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A review of the selected methods of macroalgae cultivation in marine waters

Analiza wybranych metod uprawy makroglonów w wodach morskich

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Abstract: The article presents methods of macroalgae cultivation performed worldwide in marine waters (long-lines, bottom planting, integrated cultivation). It describes a variety of technical approaches and discusses the possibility of conducting macroalgae cultivation in the Polish marine areas. All the presented methods can be tested in the Polish zone of the Baltic Sea, except integrated mariculture (IMTA). Species of the *Ulva* genus can be considered for culturing, however there is a lack of wide-ranging studies providing information on their biomass production on a larger scale and detailed chemical content. The effectiveness of cultivation will be restricted due to seasonal occurrence of species, as the conditions prevailing in the Polish marine waters are not favourable to macroalgae cultivation. Thus, it is suggested to consider implementation of a project aiming at the cultivation of perennial species *Furcellaria lumbricalis* (introduction of the species from the Gulf of Riga to the Puck Bay).

Keywords: macroalgae, cultivation methods, marine waters, Baltic Sea

Streszczenie: W artykule zaprezentowano wybrane metody uprawy makroglonów w wodach morskich na świecie (uprawy linowe w toni wodnej, uprawy na dnie, uprawy zintegrowane). Opisano różnorodne podejścia techniczne i przeanalizowano możliwość uprawy makroglonów w polskich obszarach morskich. Wszystkie zaprezentowane metody upraw makroglonów mogą być przetestowane w polskiej strefie Bałtyku, poza marikultarami zintegrowanymi (IMTA). W uprawie mogą być brane pod uwagę gatunki z rodzaju *Ulva*, jednakże brakuje szeroko zakrojonych badań nad przyrostem ich biomasy oraz składem chemicznym. Należy również podkreślić, że efektywność tych upraw będzie ograniczona ze względu na sezonowy ich charakter, gdyż warunki panujące w polskich obszarach morskich nie są sprzyjające uprawom makroglonów. Dlatego też, sugeruje się realizację projektu dotyczącego uprawy gatunku wieloletniego *Furcellaria lumbricalis* (introdukcja gatunku z Zatoki Ryskiej do Zatoki Puckiej).

Słowa kluczowe: makroglony, metody uprawy, obszary morskie, Bałtyk

Introduction

Macroalgae or "seaweeds" are comparatively large, multicellular organisms that occur in salt or fresh water ecosystems. They are fast-growing plants that can reach sizes of up to 60 m in length [39]. Generally, seaweeds are defined as lower-level plants with undifferentiated roots, leaves, and stems. Based on morphology, cell wall and pigment composition, they are classified into green (Chlorophyceae), brown (Ochrophyta), and red (Rhodophyceae) algae. Growth rates of marine macroalgae far exceed those of terrestrial biomass. They exhibit very high levels of nutrient uptake and photosynthesis [6, 28].

Recently, there has been resurgence in research investigating macroalgae cultivation due to the potential economic and environmental benefits. Currently, over 100 species of macroalgae are used directly as food or indirectly as a texturing agent, with gelling and thickening properties (carrageenan, agar, and alginates) in biotechnology (also as a culture medium for different plants and microorganisms), pharmaceutical, cosmetic, textile, and food industries. They are also applied as fertilizers (and/or as a foliar spray) and soil conditioners, animal feed, and biomass for fuel. In addition, seaweed aquaculture can mitigate eutrophication (nutrient reduction) and become an alternative occupation and source of income for coastal dwellers [3, 5, 26, 42, 55]. Some species can be employed for waste water treatment and the partial recycling of nutrients, particularly near fish farm effluents (e.g. integrated culture systems). They are also used to absorb heavy metals from industrial sewage [49, 52].

Traditionally, mariculture of macroalgae has been conducted primarily in Japan and China for more than three centuries mainly for human consumption. The culture of marine algae can be traced back to 1690, when the first recorded attempts to culture seaweed on the fences of fish cages were carried out in Japan. Yet, scientifically supported culturing techniques resulting in a much more successful commercial production were not initiated until as late as the early 1950s and then mainly in relatively protected inshore waters [7].

Nowadays, countries in East and Southeast Asia dominate the seaweed culture production (99.8 %). China is the world's largest producer of cultivated seaweed (62.8%), mostly grown on long-line systems where hatchery produced seedlings are transplanted to sea on ropes suspended vertically from a horizontal top-line. The large brown macroalgae *Saccharina japonica* (*Laminaria japonica*) known as 'sea-strap' and originally introduced to China from Japan is the world's most cultivated species by volume and value. This perennial kelp is one of the largest and most complex macroalgae, which may reach a length of 2-6 m, width of 35-50 cm and blade thickness of up to 4 mm. In commercial seafarming, it is harvested annually after an eight-month growing season [20, 41].

Other major seaweed producers are Indonesia (13.7 %), the Philippines (10.6 %), the Republic of Korea (5.9 %), Japan (2.9 %), and the Democratic People's Republic of Korea (2.8 %) [51].

Globally, the production of macroalgae is almost exclusively based on cultivated species. However, in Europe, primarily in Norway, Ireland, Iceland, and France, the majority of algae are harvested from natural stocks either by boat or manually on shore or to a lesser extent by diving [4, 50, 51].

In the Baltic Sea, there have been only few trials (pilot studies) on macroalgae cultivation, in Poland [32], Finland [51], Denmark [4, 21, 36], and Estonia [27, 37, 38]. Currently, in the Baltic Sea region, only one company in Germany is cultivating macroalgae for commercial purposes – brown algae *Saccharina latissima* for cosmetic products, food, and medical research [51].

Due to the fact that macroalgae cultivation remains a relatively unexplored field in the Baltic sea in comparison to other parts of the world, and that cultivation often brings economic and environmental benefits, a need emerges to investigate culturing technics. The paper presents selected methods of macroalgae cultivation carried out worldwide and investigates the feasibility of utilizing them in the Polish marine waters.

Methods of macroalgae cultivation

Seaweeds can be cultivated in the marine environment on suspended lines, rafts, or nets (Table I). The most common cultivation technique is the long-line due to its simplicity and low costs. Commonly used substrates for growing algae include ropes, rings or nets employed in a variety of configurations. The rope lines may be monofilament, nylon, thin high-density polyethylene string, rope, or another suitable line [48]. However, recent studies have revealed that there is a strong influence of textile chemistry and textile structure on the adhesion and growth of seaweed [1, 51]. The proper materials are usually first 'seeded' with young seaweed gametophytes grown in on-shore hatcheries and then deployed off-shore, supported by networks or stakes or suspended beneath floats. Depending on the species, the seaweed is left to grow for months to a year, before it is harvested [1]. Diverse groups of species belonging to green, brown or red algae are cultivated using the long-line technique. These types of culturing farms may be located in the open sea, closed bays, lagoons, and estuaries.

Another popular cultivation technique, especially in warm temperate climates, is bottom culture. Bottom-stocking is the simplest method for transferring vegetative thalli that grow in natural field conditions and can be of two types. The direct method consists of the insertion of thalli into a sandy bottom using different types of tools. The species can also be attached to rocks with rubber bands, stabilizing the thalli in soft sediments. The second type of bottom-stocking is the plastic tube method, generally used in subtidal regions. The method consists of fixing bundles of species thalli to plastic tubes filled with sand, which anchor the algae to the sea bottom. In this method, divers place the sand-filled plastic tubes in parallel rows about 1 meter apart, perpendicular to the sea bottom, creating an underground thallus system that sustains the production in time. Bottom planting is applied to red algae species form *Gracilaria* genus. *Gracilaria* is widely distributed all over the world, but most of the species are reported to be from tropical waters [48, 52].

Seaweeds are bioextractive organisms, taking up excess nutrients generated by other species, such as fish or shrimp. The integrated culture of fed aquaculture (fish and shrimp) with extractive aquaculture (seaweed and shellfish) is called 'Integrated MultiTrophic Aquaculture', or IMTA [47]. Integrated mariculture can take place in coastal waters and can be highly intensified. One of the cultivation methods within integrated seaweed mariculture is culturing seaweeds in the open sea near cages with animals. The integration of fish and seaweed farming may help to solve the problem of polluting the environment with effluents produced by animal farming, since seaweeds can remove up to 90% of nutrient discharge from an intensive fish farm [40]. More than 20 species, mainly brown algae, have been tested as potential biofilters of animal effluents in IMTA systems [52].

Marine macroalgae farming suffers a few drawbacks such as the possibility of introducing invasive species, grazing of weeds by fishes, fouling, and changes in nutrient composition at the cost of prolonged cultivation in the same location [6, 35, 47]. One has to take these potential problems into account when planning to run a seaweed cultivation.

Tab I. Selected methods for macroalgae cultivation in marine waters.

NO.	METHOD	PURPOSE OF CULTIVATION	DESCRIPTION
1.	Long-line culture [44]	The examination of the productivity and features of brown algae *Laminaria saccharina* sporophytes for annual and biennial harvest off the Galician coast (Spain)	The cultivation apparatus for *L. saccharina* consisted of horizontal ropes held in place at a given depth by a series of buoys, each of which were linked at their ends to a concrete block. The method to outplant the seedling string on cultivation ropes was as follows: the string was wound helicoidally around the rope, fixing it with a plastic tape at 25-cm intervals. The cultivation ropes were placed horizontally ('long-line') at a 2-metre depth. The depth of the cultivation remained the same during the growth process, except in summer, when the cultivation ropes were placed at a 7-metre depth so that the *L. saccharina* could survive more easily under higher temperatures of the summer season.
2.	Long-line culture [2]	Determination of the most sustainable method of cultivating and processing of red algae *Gracilaria chilensis* and brown algae *Macrocystis pyrifera* to bioenergy (Chile)	Cultivation of red algae *G. chilensis* was initiated by tying the previously cultivated biomass thalli to ropes. The ropes were then deployed 10 km from the landing point. The total cultivation area was considered to be 100 ha. Cultivation of brown algae *M. pyrifera* required first the inoculation of lines with spores and subsequent development in tanks as part of the hatchery process. The area of cultivation was assumed to be 100 ha.
3.	Long-line culture [46]	Green algae *Codium* and *Ulva*, red algae *Gracilaria* or brown algae *Sargassum* as food for human (Costa Rica)	Long lines were spaced 1 m apart and, depending on the species, vegetative propagules of 4 to 30 g each were tied to ropes (4-mm thick), spaced on average at 0.3-m intervals. Plots were placed in different locations ranging from rocky/ coralline and seaweed prairie flats to barren sandy bottoms on the Caribbean and above muddy flats on the Gulf of Nicoya and rocky sandy bottoms in Cuajiniquil. Plot size varied from a few lines occupying ca. 50 m^2 to the largest occupying 1200 m^2 (20 m wide × 60 m long) off the Puerto Vargas beach at the Caribbean site. Sand-filled burlap sacks were used as anchors and reused plastic bottles and jugs as floats. The system was used in the near shore waters, 1.5 to ca. 10 m deep.
4.	Long-line co-culture with mussel [53]	Biomass of brown algae *Laminaria digitata* and *Saccharina latissima* for bioenergy production (Limfjord, Denmark)	Lines seeded with *L. digitata* and *S. latissima* were twisted tightly around the already existing floating mussel lines. The lines with young sporophytes were all placed 0.5 m below surface level.
5.	Macroalgae Cultivation Rig (MACR) [21]	Production of biomass of brown algae *Saccharina latissima* and *Laminaria hyperborea* for various purposes (North Atlantic, Faroe Islands).	Vertical ropes attached to the horizontal line, seeded with *S. latissima* and *L. hyperborea* before deployment in the sea. Salmon farming within 200 meters.
6.	Long-lines with mesh bags [47]	Production of carrageenans (food and pharmaceutical industries) from red algae *Chondrus crispus* (Pacific Ocean, Baja California peninsula)	Fronds of *C. crispus* placed in mesh bags on offshore long lines.
7.	Floating rafts for vertical rope culture [43]	The aim of the study was to examine differences in growth rate, morphological features, and biomass yield that might exist in *Undaria pinnatifida* cultivated at two locations with different degrees of water motion (moderately exposed site vs. sheltered site), (Galicia, Spain)	Floating rafts for vertical rope culture were deployed at the culture sites. The culture raft consisted of floating lines suspended horizontally by marker buoys and attached to structural ropes that were fixed to the bottom by concrete blocks. The floating lines were made to float at the surface by cork floats fastened to rope at regular intervals. These culture lines were stretched horizontally by placing weight on one of the ropes attached to the structural ropes, and they were oriented parallelly to the main direction of the tidal current. The 2-m long culture ropes were hung down from cork floats fastened to the floating line and weighted down by a weight attached to their lower end. Strings with seedlings of brown algae *U. pinnatifida* were cut into small lengths and inserted into the warp of the culture ropes at intervals of about 10 cm.
8.	Ropes attached to a raft for net pens (co-culture experiment with a fish farm) [56]	Red algae *Gracilaria lemaneiformis* for nutrient bioremediation (China)	20 kg of *G. lemaneiformis* thalli (red algae) segmented into 13–15 cm in length were cultured on 200 ropes. 0.1 kg thalli were divided into 16–18 clusters and nipped in a three-helix rope (2.5 m long) at 5–6-cm intervals, so the segment of the rope with thalli was ca. 1 m long. Each rope was attached to a stone as a weight. Ropes with thalli were tied to raft for net pens (4 m x 4 m), spacing at 1 m between two ropes. The thalli were cultured 1–2 m below water surface. Ropes were used in fish-farming coastal waters.
9.	Polyethylene nets and ropes hanging on a floating rope [51]	The aim of the pilot study was to evaluate the potential of macroalgal cultivation for producing biomass for industrial applications like bioenergy and removing the excess of nutrients (Finland, Baltic Sea)	Polyethylene nets were cut into panels with a height of 60 cm and a width of 30 cm for each unit. The sides of the nets were reinforced by melting. Ropes were cut into a length of 60 cm, and 6 such pieces were used for each cultivation unit. Units had fixed metal bars in the bottom and top and they were fixed to the main line. The system was not seeded with macroalgae, tested in two localities at the southern coast of Finland (salinity 4-7 PSU).
10.	Fishing nets [32]	Developing a method to support the process of self-purification (de-eutrophication) of waters in strongly degraded areas using *Ulva* species (Baltic Sea, Poland)	Fishing nets were used as a substratum for the growth of biofiltrators (mussels and barnacles) and green algae of *Ulva* species (some nets seeded before deployment in the environment). The system was tested near the outlet of municipal sewage discharge.

11.	Ring system [7]	It was an experiment aimed at developing an appropriate technical device to grow brown algae *Laminaria saccharina*. The system had to withstand the harsh environmental conditions of the German North Sea shelf in order to utilize it in exposed offshore locations, especially when considering multi-user concepts combining wind farm installations with mariculture (North Sea, Germany)	The ring construction had a total diameter of 5 m and consisted of a polyethylene tube with a 10-mm thick wall and a diameter of 110 mm that was welded to rings. The rings were weighed down by a steel cable (30 mm in diameter) inserted into the tube and obtained their buoyancy through eight elongated fenders (23 kg buoyancy each). They consequently floated at a depth of 1.2–1.5 m. Carrier ropes were suspended radially and 80 m of culture line could be fastened like cobwebs on each ring. A crow's foot was used to fasten the ring on a common mooring system. Due to permanent chafing of the carrier ropes with the fender ropes and because the fenders themselves got entangled with each other, a modified system was developed. This consisted of one centre buoy (300 kg buoyancy) with a connected reverse crow's foot and a centre guide ring to prevent chafing of the mooring line with the carrier ropes. Furthermore, all radial splices, which connected the carrier ropes to the polyethylene tube, were replaced with metal cuffs. Three loops were welded to these cuffs, one to the centre to fix the carrier ropes and the other two to the bottom and the top of the cuff, to connect both crow's feet. *L. saccharina* was seeded on ropes.
12.	Bottom planting [8]	Biomass production of red algae *Gracilaria* for various industry purposes, e.g. agar (Chile)	Direct method – direct insertion of red algae *Gracilaria* thalli (*G. lemaneiformis*, *G. verrucosa*) into the sandy bottom using different types of tools (e.g. spade, fork). Plastic tube method – fixing bundles of *Gracilaria* thalli to plastic tubes filled with sand that anchor the algae to the sea bottom.
13.	Bottom planting [2]	Determination of the most sustainable method of cultivating and processing macroalgae to bioenergy (Chile)	Thalli of red algae *Gracilaria chilensis* was planted 1 km from the landing point and processing facilities. The total cultivation area was 20 ha. The biomass was harvested by a diver.
14.	Integrated multi-trophic aquaculture (IMTA) with salmon [22]	The main objective of this study was to compare the growth responses of brown algae *Saccharina latissima* cultivated in close proximity to Atlantic salmon (*Salmo salar*) aquaculture with that of sporophytes kept at a control site in coastal waters off the coast of Central Norway. Secondary objectives were to study seasonal- and depth-dependent growth and the seasonal variation of the chemical composition of *S. latissima* (Norway)	Vertical ropes seeded with *S. latissima* were deployed at 2.5 m and 8 m depths at a salmon farm and at reference station 4 km away.
15.	Integrated multi-trophic aquaculture with salmon (IMTA) [9]	Using red algae *Gracilaria chilensis* and brown algae *Macrocystis pyrifera* as biofilters (Chile)	A 100-m long-line was installed about 100 m from a salmon farm. The seaweed *G. chilensis* and *M. pyrifera* long-line was installed in the main water flow in the bay receiving most of the nutrient discharges during the flood current period. The long-line design permitted the cultivation of *M. pyrifera* and *G. chilensis* at three depths, while the culture lines were divided into six sections that allowed three randomly distributed culture sections for *Macrocystis* and another three for *Gracilaria* at each culture depth. The extension of one replicate culture line was 10 m for *Macrocystis* and 3 m for *Gracilaria*.

Cultivation in the Polish marine waters

The use of macroalgae from Polish marine waters for industrial purposes was carried out in the 1960s. In 1963-1973, brown algae *Fucus vesiculosus L.* and red algae *Furcellaria lumbricalis* (Hudson) J.V. Lamouroux were collected on an industrial scale. They were harvested from the Inner Puck Bay for agar production [16, 17]. Around 6,500 tons of wet weight of *F. vesiculosus* and *F. lumbricalis* were harvested during 10 years of exploitation, so on average 590 tons per year.

At the end of the exploitation period, i.e., in 1972, it was noted that in comparison with 1968, the proportion of *F. vesiculosus* and *F. lumbricalis* in the biomass of harvested plants decreased and a share of "other" algae, which ranged from 18% to 32% of the total biomass increased notably. Among these "other" algae, a significant role was played by filamentous brown algae *Pylaiella littoralis* (Linnaeus) Kjellman and *Ectocarpus siliculosus* (Dillwyn) Lyngbye as emphasized by Wiktor [54]. The increase of their biomass in the 1970s, which caused pollution of the extracted material – *F. vesiculosus* and *F. lumbricalis*, influenced the decision about ending algae exploitation. It was also determined by economic aspects, because it turned out that the cost of importing algae from other countries, like Japan, was lower than their exploitation in the Puck Bay.

The eutrophication of the Puck Bay, especially of its internal part, which was progressing at the turn of the 1970s, caused degradation of underwater meadows, including *Zostera marina* L., as well as free-floating forms of *F. vesiculosus* and *F. lumbricalis*. Since the early 1980s, *F. vesiculosus* and *F.lumbricalis* have not been found in the basin again [14, 29]. The degradation of underwater meadows was caused by the massive development of annual filamentous brown algae *Pylaiella littoralis* and *Ectocarpus siliculosus*, which formed so-called "algal mats" which were 30 cm thick, shading rooted plants and those lay-

Tab. II. *Ulva* sp. biomass (g dw·m^{-2}) on net reefs in the Gulf of Gdańsk, near the sewage treatment plant at Mechelinki, at stations M, M1 and M2, in the period 11.05.-11.07.1995 [32]

DEPTH OF NET SUSPENSION [m]	DISTANCE FROM SEWAGE PLANT COLLECTOR [m]				
	M - 150	M2 - 300	M1 - 500		
	"CLEAN" NETS	"IMPLANTED" NETS	"CLEAN" NETS	"IMPLANTED" NETS	"CLEAN" NETS
0.1	6.5	14.64	6.9	22.42	14.5
1.0	3.47	4.52	-	-	-
1.3-1.5	2.27	2.3	7.48	5.64	-
2.5	-	-	no growth	no growth	1.08

"clean" nets – not implanted with Ulva spores

"implanted" nets – implanted with Ulva spores

ing on the bottom. Decaying masses of filamentous brown algae also influenced the reduction of redox potential of sediments [10, 11, 30].

Degradation of the Puck Bay biocenosis was an inspiration to undertake activities aiming at the reconstruction of degraded underwater meadows. The project of such activities was elaborated at end of the 1980s for the Inner Puck Bay, on the basis of research carried out in 1987 and 1988-1989 [10, 11, 13, 14, 31, 32, 33].

The project included the following biotechnical activities:

- Removal of filamentous brown algae degrading the environment;
- Extension of the range of underwater meadows by means of introduction of *F. lumbricalis* and transplantation of *Z. marina*;
- Reconstruction of fouling flora and fauna communities by forming an artificial hard substrata;
- Increase of fishing production through the construction of artificial spawning grounds.

In order to eliminate filamentous brown algae, a device for mechanical removal was developed. It could catch about 240 tons of these algae within three months (April-June). The tests of the material collected by the device did not show a significant loss of benthic fauna and ichthyofauna taken along with algae [14, 15]. With harvesting of filamentous brown algae, it was planned to introduce loose forms of *F. lumbricalis* from the Gulf of Riga (Estonia) to the Puck Bay and to recreate its biomass from the 1950s. The introduction was planned in autumn when filamentous brown algae would finish its development cycle. In early spring (March), the introduced *F. lumbricalis* was supposed to eliminate the excess of biogenic nutrients accumulated in the water during winter. The cultivation of *F. lumbricalis*, due to the summer mass appearance of the filamentous brown algae was to be conducted at the bottom of the basin in areas limited by a fence from a fishing net. Along with the extraction of filamentous brown algae, it was planned to increase annually the number of areas intended for development of *F. lumbricalis*. The species was supposed to be introduced in the amount of 250 tons per year. The elimination of filamentous brown algae with simultaneous introduction of *F. lumbricalis* and planting of *Z. marina*, as well as the implementation of the biological sewage treatment system in sewage treatment plants which discharged wastewaters to the Puck Bay were supposed to improve the environmental condition of the basin [14, 15].

The project is promising, but its implementation requires considerable financial support and cooperation of scientists with local authorities and with Estonian specialists. So far, only activities related to limiting the input of nutrients to the basin have been undertaken, through the modernization of wastewater treatment plants. These activities had little effect on the improvement of the environmental condition. *F. lumbricalis* and *F. vesiculosus* had never been restored in this basin, only the bottom surface has overgrown with *Z. marina* and other vascular plants have slightly increased. The filamentous brown algae are still an important element of the quantitative structure of the Puck Bay macrophytes.

In Poland, one experiment aiming at assessing biomass increase of cultivated algae has taken place and it was in the Gulf of Gdańsk in 1995 [32]. Fishing nets were set near the discharge from the sewage treatment plant and served as a substratum for the growth of biofiltrators and *Ulva* species. The time of exposure of nets was one to three months. The objective was to develop a method to support the process of self-purification of waters in strongly degraded regions.

The studies showed that when *Ulva* species is planted on nets before their deployment in the environment, it increases biomass growth by 2-4 higher times in comparison with natural substrata (stones) or 2 to 3 times in comparison with non-implanted nets [Tab. II].

In Poland, there is lack of traditions in the use of macroalgae. Nowadays, the cultivation of algae is not carried out in the Polish marine waters.

Generally, cultivation of seaweeds, growth and biomass intensification depends on various environmental factors such as temperature, salinity, light availability, water motion and nutrient composition [48, 50].

Traditionally, large-scale algal production is the most productive in sub-tropical and warm temperate areas. The idea that algae can grow well in cold temperate regions is often dismissed due to the limitations of the production period. The typical range for al-

Tab. III. Analysis of factors affecting macroalgae culturing in the Polish marine waters, based on current knowledge

SPECIES	MORPHOLOGY	VEGETATION PERIOD	AREA OF POTENTIAL CULTIVATION	TECHNICAL AND TECHNOLOGICAL PROJECT OF CULTIVATION	KNOWLEDGE ABOUT BIOMASS INCREASE IN CULTIVATION	KNOWLEDGE ABOUT CHEMICAL CONTENT	KNOWLEDGE ABOUT MARKET NEEDS
Ulva spp.	Thallus is branched or unbranched, flattened, delicate, up to 40 cm long and 15 mm wide [45]	May - August	coastal area of the Puck Bay (down to 10 m depth)	none	2-4 times [32]	The highest lipid content in April-May: 5.0 and 6.0% of dw [23] Lipid content from 3.47±1.76% to 4.36±2.17% of dw; protein content from 9.42±4.62% to 20.60±5.00% of dw, level of carbohydrate from 29.09±6.44% to 39.81±11.15% of dw [24]	lack of

gal production is 55˚S-55˚N, which includes Polish marine waters. However, there are a few environmental factors that significantly influence macroalgae cultivation there. One of them is short vegetation season (June-September), limited by both light and temperature, so cultivation cannot be carried out all year round. The ice cover is another limiting factor to large-scale algal production, it is highly variable between years and seldom extends to the Baltic Proper. The ice cover is a problem, mainly in coastal areas. The construction must be then moved below the ice cover or removed to land. Numerous claims have been made on biomass productivity based on small-scale experiments and high value algal products in warm temperate regions. It is necessary to know whether these claims can be extrapolated to large-scale production and to other regions. Realistically, algal production in terms of biomass will not compete with that of warmer regions [33].

In the Baltic Sea, salinity is the most important abiotic factor controlling the distribution of macroalgae species. It affects species diversity, reproduction cycles, and growth rates. Generally, the number of marine species decreases from a few hundred in the Danish Straits (salinity 25) to less than 100 in the almost fresh waters in the Bothnian Bay (salinity 2) [50]. In Polish marine waters (salinity 7), there are several macroalgae species of marine origin, among which the most common are red algae *Polysiphonia fucoides* (Hudson) Grevill, *Furcellaria lumbricalis*, *Ceramium diaphanum* (Lightfoot) Roth, and brown algae *Pylaiella littoralis*. Their thallus is filamentous and delicate, except *F. lumbricalis* which has cartilaginous fronds. They reach the maximum length between 15 cm (*C. diaphanum*) and 40 cm (*P. littoralis*) [45].

The main constraint to macroalgae cultivation in the Polish marine waters, as in the whole Baltic Sea, is the low growth rate of marine species in sub-optimal conditions. However, some areas may be more suitable than others, depending on the species and purpose of use. In general, higher salinity is favorable for species of marine origin and is necessary to ensure high growth rates in large perennial brown algae which are popular for cultivation in other parts of the world. On the other hand, ephemeral filamentous macroalgae which occur in great amounts during summer, may be a solution for cultivation that can work even in brackish waters with lower salinities. An example is the species of green algae from *Ulva*, which are common in the coastal zone of the Puck Bay (Table III). They are generally more tolerant and show high growth rate under the favorable conditions, i.e., high level of nutrients, high temperature and good light availability. As the experiment suggests [32], the *Ulva* cultivation, when set near a discharge of wastewaters, mitigates nutrient input and counteracts eutrophication, which is a major problem in the Polish marine waters and in the whole Baltic Sea [25]. However, *Ulva* species are rather small and develop during very short spring-summer period, comparing to the world's most cultivated species *Saccharina japonica*. What is more, *Ulva* thallus is very fragile, so it can be cultivated only in calm, sheltered areas, of which there are not many in Poland. There is a potential in *Ulva* cultivation in the Polish marine waters, but it needs more wide-ranging research including benefits for the environment and economy.

To sum up, the Polish marine waters do not create favorable conditions for macroalgae cultivation. Species of *Ulva* genus can be considered for culturing, however there is a lack of wide-ranging studies bringing information on their biomass production on larger scale and detailed chemical content (e.g. vitamins, minerals, fiber, hormones). Lack of knowledge is the largest obstacle to convince potential investors about the profitability of macroalgae cultivation. All techniques of macroalgae cultivation discussed in the paper can be tested, except integrated mariculture (IMTA), as there is no fish or shrimps aquaculture in the Polish marine waters.

If one consider cultivation of macroalgae in the Polish marine waters for economic purposes, first of all, the following task should be carried out:

- Elaboration of technical and technological project of cultivation, harvesting, preservation and processing of macroalgae.
- Investigation of the effectiveness of the cultivation by broad-ranging *in-situ* experiment; designation of cultivation areas depending on the use of macroalgae biomass (removal of nutrients from eutrophic waters, biogas production, algae extracts etc.).
- Laboratory analyses of cultivated macroalgae in terms of chemical components which are industrially important and possible hazardous substances.
- Assessment of the impact of cultivation on the environment.
- Market analysis regarding demand for macroalgae material (e.g. biomass, biologically active compounds) by diffe-

References:

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