GROWTH OF NORI (*Porphyra tenera*) IN AN EXPERIMENTAL OCEAN THERMAL ENERGY CONVERSION SYSTEM AT THE NATURAL ENERGY LABORATORY OF HAWAII

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INTRODUCTION

Porphyra species, known as nori in Japan, are among the world's most valuable seaweeds in terms of both total annual crop value and price per unit weight (Kramer, Chin, and Mayo, Inc., 1982; Tseng, 1982). Most nori is sold as dried, paper-like sheets for use in many Japanese dishes; the U.S. market for nori sheets is worth several million dollars and growing (Kramer, Chin, and Mayo, Inc., 1982). *P. tenera*, the traditionally used species (Ueda, 1973), is generally the highest-quality species for sheet production (Noda and Iwata, 1978). *P. tenera* has been cultured by the Japanese for years, and its biology is well known (e.g., Ueda, 1973; Kurogi et al., 1971; Kurogi, 1961). Because of the large market for *P. tenera* and because of its high price, it was chosen as a species for culture in simulated ocean thermal energy conversion (OTEC) effluent water.

The opportunity for OTEC-related nori culture trials first arose in 1979 when the deployment of OTEC-1, a federally sponsored research vessel, was planned off the island of Hawaii. Efforts to secure research space on board OTEC-1 failed. Subsequently, a proposal was submitted to conduct experiments on board the Mini-OTEC barge, another floating platform, during its expected second deployment off Keahole Point. The proposal was accepted by the University of Hawaii Sea Grant College Program and co-funded by the Hawaii Department of Planning and Economic Development. When the redeployment of Mini-OTEC was canceled, a deep-water pipe was installed at the Natural Energy Laboratory of Hawaii (NELH) site at Keahole Point. The nori culture facilities were constructed at this site in early 1982 and experiments ran from mid-1982 until February 1983.

Warm surface seawater and cold deep seawater, similar to those available from the effluents of an OTEC facility, offers the following attractive advantages for nori culture:

1. Low pumping costs for very large volumes of water through shared use between the OTEC and aquaculture facilities.
2. Water temperature range from approximately 8°C to 25°C permits the aquaculture system to achieve optimal temperatures year-round. The optimal water temperature for *P. tenera* is

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about 15°C (Iwasaki, 1961); this temperature could not be achieved economically in an aquaculture system in Hawaii without the use of the cold deep seawater.

3. Higher nutrient concentrations in the deep water (44.0 µg-at/l N and 3.2 µg-at/l P off Hawaii) compared with levels in surface water (0.6 µg-at/lN, 0.2 µg-at/l P).
4. Near-absence of disease-producing, epiphytic, or other contaminating organisms in the deep water.

The potential benefits of using deep seawater for aquaculture were recognized by Othmer and Roels (1973). Subsequently, experiments showed that upwelled water, when mixed with surface water, improved algal growth (Roels et al., 1978; North, 1977).

The experiments performed at NELH were designed primarily to establish the technical feasibility of nori production in simulated OTEC effluents. Therefore, the main questions asked were, "Can *P. tenera* be grown intensively using mixed deep and surface waters in Hawaii?" and "How fast does *P. tenera* grow under these conditions?" Production rate alone, however, is not sufficient to determine the success of a nori culture facility. Quality is a critical determinant of nori price. Nori quality is judged by many factors, including flavor, color, luster, aroma, texture, and degree of contamination. About 100 different degrees of quality are recognized by Japanese nori graders (Woessner, 1983).

MATERIALS AND METHODS

Nori was cultured at NELH using an air-lift suspension method similar to that described in Ryther et al. (1979). The outdoor macroalgae culture facility at NELH consisted of 10 rectangular tanks (3 m long x 1 m wide x 1 m deep), each divided into 3 1-m^3 compartments. Air bubbling from a perforated pipe on the bottom of each tank kept the algae in continuous suspension and circulation. This technique promotes rapid growth of several seaweeds at high culture densities (Ryther et al., 1979; Neish and Knutson, 1979; Bidwell et al., 1985) and uses available sunlight efficiently.

Most experimental systems of this type have been used to culture seaweeds such as *Gracilaria* and *Chondrus* which can, in theory, grow in a vegetative phase essentially indefinitely. *Porphyra*, in contrast, ages noticeably after several weeks, making it a less desirable commercial product. However, raised in batch culture, a 4 to 5-week culture period appears to permit growth to harvestable size without visible quality deterioration.

The leafy thallus phase of the *P. tenera* life cycle is a winter (short-day) phase in Japan (Figure 1). Environmental conditions were therefore altered to foster *P. tenera* growth in Hawaii. Opaque tank covers allowed photoperiod control. In most cases, an 8-hour photoperiod recommended by Iwasaki, (1961) was maintained. The mixture of deep seawater and surface seawater entering each compartment was controlled individually, varying temperature and nutrient conditions simultaneously.

Nori stock material — obtained from Japan as partly dehydrated, frozen fronds on nets — was maintained at -20°C. Nori frozen in this manner remains viable for months and, in Japan, is used to restock culture beds in case of loss (Kurakake, 1969). The nets had been seeded with *P. tenera*, but

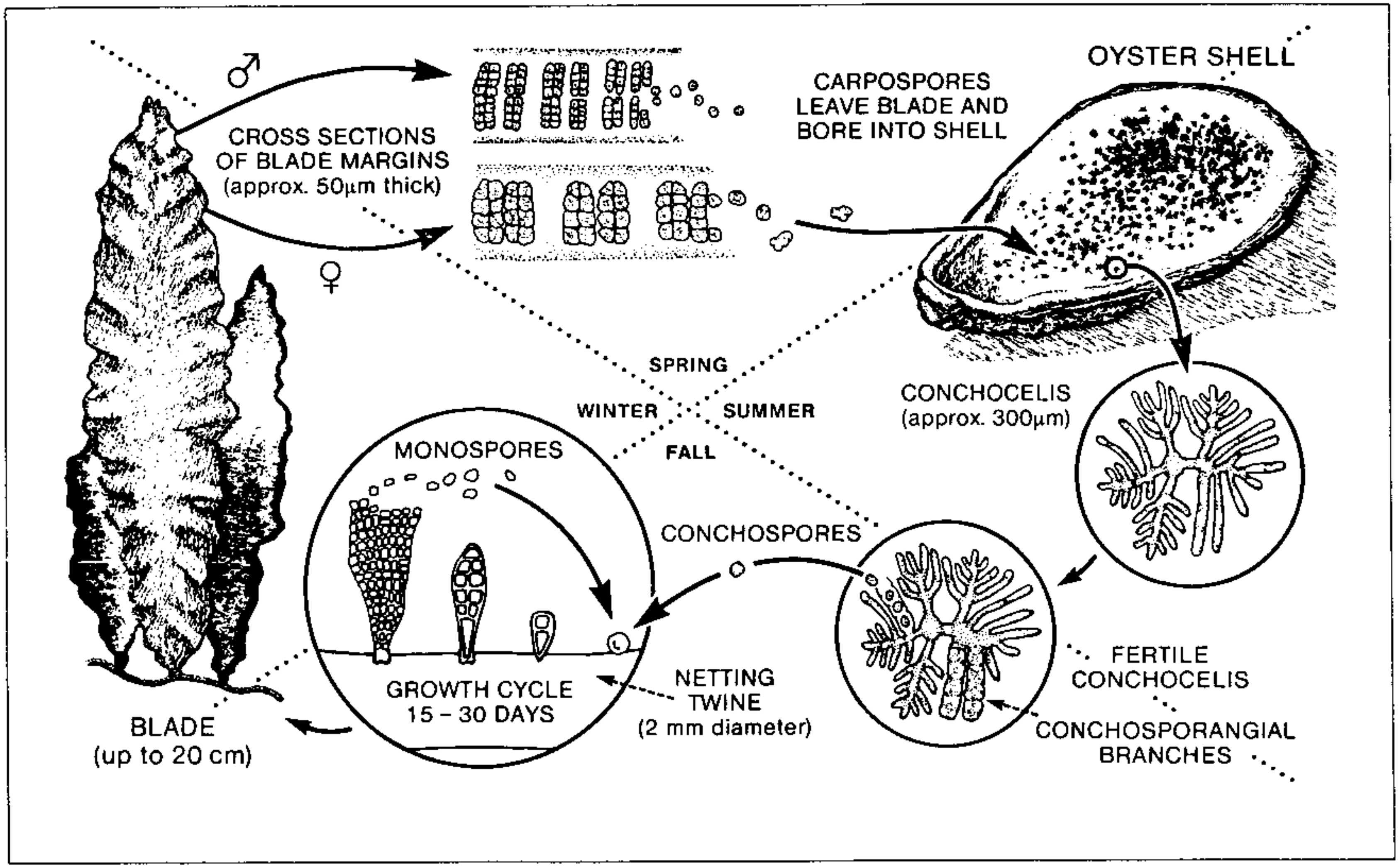

Figure 1. Life history stages of Porphyra *spp. The plant form alternates between the microscopic conchocelis stage which bores into bivalves shells and the thallus stage. (From* Final Programmatic Environmental Impace Statement: Nori Farming and Processing in Washington State. *Reprinted by permission of the author, T. F. Mumford).*

small numbers of thalli of other *Porphyra* species may have been present (O. Imada, Kyowa Hakko Kogyo Co., Tokyo, Japan, 1980: personal communication).

At the beginning of an experiment, a portion of a net was cut into short strands. The strands, with their attached fronds (initially less than 3 cm long) were placed in a tank compartment and "tumble-cultured" at 15°C for approximately 3 days. This procedure allowed the juvenile fronds to rehydrate, begin growth, and become large enough to be retained by the drain screens in the compartments. The nori fronds were then stripped from the net strands, centrifuged briefly to remove excess water, and weighed. For later growth measurements, the nori was collected by draining the contents of each compartment into a mesh bag at the drain outlet. The nori samples were centrifuged to remove excess water and weighed. Small (1 – 4 g wet wt) subsamples were taken from each sample for dry weight determinations and, when desired, for composition analysis before the nori was returned to the tanks.

Incident light was monitored continuously using a Licor quantum sensor and integrator. Influent and effluent pH were measured at noon with a Corning pH meter. Other parameters — including influent and effluent nutrient concentrations, CHN composition of the dried nori samples, and, in one case, metal content of the nori — were measured to the degree that funding allowed. Nutrient and CHN analyses were done by staff of the Hawaii Institute of Marine Biology analytical services facility.

To evaluate the quality of nori produced in the NELH culture system, it was necessary to send samples to Japan for processing. Neither nori processing equipment nor experts in processing techniques and nori grading were available in Hawaii. In February 1983, nori cultured at NELH was taken to Japan by Dr. James Woessner of the Hawaii experimental team. Most of the material was shipped frozen, except for one batch which was fresh-chilled. In Japan, the nori was processed into sheets and then the quality of the product was evaluated by expert graders from Yamamoto Nori and Ohmori Suisan. Both companies specialize in high-quality nori products.

RESULTS AND CONCLUSIONS

Growth trials conducted during the summer of 1982 demonstrated that *P. tenera* can be grown successfully using simulated OTEC effluents in Hawaii. Nori fronds reached harvestable size (30 to 40 cm in length for large individual plants) from the initial size of 3 cm or less in 3 to 5 weeks. These experiments were conducted using low initial culture densities of 10 to 100 g wet wt/m^2. Maximum production was achieved at densities greater than 2 kg wet wt/m^2. Production rates as high as 40 to 60 g dry wt/m^2/day were measured at densities of 2 to 3 kg wet wt/m^2; these yields equal or exceed those attained by other rapidly growing seaweeds in tumble culture (e.g., Ryther et al., 1979). Dry weight production increased rapidly for about the first 3 weeks, after which time it leveled off and then decreased due to shading and perhaps nutrient limitation (Figure 2). Although production per unit area decreased after some period, total biomass continued to increase after more than 40 days (Figure 3).

A later experiment, conducted during September and October 1982, gave a maximum *P. tenera* production rate of 28 g dry wt/m^2/day. During this experiment, nutrient uptake by the nori cultures and nitrogen content of the nori tissue were monitored closely. The cultures showed a strong diel

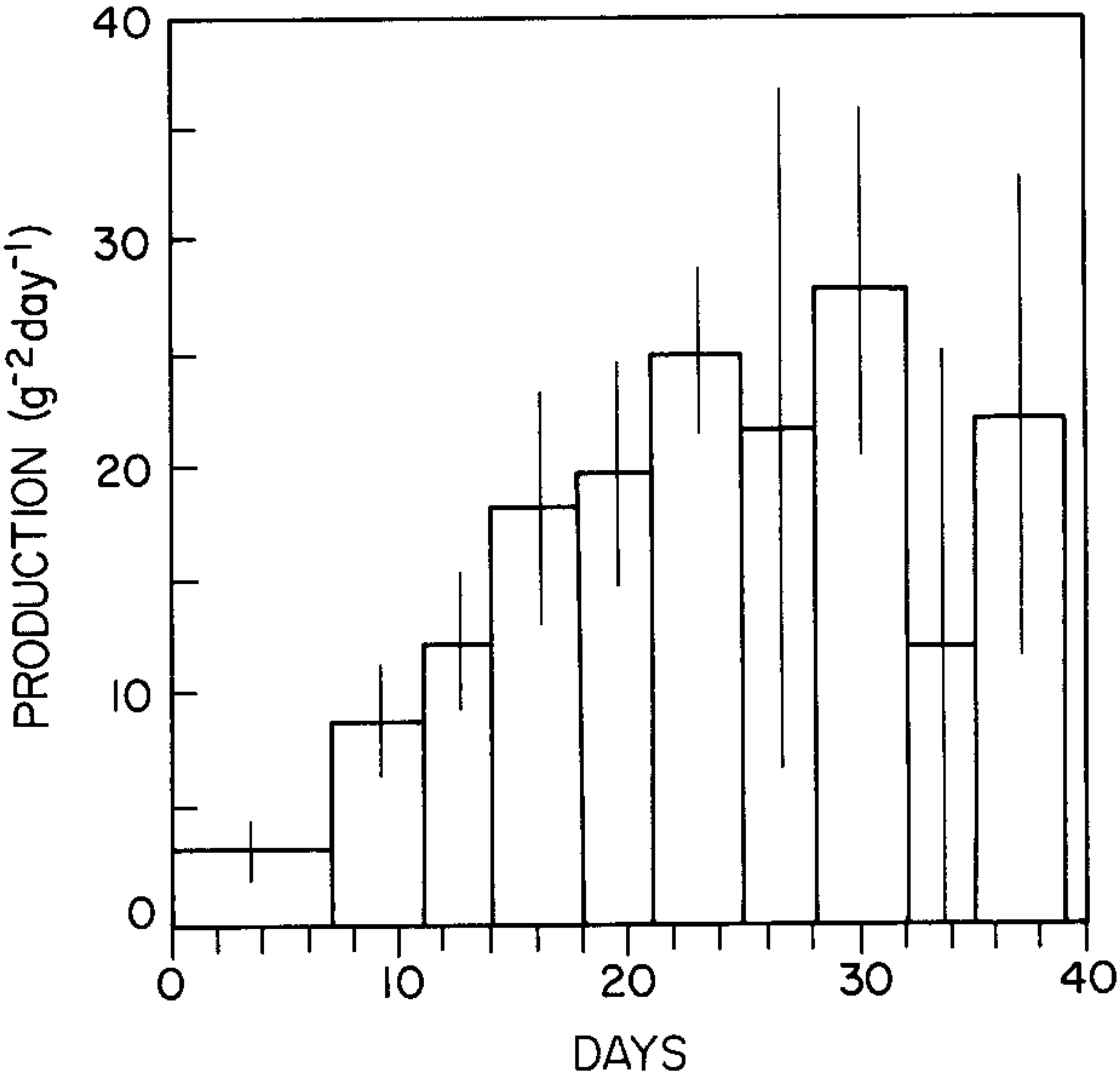

Figure 2. Mean dry weight production between sample periods of Porphyra tenera *cultured at NELH in a mixture of deep and surface waters (mean ± S.D.; n=7). (From Mencher et al., 1983)*

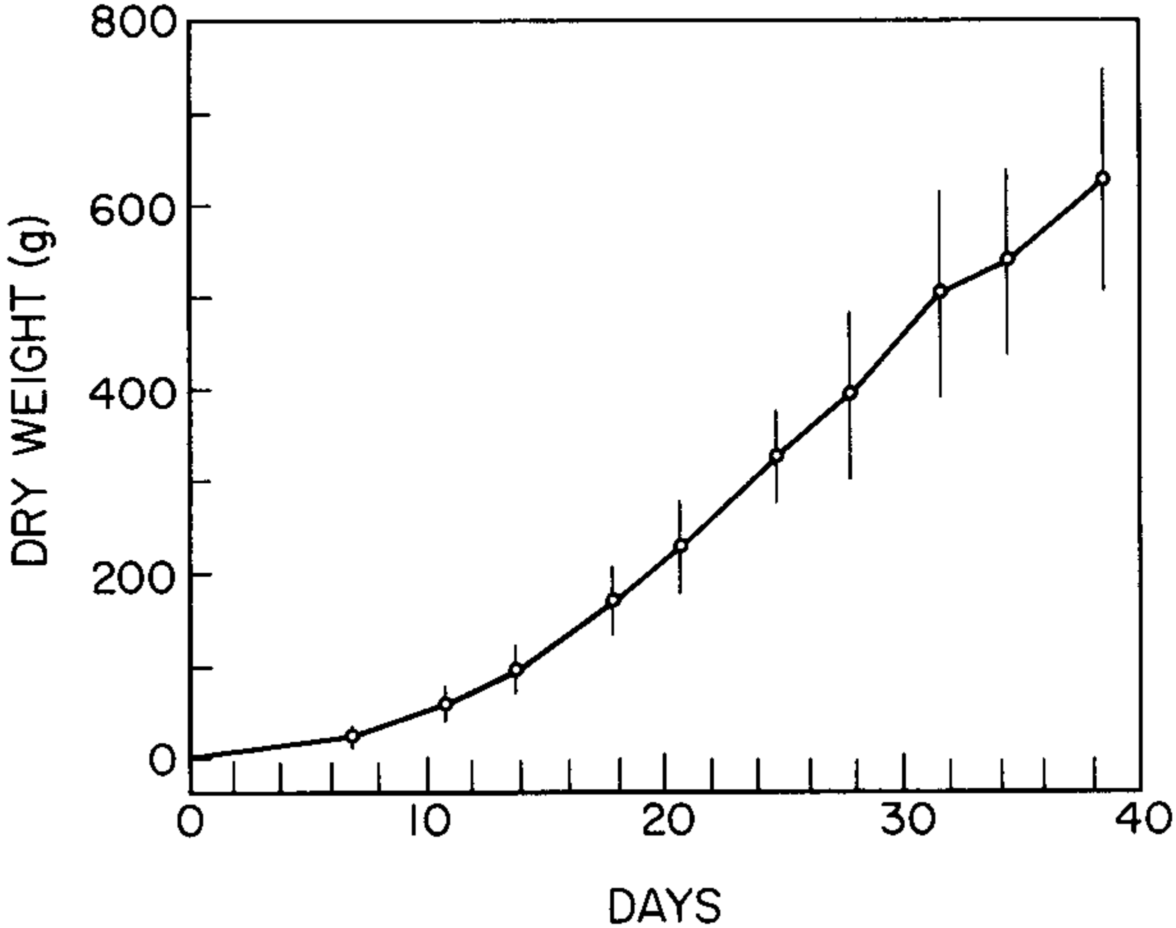

Figure 3. Mean dry weight increase of Porphyra tenera *cultured for 40 days at NELH in a mixture of deep and surface waters (mean ± S.D.; n = 7). Initial dry weight was 4.1 g/m². (From Mencher et al., 1983)*

periodicity of nitrate and phosphate uptake. These nutrients, especially nitrogen, were taken up much more rapidly during the day than at night (Figure 4). This characteristic is not unique to *P. tenera*. Several other seaweeds exhibit a similar reduction in nutrient uptake at night: *Codium fragile* (Hanisak and Harlin, 1978), *Laminaria longicruris* (Harlin and Craigie, 1978), and *Hypnea musciformis* (Haines and Wheeler, 1978). Under the conditions of this experiment, the nori removed up to 57% of the nitrate/nitrite and 27% of the phosphate from the water as it passed through the compartments. Knowledge of the nutrient uptake capabilities of the nori cultures will help in predicting the potential productivity of an OTEC-supplied nori culture system.

Nitrogen content as a percentage of dry tissue weight increased from 6.9 ± 0.2% to 7.7 ± 0.5% during the first 3 weeks of the experiment, and then declined abruptly to 6.5 ± 0.3%. It remained nearly constant after the third week of culture. Since high nitrogen content is correlated with high quality of nori (Noda, 1971), this result suggests that the OTEC-cultured nori may have been higher in quality during the third and fourth weeks of culture than it was thereafter. The drop in nitrogen content may have been caused by lower nutrient availability in the dense cultures, or it may have been caused by an aging effect. In the former case, it may be desirable to increase the water and nutrient exchange rates or to supplement them with additional nutrients; whereas in the latter case, earlier harvesting of the cultured nori might yield a higher-quality product.

Disease (e.g., *Pythium*) causes crop losses in Japanese nori culture grounds (Nihon Suisan Gakkai, 1973). There was no evidence of such disease or of epiphytes in the cultured nori at NELH. During one experiment, two compartments showed minor contamination with *Ulva* sp., a green alga; proper sanitation will eliminate this contamination. Freedom from disease, epiphytes, and contamination will result in the production of more uniform better quality nori sheets.

Asexual reproduction (monospore settling and growth) occurred regularly in the tanks as it does during net culture in Japan (Yoshida, 1972; Kurogi, 1961). Monospore production might provide an alternative or a supplement to the more traditional conchocelis phase cultivation as a source of seedstock for a culture operation.

Nori cultured at NELH in a mixture of surface and deep waters had a significantly different metal content profile compared with nori cultured in surface waters in Korea (Pak et al., 1977). Zinc, chromium, and cadmium concentrations in NELH nori were significantly greater ($p < .05$) than in nori cultured in Korea (Table 1). These differences could be a reflection of the greater concentrations of those elements in the NELH deep water. Fast et al. (see paper in this publication) also discuss this situation for salmon reared in NELH deep water. Whatever the case, the concentrations of heavy metals in nori cultured at NELH were within safe limits for human consumption.

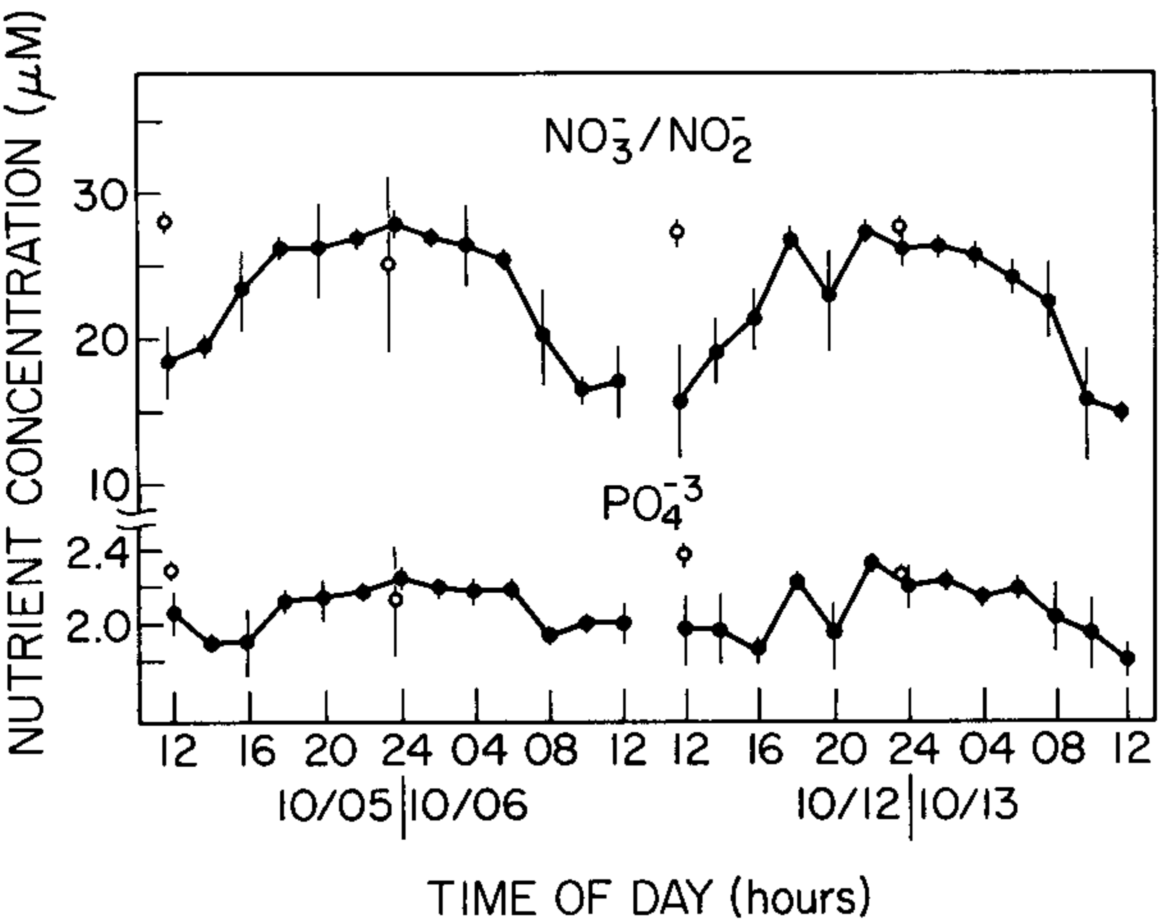

Figure 4. Mean influent water (open circles) and effluent water (solid circles) nutrient concentrations at NELH during the two 24-hour sampling periods of Porphyra tenera *(mean ± S.D., 3 compartments). Upper curves show nitrate/nitrite concentration; lower curves show phosphate concentration. The large variability of influent concentrations at 2400 hours on 10/5 is a sampling artifact caused by incomplete mixing of deep and surface waters in the sample. (From Mencher et al., 1983)*

TABLE 1. METAL CONTENTS OF *P. TENERA* GROWN IN MIXED DEEP AND SURFACE WATERS AT NELH COMPARED WITH THOSE GROWN IN SURFACE WATERS IN KOREA (FROM MENCHER ET AL., 1983)

Metal Concentrations (µg/g dry wt)	NELH[a] (Mean ± S.D.)	Korea[b] (Mean ± S.D.)
Fe	293 ± 29	243 ± 80
Zn	64.3 ± 5.4	32.8 ± 19.0
Cu	13.5 ± 3.4	24.8 ± 13.8
Ni	<0.2	—
Pb	6.8 ± 3.4[c]	2.3 ± 1.9
Cr	5.8 ± 0.9	1.8 ± 1.2
Cd	8.9 ± 1.5	1.1 ± 0.5

[a]Data from this study; 3 samples with 2 replicate subsamples
[b]Data from Pak et al. (1977); 4 samples
[c]Pb levels for one sample were an order of magnitude less than those of two others.

PROCESSING TRIALS IN JAPAN

The transport and processing of NELH-produced nori in Japan are detailed in Woessner (1983) and are summarized here.

Nori used for the processing trials in Japan was cultured in January and February 1983. About 20 kg fresh weight of nori were processed. After arrival in Japan, the frozen material was thawed in cold (5°C to 10°C) seawater. The thawed nori was judged to be too red, without aroma, too flat in taste, and without cohesiveness (stickiness), relative to good-quality Japanese nori. The NELH nori also contained wrinkled fronds, which are not normally encountered in Japanese nori culture.

The nori was mixed with fresh water, chopped, and made into sheets with a Nichimo Wonman processing machine. The Japanese nori-grading experts judged the processed OTEC-cultured nori to be too red, low in luster, and too flat in taste, but clean and not too hard. Without natural cohesiveness, the sheets had to be made thick in order to prevent holes, resulting in a rough, "fluffy" product. Overall, the nori was judged to be of very low quality relative to Japanese-cultured nori. Nevertheless, the Japanese considered the NELH nori to be a good first-try effort and suggested ways in which the quality could be improved.

One reason for the low quality of the processed nori appeared to be cell damage during freezing. Apparently the nori had been frozen with too much water before being taken to Japan. In addition, the nori cells had not been exposed to significant variations in environmental conditions as they would be in Japanese culture beds. This nonexposure decreased the resistance of the cells to the stresses of freezing, processing, and drying. In principle, an OTEC-nori culture system should be flexible enough to allow intentional variation of environmental parameters such as temperature and perhaps light intensity as well as periodic drying during the early growth stages of the nori to improve quality.

The Japanese experts noted that seedstock quality can strongly affect the quality of the final product. The seedstock used for the NELH experiments was held in a frozen state for several months — longer than is considered desirable in Japan. Partial cell damage to the seedstock could have caused the wrinkled nori fronds observed in the NELH culture system. On-site production of seedstock and, ultimately, selection of nori strains better adapted to tank culture conditions should prevent the problems associated with poor-quality seedstock.

In addition to varying environmental conditions to promote cell strength, changing the overall culture conditions from those used in the baseline studies at NELH is a possible means of improving product quality. For example, lower light intensities — which can be achieved either by shading or by an increase in culture density — might result in the production of a darker, less red-colored nori than that exposed to full Hawaiian sunlight. However, because of time and funding limitations, it was not possible to examine a wide range of environmental factors in relation to the quality of OTEC-cultured nori.

Finally, the quality of OTEC-cultured nori could also be improved if it did not have to be transported long distances to be processed. On-site processing is ideal, but this was not possible during our relatively small-scale experiments.

ONGOING RESEARCH

Additional research and development work has been conducted to determine the feasibility of producing superior-quality nori on a commercial scale. One of us, Steven A. Katase, conducted pilot-scale research on nori aquaculture from March 1986 to March 1987 with assistance from Takaokaya Company Limited of Tokyo, Japan, and a Phase I grant from the U.S. Department of Agriculture's Small Business Innovative Research program.

Innovative aquaculture techniques with potential commercial applications were developed to culture another species of nori, *Porphyra yezoensis*. The nori was cultured in land-based tanks using the cold deep seawater and warm surface seawater available at NELH. Two 25-m^3 (23.7 m^2 surface area) circular growout tanks were constructed and modified to provide conditions for rapid growth. Up to 211 g fresh wt/m^2/day were produced in the tanks during a 9-day period, or 45 kg per tank. The average water flow was 57 l/min cold seawater and 38 l/min warm seawater, with an average water temperature of 18°C. Initial stocking density was 200 g/m^2 of cut nori fronds from a commercial nursery operation at NELH (Figure 5).

Nori experts from Japan graded the nori grown in these experiments as high quality, with good dark color, luster, texture, and taste. Mr. Kabashima, president of Kabashima Fisheries, and Mr. Takaoka and Mr. Ito, president and vice-president of Takaokaya, stated that the quality of the nori grown during the 1986–87 experiments was a tenfold improvement over that produced during the 1982–83 experiments. The large improvement in quality was attributed to (1) use of a high-quality

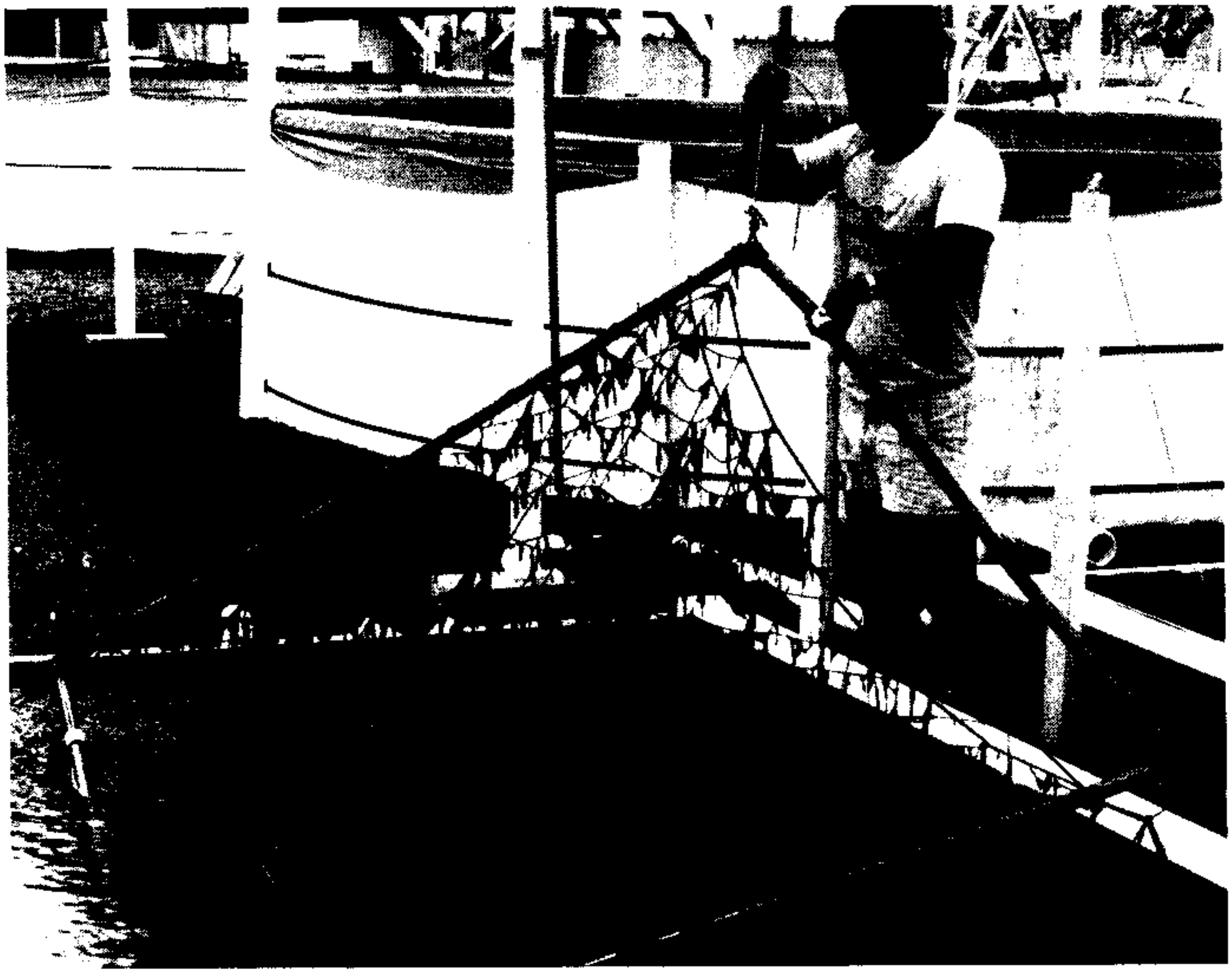

Figure 5. Nori (Porphyra yezoensis) *seed on nets sent from Japan under culture by Aquaculture Concepts at NELH during 1986. After initial growth on the nets, the seed is stripped into larger culture tanks for tumble culture using compressed air.*

strain of *P. yezoensis* developed in Japan, (2) production of juvenile nori fronds in Hawaii rather than using frozen material, (3) use of shade cloth to decrease the high light levels found in Hawaii, (4) reduction of growout time, and (5) time of day the nori was harvested.

Additional experiments remain to be conducted on the nursery system in order that larger volumes of juvenile nori fronds can be produced on a consistent basis. Further research is also required to develop a site-specific strain of nori with superior-quality traits which will not become sexually reproductive during a 14-day growout period.

An 8-acre site at NELH has been reserved for potential Phase II nori research and Phase III commercialization. Private funds have been secured for the development of the new site and a Phase II proposal has been submitted to the Small Business Innovative Research program requesting funds for research operations. Ground preparation of the site will take place in September 1987.

CONCLUSIONS

The experiments conducted at NELH during 1982–83 demonstrated that nori can be grown at high production rates in an intensive tank culture system using simulated OTEC effluents. The nori produced at NELH was initially of low quality relative to Japanese-cultured nori, but the flexibility of an OTEC-related aquaculture system may permit substantial quality improvements. If future studies are conducted at NELH, they should include the following:

- Examination of the effects of short-term and long-term variations of environmental factors on the growth and quality of tank-cultured nori
- Development of seedstock production methods specifically suited for a high-density, unattached growout system
- On-site processing by personnel experienced in the production of high-quality nori sheets
- Based on the above, an economic analysis of nori production at NELH, or a similar site, using mixed deep and surface waters

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