http://www.iopan.gda.pl/oceanologia/OC_19/OC_19_101-115.pdf
- 839 Rueness, J., Tananger, T., 1984. *Growth in culture of four*
840 *red algae from Norway with potential for mariculture.*
841 *Proc. 11th Int. Seaweed Symp., Springer Netherlands,*
842 303–307.
843
- 844 Saletnik, B., Saletnik, A., Słysz, E., Zaguła, G., Bajcar, M.,
845 Puchalska-Sarna, A., Puchalski, C., 2022. *The static*
846 *magnetic field regulates the structure, biochemical ac-*
847 *tivity, and gene expression of plants.* *Molecules* 27(18),
848 5823.
849 <https://doi.org/10.3390/molecules27185823>
- 850 Sánchez-Saavedra, M., Voltolina, D., Simental, J., Carbajal-
851 Miranda, M. J., 2008. *Removal of epiphytes of the kelp*
852 **Macrocystis pyrifera* (L.) Agardh using different bio-*
853 *cides.* *Hidrobiológica* 18(2), 99–104.
854
- 855 Santini, M. T., Ferrante, A., Rainaldi, G., Indovina, P., Indov-
856 ina, P. L., 2005. *Extremely low frequency (ELF) mag-*
857 *netic fields and apoptosis: a review.* *Int. J. Radiat. Biol.*
858 81(1), 1–11.
859 <https://doi.org/10.1080/09553000400029502>
- 860 Santos, L. O., Deamicis, K. M., Menestrino, B. C., Garda-
861 Buffon, J., Costa, J. A. V., 2017. *Magnetic treatment of microal-*
862 *gae for enhanced product formation.* *World J. Microbiol.*
863 *Biotechnol.* 33, 1–6.
864 <https://doi.org/10.1007/s11274-017-2332-4>

- 865 Sarraf, M., Kataria, S., Taimourya, H., Santos, L. O., Menegatti,
866 R. D., Jain, M., Ihtisham, M., Liu, S., 2020. *Magnetic field*
867 *(MF) applications in plants: An overview*. *Plants* 9(9),
868 1139.
869 <https://doi.org/10.3390/plants9091139>
- 870 Scott, K., Harsanyi, P., Lyndon, A. R., 2018. *Understand-*
871 *ing the effects of electromagnetic field emissions from*
872 *Marine Renewable Energy Devices (MREDS) on the com-*
873 *mercially important edible crab, Cancer pagurus (L.)*.
874 *Mar. Pollut. Bull.* 131, 580–588.
875 <https://doi.org/10.3389/conf.fmars.2018.06.00105>
- 876 Ślesińska, B., 1977. *The species composition of plants when*
877 *collecting Furcellaria from Puck Bay*. *Zeszyty Naukowe*
878 *UG, ser. Oceanografia* 3, 139–148. (in Polish)
- 879 Small, D. P., Hüner, N. P., Wan, W., 2012. *Effect of static*
880 *magnetic fields on the growth, photosynthesis and ul-*
881 *trastructure of Chlorella kessleri microalgae*. *Bioelec-*
882 *tromagnetics* 33(4), 298–308.
883 <https://doi.org/10.1002/bem.20706>
- 884 Soares-Ramos, E. P., de Oliveira-Assis, L., Sarrias-Mena, R.,
885 Fernández-Ramírez, L. M., 2020. *Current status and*
886 *future trends of offshore wind power in Europe*. *Energy*
887 202, 117787.
888 <https://doi.org/10.1016/j.energy.2020.117787>
- 889 Stankevičiūtė, M., Jakubowska, M., Pažusienė, J., et al., 2019.
890 *Genotoxic and cytotoxic effects of 50 Hz 1 mT electro-*
891 *magnetic field on larval rainbow trout (Oncorhynchus*
892 *mykiss), Baltic clam (Limecola balthica), and common*
893 *ragworm (Hediste diversicolor)*. *Aquat. Toxicol.* 208,
894 109–117.
895 <https://doi.org/10.1016/j.aquatox.2018.12.023>
- 896 Suzuki, Y., Toyama, Y., Miyakoshi, Y., Ikehata, M., Yoshioka,
897 H., Shimizu, H., 2006. *Effect of static magnetic field on*
898 *the induction of micronuclei by some mutagens*. *Envi-*
899 *ron. Health Prev. Med.* 11, 228–232.
900 <https://doi.org/10.1265/ehpm.11.228>
- 901 Svahn, C., Maria Gylle, A., Ekelund, N. G., 2012. *Photosyn-*
902 *thetic activity in marine and brackish water strains of*
903 *Fucus vesiculosus and Fucus radicans (Phaeophyceae)*
904 *at different light qualities*. *Photochem. Photobiol* 88(6),
905 1455–1460.
906 <https://doi.org/10.1111/j.1751-1097.2012.01187.x>
- 907 Thomas, J.-B. E., Sodrė Ribeiro, M., Potting, J., Cervin, G., Ny-
908 lund, G. M., Olsson, J., Albers, E., Undeland, I., Pavia, H.,
909 Gröndahl, F., 2020. *A comparative environmental life*
910 *cycle assessment of hatchery, cultivation, and preser-*
911 *vation of the kelp Saccharina latissima*. *ICES J. Mar.*
912 *Sci.* 78(1), 451–467
913 <https://doi.org/10.1093/icesjms/fsaa112>
- 914 Trokowicz, D., Skrodzki, M., 1964. *Patent description 53780*
915 *– The method of obtaining alginic acid and agar-agar*
916 *from seaweed*. (in Polish)
- 917 Tu, R., Jin, W., Xi, T., Yang, Q., Han, S. F., Abomohra, A. E.
918 F., 2015. *Effect of static magnetic field on the oxygen*
919 *production of Scenedesmus obliquus cultivated in mu-*
nicipal wastewater. *Water Res.* 86, 132–138. 920
<https://doi.org/10.1016/j.watres.2015.07.039> 921
- Wallentinus, I., 1978. *Productivity studies on Baltic macroal-*
922 *gae*. *Bot. Mar.* 21, 365–380. 923
<https://doi.org/10.1515/botm.1978.21.6.365> 924
- Wallentinus, I., 1984. *Comparisons of nutrient uptake rates*
925 *for Baltic macroalgae with different thallus morpholo-*
926 *gies*. *Mar. Biol.* 80, 215–225. 927
<https://doi.org/10.1007/bf02180189> 928
- Wang, H. Y., Zeng, X. B., Guo, S. Y., Li, Z. T., 2008. *Effects*
929 *of magnetic field on the antioxidant defense system of*
930 *recirculation-cultured Chlorella vulgaris*. *Bioelectro-*
931 *magnetics* 29(1), 39–46. 932
<https://doi.org/10.1002/bem.20360> 933
- Weinberger, F., Paalme, T., Wikström, S. A., 2020. *Seaweed*
934 *resources of the Baltic Sea, Kattegat and German and*
935 *Danish North Sea coasts*. *Bot. Mar.* 63(1), 61–72. 936
<https://doi.org/10.1515/bot-2019-0019> 937
- West, J. A., McBride, D. L., 1999. *Long-term and diurnal car-*
938 *pospore discharge patterns in the Ceramiaceae Rhodo-*
939 *melaceae and Delesseriaceae (Rhodophyta)*. 16th Int.
940 *Seaweed Symp., Springer, Dordrecht*, 101–113. 941
- Zgrundo, A., Złoch, I., 2022. *Gone and back – The anthro-*
942 *pogenic history of Coccotylus brodiei (Turner) Kützing*
943 *and Furcellaria lumbricalis (Hudson) JV Lamouroux in*
944 *the Gulf of Gdańsk (Southern Baltic Sea)*, *Water* 14(14),
945 2181. 946
<https://doi.org/10.3390/w14142181> 947