Effects of Water Temperature on the Growth of Red Alga *Porphyra yezoensis* form. *narawaensis* (Nori) Cultivated in an Outdoor Raceway Tank^{*1,2}

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In order to examine effects of seawater temperature on the growth of *Porphyra* foliose thalli, outdoor raceway tanks with circulating water were newly designed, and provided the experimental condition simulating Nori cultivation farms in the sea. Frozen seed nets of *Porphyra yezoensis* form. *narawaensis* were set in the raceway tanks. During the period of the two experiments, December in 1985 and February in 1986, mean seawater temperature ranged from 8.0 to 23.4°C. Standing crop of foliose thalli increased normally at 10–17°C, but the increase rate of standing crop lessened at the temperature higher and lower beyond these limits. Visible absorption spectra of living foliose thalli, indicating concentrations of photosynthetic pigments, did not vary much within the range of seawater temperature from 8 to 20°C. The optimum seawater temperature for the growth of *Porphyra* foliose thalli ranged from 10 to 17°C in the raceway tanks. This temperature range confirmed results obtained through *in vitro* experiments but was higher than that in Nori cultivation farm.

Nori (*Porphyra*, Bangiales, Rhodophyta) cultivation is one of the most important items of mariculture in Japan. Although a number of papers on the physiology and ecology of cultivated *Porphyra* have been published, they are mostly concerned with either field surveys as case studies or *in vitro* experiments under fully controlled conditions (reviewed by Kurogi and Iwasaki,¹⁾ Yoshida and Akiyama,²⁾ Kito *et al.*,³⁾ and Tokuda *et al.*⁴⁾).

Steam electric power plants in Japan are usually located near the coast using seawater for their cooling systems. They discharge a considerable amount of thermal effluent to the coastal sea, where Nori cultivation can be performed. It is necessary to estimate the response of *Porphyra* thalli to the change of seawater temperature that may be accidentally caused by thermal effluents discharged from electric power plants.

However, field surveys are not considered adequate to evaluate the thermal effect on the growth of *Porphyra* thalli. Results of *in vitro* experiments cannot be applied directly to the phenomena in the sea. Outdoor experimental

cultivation of *Porphyra* thalli is, therefore, needed to fill the gap between field surveys and *in vitro* experiments.

For the outdoor experimental cultivation of *Porphyra* foliose thalli, raceway tanks with circulating water were newly designed. The raceway tanks provided experimental conditions simulating Nori cultivation farms in the sea.

The present paper deals with the structure and the function of the raceway tanks, and the investigation into the effects of seawater temperature on the growth of *Porphyra* foliose thalli by using raceway tanks.

Materials and Methods

Experimental Facility

Figure 1 diagrammatically represents the raceway tank. The raceway tank consists of two parallel straight channels, which are 7 m long and 1 m wide, connected by two semicircular channels at their ends. Wall to wall distance between the straight channels is 1 m. Water depth was set at 0.65 m and the tank contained

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Fig. 1. Diagrammatic representation of a set of raceway tank and mixing tank. B; Baffle. I; Inlet. N; Net on which *Porphyra foliose* thalli grow. O; Outlet. Arrow; Direction of flow.

Fig. 2. The whole flowing system of experimental facility. M; Mixing tank. R; Raceway tank. h; Heated seawater. n; Natural seawater. o; Outlet. t; Thermal effluent. v; Valve.

about 15 m³ of seawater, which was renewed at a rate up to 30 m³/h.

The laboratory, where the raceway tanks are installed, is located in Kashiwazaki, Niigata Prefecture, facing the Sea of Japan and supplied with the natural seawater and the thermal effluent discharged from the Kashiwazaki-Kariwa Nuclear Power Station, the Tokyo Electric Power Co. The temperature of the thermal effluent was 6–7°C higher than the seawater temperature at the intake site. A part of the thermal effluent was heated by 10°C. There were therefore three kinds of seawater of different temperature available at the laboratory.

Figure 2 shows the flowing system of the experimental facility. The seawater temperature of the raceway tank was expressed in terms of

the elevation level of ΔT (°C). According to the elevation level, the temperature of each raceway tank was elevated above the temperature of the natural seawater. The regulation of seawater temperature was achieved by mixing the three kinds of seawater at proper ratios within the mixing tank connected to each raceway tank.

The mixing tank supplied seawater to the raceway tank through two nozzles, the directions of which generated the horizontal circulating current. Current velocity was mainly determined by the amount of seawater supply. In the present study, seawater was supplied at the rate of 30 m³/h, and current velocity was 3–6 cm/sec.

Materials

Frozen seed nets, on which young foliose thalli

of *Porphyra yezoensis* form. *narawaensis* grew, were used for experimental cultivations. The frozen seed nets were prepared by means of artificial seeding in late September at a Nori farm in Tokyo Bay, and stored in a refrigerator from early November, 1985 by Nori cultivators of Funabashi Fisheries Co-operative Association, Chiba Prefecture. Thereafter, they were transported by a refrigerator car to a refrigerator of the laboratory.

Before each experimental cultivation, the frozen seed nets were well thawed and precultivated for three days in running seawater at ambient temperature. After the precultivation, the nets were cut to sizes 5 m long and 0.9 m wide to fit to the channel size.

Methods

Two series of experimental cultivations of *Porphyra* foliose thalli were carried out with the same treatment at different seasons; Experiment I and II were conducted during December 3–24 in 1985 and February 4–25 in 1986, respectively. In each experiment, six raceway tanks were used for six elevation levels of seawater temperature, i.e. ΔT 's of 0, 2, 4, 6, 8, and 10°C. ΔT of 0°C was provided only by the natural seawater, ΔT 's of 2 and 4°C by the mixture of the natural seawater and the thermal effluent, ΔT of 6°C only by the thermal effluent, and ΔT 's of 8 and 10°C by the mixture of the thermal effluent and the heated seawater.

One seed net was horizontally set at the 5 cm depth in each tank and cultivated for twenty-one days. Salinity, DO, and pH of seawater supplied to raceway tanks were 31.5–33.0, 6.5–12.8 ppm, and 8.0–8.3, respectively. COD and SS were low; <0.4 ppm and <10 mg/l, respectively. The dissolved inorganic nitrogen concentration was 1.8–5.2 $\mu\text{g-at/l}$. The phosphate-phosphorus concentration was 0.3–3.1 $\mu\text{g-at/l}$.

The solar radiation (395 to 715 nm), measured at the surface of seawater in the raceway tanks, varied with the weather, ranging from 2 to 21 $\text{E/cm}^2/\text{day}$. No artificial illumination was used in these experiments.

During three weeks of cultivation, five to 10 pieces of 15 cm long netting twines, on which *Porphyra* thalli grew, were randomly cut off from each net every 3, 4, or 7 days. The standing crop of *Porphyra* (g wet weight/cm netting twine) was obtained by weighing thalli growing on sampled netting twines. Growth of *Porphyra*

foliose thalli can be regarded as exponential and described by the compound interest law³⁾:

$$W_t = W_0 (1 + R_g/100)^t,$$

where W 's stand for mass of thalli (in wet weight), t for time of cultivation (in day), and R_g for relative daily growth rate (%/day) of thalli. However, when the amount of lost thalli is not negligible during cultivation, this equation is inapplicable. Then, on the assumption that relative daily loss rate (R_L) of thalli is constant, the equation can be modified:

$$W_t = W_0 (1 + R_g/100 - R_L/100)^t.$$

By the second equation, relative daily increase rate (R. D. I. R., $R_g - R_L$) of standing crop was calculated.

Photosynthetic pigment contents of *Porphyra* foliose thalli, being related with the quality as materials of dried sheets of Nori,⁹⁾ can be estimated by measuring visible absorption spectra of living thalli. Each of five foliose thalli, picked off from sampled netting twines of each net, was rinsed well with filtered seawater and put between two clear slide glasses with filtered seawater. Then, the visible absorption spectra of foliose thalli preparations were recorded with filtered seawater as a reference.

Results and Discussion

Function of Facility

As shown in Figures 3 and 4, the temperature of the natural seawater ($\Delta T=0^\circ\text{C}$) fell slightly during Experiment I, and fluctuated over a limited range during Experiment II. During both of Experiments I and II, the thermal effluent was 6.5 to 6.8°C warmer than the natural seawater. Table 1 shows means and actual ΔT 's of seawater temperature. The means of seawater temperature were calculated from data recorded every 30 minutes. The regulation of seawater temperature was almost satisfactory in six tanks during both experiments.

Growth of *Porphyra* Foliose Thalli

Figures 5 and 6 show changes of the standing crop during Experiments I and II, respectively. The standing crop in each raceway tank was 0.043–0.175 g wet weight/cm netting twine at the beginning of two experiments, and ranged from 0.042 to 0.593 g/cm at the 10th day. The standing crop increased exponentially in the first 10 days,

Fig. 3. Seawater temperatures and their elevation levels above natural seawater in the raceway tanks during the period of Experiment I (December 3 to 24 in 1985).

Fig. 4. Seawater temperatures and their elevation levels above natural seawater in the raceway tanks during the period of Experiment II (February 4 to 25 in 1986).

Table 1. Elevation levels and means of seawater temperature in raceway tanks during Experiments I and II

Exp.	Period	Tank no.	Seawater temperature (°C)		
			ΔT^*	Actual ΔT	Mean
I	3–24 Dec. '85	1	0	—	12.9
		2	2	2.2 ± 0.2	15.0
		3	4	4.5 ± 0.3	17.3
		4	6	6.6 ± 0.2	19.5
		5	8	8.7 ± 0.3	21.6
		6	10	10.5 ± 0.3	23.4
II	4–25 Feb. '86	2	0	—	8.0
		6	2	2.4 ± 0.1	10.4
		5	4	4.6 ± 0.2	12.6
		3	6	6.7 ± 0.2	14.7
		1	8	8.6 ± 0.2	16.6
		4	10	10.4 ± 0.4	18.4

* Elevation level of temperature above natural seawater temperature.

Fig. 5. Effects of the elevation levels of temperature above natural seawater (averaging 12.9°C) on the standing crop of *Porphyra foliose* thalli during Experiment I.

at ΔT 0–4°C in Experiment I and at ΔT 2–6°C in Experiment II, where means of seawater temperature were within the range of ca. 10–17°C (table 1). After the 10th day, the standing crop leveled off or decreased in almost all of tanks. At the seawater temperature above 20°C or ΔT 8 and 10°C in Experiment I, considerable amount of *Porphyra* thalli was lost from netting twine,

and the standing crop scarcely increased.

The effects of seawater temperature on the increase rate of standing crop and absorption spectra are shown in Figure 7. Throughout the two experiments, the increase rate in the first 10 days had a peak between 10 and 17°C. The increase rate declined as the temperature was raised or lowered beyond these limits.

Fig. 6. Effects of the elevation levels of temperature above natural seawater (averaging 8.0°C) on the standing crop of *Porphyra* foliose thalli during Experiment II.

Fig. 7. Effects of seawater temperature on the relative daily increase rate of the standing crop of *Porphyra* foliose thalli (circle) during the first ten days and the absorbance of 680 nm of living foliose thalli (triangle) at the 10th day. Open symbol, Experiment I; closed symbol, Experiment II.

In each experiment, absorbance at 680 nm of living thalli on the 10th day, indicating chlorophyll concentration, did not vary much with the temperature ranging approximately from 8 to 20°C. However, the absorbance showed an exceptionally high value at the highest temperature in Experiment I. This exceptional value was obtained from the foliose thalli remaining on the net where a large amount of thalli had been lost. The thick cell wall of the remainder thalli caused the exceptional value. Absorbances at 480, 565, 620 nm, indicating carotenoid, phycoerythrin, and phycocyanin concentration, respectively, showed almost the same responses as that at 680 nm.

Seawater temperature affected the increase rate of standing crop, but it was very slightly implicated in photosynthetic pigment concentration. The relative daily increase rate of standing crop indicated that the optimum temperature for the growth of *porphyra* foliose thalli in the raceway tank was between 10 and 17°C.

Porphyra cultivation begins along the Japanese coast when seawater temperature falls to 23 to 22°C in the autumn. Seawater temperature further falls and ranges approximately from 15

to 20°C at the end of the period of making nursery-nets, when some of nets are stored in refrigerators as frozen seed nets, and others are cultivated continuously for the first harvest. Thereafter, *Porphyra* thalli are exposed to the seawater temperature varying with the weather and the sea condition, and to air temperature at low tide. The air temperature occasionally falls below the freezing point. The survival temperature of *Porphyra* foliose thalli is considered to range from freezing point to 20°C in cultivation farms.

The temperature within the survival range for plants affects the enzyme reaction rate of photosynthesis and respiration. Aruga⁷⁾ measured photosynthetic rate and respiratory rate of *P. yezoensis* foliose thalli by the light-and-dark bottle technique, and described the temperature-photosynthesis curve with a peak between 13 and 18°C, and the respiratory rate increasing with temperature ranging from 5 to 25°C. Iwasaki and Matsudaira,⁸⁾ and Ogata⁹⁾ also reported that respiratory rate of *P. tenera* foliose thalli increased with temperature.

The growth of *Porphyra* thalli is consequent on photosynthesis and respiration. In *in vitro* experiments, the temperature of 15°C or thereabout is considered optimum for the growth of *Porphyra* foliose thalli.¹⁰⁻¹²⁾ Then, the present results in the raceway tanks conform to the knowledge of *in vitro* experiments.

In Nori cultivation farms in the sea, the optimum temperature, especially for commercial production, is considered to range from 8 to 10°C.¹³⁾ This optimum temperature range is lower than its counterparts obtained through *in vitro* experiments and the present outdoor experimental cultivations in raceway tanks. This difference may partly be a reflection of the condition that the seawater temperature in Nori cultivation farm does not change independently but changes along with other factors.

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