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Mass cultivation of seaweeds: current aspects and approaches

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Abstract

A word-wide overview is presented of the current state of mass cultivation of seaweeds. In comparison with a total annual commercial production of fish, crustaceans and molluscs of about 120×10^6 t, of which one-third is produced by aquaculture, the production of seaweeds is about 10×10^6 t wet weight; the majoirty of this comes from culture-based systems. The Top Ten Species List is headed by the kelp *Laminaria japonica* with 4.2×10^6 t fresh weight cultivated mainly in China. The productivity of a well-developed, multi-layered, perennial seaweed vegetation is as high as dense terrestrial vegetation, and even higher annual values for productivity have been reported for tank cultures of macroalgae. Epiphytes provide a major problem for the seaweed cultivator, but can be controlled by growing plants at high densities in rope cultures in the sea, or, more easily, in seaweed tank cultures on land. The main environmental problem of animal (fed) aquaculture is the discharge of nutrient loads into coastal waters, e.g., 35 kg N and 7 kg P t^{-1} aquacultured fish. Integration of fish and seaweed farming may help to solve this problem, since seaweeds can remove up to 90% of the nutrient discharge from an intensive fish farm. Mass culture of commercially valuable seaweed species is likely to play an increasingly important role as a nutrient-removal system to alleviate eutrophication problems due to fed aquaculture.

Introduction

Marine macroalgae form dense stands on the well-illuminated rocky margin of all continents and the productivity of a well-developed, multi-layered, perennial seaweed bed is as high as a dense forest or a man-made microalgal culture (Lüning 1990). It is therefore no wonder that seaweeds have been utilised and farmed by man for hundreds of years as food and fodder, particularly in the Far East. What are the current goals, problems and approaches in seaweed cultivation? Global utilization of seaweeds for food, fodder, chemicals and pharmaceuticals is on the increase and, in terms of harvested biomass per year, seaweeds are among the most important cultivated marine organisms, as will be discussed below.

Top ten cultured species and trends in worldwide seaweed production

The present world production of fish, crustaceans and molluscs is approximately 120×10^6 t, and about one third of this is produced by aquaculture (FAO 2001). In addition, approximately 10×10^6 t seaweed (fresh weight) are produced, the largest part of which comes from culture-based practices (FAO 2001). The Top Ten Species List for aquaculture production is headed by the kelp *Laminaria japonica* with 4.2×10^6 t, cultivated mainly in China, followed by the Pacific oyster *Crassostrea gigas* with 2.9×10^6 t (FAO 2001).

Commercial farming of seaweed has a long history. At present there are approximately 200 species of seaweeds used worldwide (Zemke-White and Ohno 1999), of which about 10 species or genera are intensively cultivated, such as the brown algae *Laminaria japonica* and *Undaria pinnatifida*, the red algae *Porphyra, Eucheuma*, *Kappaphycus* and *Gracilaria*

Table 1. Seaweed production (t fresh weight) in three Asian countries and a few examples from other countries in 1999 (FAO 2001)

	Brown algae	Red algae	Green algae
World production	5987490	1974110	71779
China	4474090	426733	47
Japan	231443	413057	313
Korea	270717	208610	6447
Philippines	–	617715	3538
USA	7955	81	–
Norway	17892	–	–
France	6939	2492	119
Spain	28	14790	–
Portugal	–	1949	–

and the green algae *Monostroma* and *Enteromorpha* (Wikfors and Ohno 2001). An increasing number of people are becoming aware of the benefits and potential of macroalgae and new algal products and novel uses of seaweeds are acting as a stimulant to encourage more research and development of seaweed cultivation. At present, the main areas, where seaweeds are cultured are concentrated in eastern Asia where eating algae has been commonplace for thousands of years (Table 1).

Productivity in the natural environment and mass culture

In the natural environment, values for maximum productivity are 10 times higher for a seaweed stand than for a plankton population which is due to the fixed position of a seaweed on a substrate (Lüning 1990). This ecological advantage allows macroalgae to form a stable, multi-layered, perennial vegetation capturing almost every photon falling on a square metre of rocky bottom, as in a dense terrestrial forest, where almost no light reaches the forest floor. The parameters for a highly productive ecosystem are the same on land and in the sea, with maximum productivity at 1.8 kg C m^{-2} yr^{-1} and a maximum chlorophyll content of 3 g m^{-2} ground or illuminated surface. In a seaweed stand, this is achieved with an algal biomass of approximately 10 kg m^{-2} (Lüning 1990). In contrast, most of the photons falling on a natural planktonic community are absorbed or scattered by abiotic particles, because the algae are so thinly distributed. This results in much lower productivity in a planktonic community than in a macroalgal stand.

Cultivation of microalgae involves packing the cells very densely in a bottle or pond and this results in productivity similar to that in a fixed macroalgal community. One might say that the rigid walls of the bottle or the pond are as efficient in concentrating a maximum of photosynthetically active cells on a square meter of ground as a rocky shore is as concentrating the fixed life forms of the macrophytes. The same is valid for tank cultivation of free-floating seaweeds, with a maximum of approximately 10 kg wet algal biomass per square meter of illuminated tank surface. The tank walls keep this high amount of biomass together, while in the field the free-floating seaweed biomass would drift away and dilute in all directions. In this way the seaweed cultivator may take apart the different layers of a multi-layered seaweed community and cultivate each of the components separately, free-floating in a tank culture due to air agitation.

Cultivators of micro- or macroalgae should thus be able to reach productivity values, which are at least as high as, under optimum conditions, in a natural, highly productive ecosystem. In fact, higher annual productivity values have been reported in macroalgal tank cultures, e.g., a mean of 39.7 g dry weight m^{-2} d^{-1} over the whole experimental period of 32 months in *Gracilaria ferox* grown continuously in tanks under a pulse-fed nutrient regime in Key Largo, Florida (Capo et al. 1999). This productivity is equal to 5.4 kg C m^{-2} yr^{-1}, and thus three times higher than in a highly productive ecosystem, taking into account that 25% dry weight is mineral ash and 50% of the remaining organic weight is carbon (Lüning 1990). Obvious reasons for such higher productivity in monoculture of seaweeds in outdoor tanks are beneficial factors such as continuous nutrient supply, absence of grazers or minimum disturbance by epiphytes, if readily achieved by the cultivators.

Epiphytes: a major problem in seaweed cultivation and how to control them in tank culture

It is difficult to control epiphytes when seaweeds are cultured under non-unialgal conditions. As to seaweed cultivation on ropes in the sea, motile propagules of algae and animals have free access to all surfaces of the cultivated seaweeds and there is plenty of underwater light available to encourage the growth of epiphytic algae. Epiphytism of seaweeds on ropes in the sea or in land-based tanks can be controlled by growing plants with high densities. This approach was described for tank cultivation in details by Bidwell *et al*. in Nova Scotia when they developed their tank cultivation system for Irish moss, *Chondrus crispus* (Bidwell et al. 1985). At a density of approximately 10 kg wet biomass m^{-2} of tank surface and a tank depth of 60–90 cm, there is essentially complete light absorption by the plant material, and the irradiance near the tank bottom is almost zero. Creation of circulating cells of water by rising air bubbles from bottom air pipes was found to be the best method of keeping a dense algal biomass in constant motion, and vigorous aeration also ensured exposure of plants to light for a short time every minute. The water circulation time in the circulating cells was about 1.0 to 1.5 minutes, and the algae were alternately exposed to bright sunlight at the tank surface for about 10 seconds and then plunged to the depths of the tank and virtual darkness with little or no photosynthesis during the remaining 50 seconds (Bidwell et al. 1985). In a tank with a surface area of 2.6 m^2 and a depth of 0.8 m inoculated with *Palmaria palmata* at a density of 8 kg m^{-2} we found that the irradiance at 0.5 m depth was 0.05% of surface irradiance.

Although growth rate of individual plants is lower in a dense culture, the yield per square metre tank surface is high, simply because there is so much biomass in the tank that small increases of the individual thalli add up to an impressive overall yield. In contrast, germlings of algal epiphytes such as species of *Enteromorpha*, *Ulva* and *Ectocarpus* cannot establish a substantial biomass in these conditions, because they are fast-growing, opportunistic organisms and require high irradiances (r strategist). As an example, the mean epiphyte biomass, mainly *Giffordia* and *Enteromorpha*, was only 2.7% of the biomass of *Gracilaria ferox* in the tank cultures in Key Largo, Florida (Capo et al. 1999). Perennial seaweeds such as *Gracilaria* (K strategists) collected from the undergrowth of a multi-layered seaweed community are guarded against epiphytes by high-density cultures, which act as a ″light umbrella″. In natural populations, these plants are shielded from excess irradiance often by larger algae, e.g., by the kelp canopy.

The method of reducing growth of epiphytes by cultivation at high densities was first developed by Ryther et al. (1979) working in Massachusetts and Florida, and later by Bidwell et al. (1985) working in Nova Scotia. In the early 1970's the Ryther group at Woods Hole, Massachusetts and Harbor Branch Foundation, Florida started seaweed cultivation by screening different species of seaweeds for their growth potential in raceways and tanks. The best yields, mainly of the agarophyte *Gracilaria foliifera* and the carrageenophyte *Neoagardhiella baileyi*, were obtained in full sunlight, at low nutrient concentrations, with turnover rates of at least 20 volumes d^{-1} and at a density of 2–4 kg wet weight m^{-2} of tank surface. That observation led to harvesting by halving the density of cultures from 4 to 2 kg m^{-2} after whatever time was needed for such a doubling. Bidwell et al. cultured Irish moss (*Chondrus crispus*) at densities as high as 8–12 kg m^{-2} (Bidwell et al. 1985). They found that large amounts of plant material can be held in reserve in small tanks for up to 6 weeks in summer at density of 20 kg m^{-2} and with very low level of aeration without any sign of deterioration, epiphyte infestation or disease. Returning plants to normal cultivation conditions started growth at the expected rate.

A second method of reducing epiphytism is more recent and may be described as meristem activation by short-day treatment in summer. In laminarian species it had been found that the seasonal growth rhythm (with fast growth in winter and spring and growth reduction in summer) is controlled by endogenous, circannual rhythmicity and is synchronised by the annual course of daylength, with short days in early winter starting the new growth (Lüning 1993). Treatment with continuous short days in the laboratory acts as a strong, environmental zeitgeber signal and results in continuous activation of the basal blade meristem and continuous growth throughout the year. In other words, the normal seasonal sequence of growth-on and growth-off is interrupted and turned into arrhythmic, continuous growth. When *Laminaria digitata* was cultured in outdoor cultures with automatic blinds allowing 8 hours of light per day in summer, continued high growth activity throughout the summer was observed (Gomez and Lüning 2001). In a control tank at ambient daylength, growth rate was down-regulated due to the annual course of daylength as a zeitgeber. Continuous growth activity in summer would counteract the natural reduction of growth rate in summer in perennial algae and may help to reduce or prevent growth of epiphytes. Several commercially valuable perennial red algae are currently being tested in this respect as part of the EU project SEAPURA which aims to develop cultivation techniques for red algae, not used before in integrated culture with fish.

Seasonality problems and the perennial seaweed life form

Another ecological advantage in many seaweed species is their perennial life form, with a potential life span of up to 15 years in certain *Laminaria* species. At mid- and high latitudes, storage of carbohydrates in summer in the perennial thallus portions allows growth to start in winter and thus a strategy of ″early nutrient scrubbing″. Growth of the new year's thallus portions in a perennial seaweed starts from December/January onwards, even when underwater irradiance is low. In this way perennial seaweeds exploit the high levels of nutrients in seawater during winter using stored carbohydrates as sources of energy and building material for the new parts of the thallus. In contrast, planktonic algae have to wait for the light to increase in early spring to start the spring bloom.

However, longevity of the perennial life form of a seaweed has two disadvantages, both important for the cultivator, because it facilitates and/or encourages the growth of epiphytes. Firstly, the perennial thallus is an ideal substrate for many pelagic and benthic plant and animal cells. These epiphytes reduce or eliminate the supply of irradiance, carbon and nutrients to the surface cells of the perennial seaweed and therefore reduce the productivity of the basiphyte. The perennial seaweed has developed several strategies to reduce this danger, firstly by producing the first cells of the new year's thallus portions in early winter from reserve materials when low underwater irradiance makes life difficult also for epiphytic microalgae such as benthic diatoms. In addition to this, antibiotic substances may guard the young, newly grown thallus portions, while the old portions are used for supporting growth of the young thallus portions by translocation of organic substances and minerals and also for production of sporangia and gametangia. Spores and gametes of the perennial seaweed are released from the heavily overgrown old thallus portions into the water. Thereafter, the old portions may eventually be cast off as a useless portion of the perennial algal thallus, also taking with them all the epiphytes whose original ″intention″ had been to find a place for life as safe as a piece of rock.

A second disadvantage of longevity in a perennial seaweed at mid- and high latitudes is the necessary reduction of growth rate in summer, even in the presence of sufficient nutrients (Lüning 1979). Since the bulk of photosynthate produced in summer has to be stored as carbohydrate to be used in winter for survival of the remaining perennial thallus and production of the first new thallus portions, growth rate must be reduced in summer. This process is controlled and synchronised by the long-day signal in laminarian species (Lüning 1993). The reduction of growth rate in summer in a perennial alga may result in epiphytism by animal and other algal cells.

Integrated cultivation: seaweeds as biofilters for the fed aquaculture of finfish

Fed aquaculture (animal culture) is a booming industry, but it discharges heavy nutrient loads into coastal waters, e.g., 35 kg N and 7 kg P t^{-1} aquacultured fish (Chopin et al. 2001). A possible solution to this problem is to integrate seaweeds into fish farming, in other words, to combine fed aquaculture with extracting aquaculture (seaweed culture). Numerous studies have been performed which combine seaweed culture with land-based fish tanks or open sea fish cages (e.g., Buschmann et al. (2001), Troell et al. (1999), Chopin et al. (1999, 2001), Neori et al. (2000) and Hernández et al. (2002)). Seaweeds removed up to 90% of the nutrients discharged from an intensive fish farm (Neori et al. 1996). Algal farming along the coasts, therefore, may function as an effective biofilter to alleviate the eutrophication problem worldwide. Another relevant issue to integrate seaweeds into fish farming year around is to alternate cultivated seaweed species with seasons. This means a comprehensive search is required to find seaweed species suitable for year-round cultivation and have economic uses in both land-based and open sea cultivation systems.

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