JOURNAL OF AQUACULTURE VOL. 2. (NO. 2) : 53~90 : (1989) 韓國養殖學會誌 2(2) : 53~90 : (1989)

Influence of Oxygen Concentration on the Food Consumption and Growth of Common Carp, *Cyprinus carpio* L.

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잉어 *Cyprinus carpio*의 먹이 攝取量과 成長에 미치는 溶存酸素量의 영향

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ABSTRACT

Feeding proper level of ration matchable with the appetite of fish will enhance production and also prevent waste of food and its consequence, side effects such as pollution of culture medium. To pursue this goal, elaborate studies on dissolved oxygen concentrations－as the major force in inducing appetite and the growth outcome are necessary.

The growth of common carp of 67, 200, 400, 600, and 800 gram size groups was studied at oxygen concentrations ranging from 2.0 to 6 mg/ℓ in relation to rations from 1 to as many percent of the initial body weight as could be consumed under constant temperature of 25℃. The results from the experiments are summarized as followings ;

1. Appetite : The smaller fish exhibited higher degree of appetite than the bigger ones at the same oxygen concentrations. The bigger the fish the less tolerant it was to the lower oxygen thersholds, and the degree of tolerence decreased as ration level increased.
2. Growth : Growth rate (percent per day) increased－unless consumption was suppressed by low oxygen levels－ as the ration was increased to maximum. In case of 67 g fish, it reached the highest point of 5.05%／day at 7% ration under 5.0 mg/ℓ of oxygen. In case of 200 g fish, the maximum growth rate of 3.75%/day appeared at the maximum ration of 6% under 5.5 mg/ℓ of oxygen. In 400 g fish, the highest growth of 3.37%/day occurred at the maximum ration of 5% and 6.0 mg/ℓ of oxygen. In 600 g fish, the highest growth rate of 2.82%/day was at the maximum ration of 4% under 5.5 mg/ℓ oxygen. In case of 800g fish, the highest growth rate of 1.95%/day was at maximum tested ration of 3% under 5.0 mg/ℓ oxygen.
3. Food Conversion Efficiency : Food conversion efficiency (% dry feed converted into the

fish tissue) first increased as the ration was increased, reached maximum at certain food level, then started decreasing with further increase in the ration. The maximum conversion efficiency stood at higher feeding rate for the smaller fish than the larger ones. In case of 67 g fish, the maximum food conversion efficiency was at 4% ration within 3.0−4.0 mg/ℓ oxygen. In 200 g fish, the maximum efficiency was at 3% ration within 4.0−4.5 mg/ℓ oxygen. In 400 g fish, the maximum efficiency was at 2% ration within 4.0−4.5 mg/ℓ oxygen. In 600 and 800 g fish, the maximum conversion efficiency shifted to the lowest ration (1%) and lower oxygen ranges.

4. Behaviour : The fish within uncomfortably low oxygen levels exhibited suppressed appetite and movements and *were observed* to pass feces quicker and in larger quantity than the ones in normal condition ; in untolerably low oxygen the fish were lethargic, vomited, and had their normal skin color changed into pale yellow or grey patches. All these processes contributed to reducing food conversion efficiency. On the other hand, the fish within relatively higher oxygen concentrations exhibited higher degree of movement and their food conversion tended to be depressed when compared with sister groups under corresponding size and ration within relatively low oxyen level.

5. Suitability of Oxygen Ranges to Rations : The oxygen level of 2.0−2.5 mg/ℓ was adequate to sustain appetite at 1% ration in all size groups. As the ration was increased higher oxygen was required to sustain the fish appetite and metabolic activity, particularly in larger fish. In 67 g fish, the 2% ration was well supported by 2.0−2.5 mg/ℓ range ; as the ration increased to 5%, higher range of 3.0−4.0 mg/ℓ brought better appetite and growth ; from 5 till 7% (the last tested ration for 67 g fish) oxygen levels over 4.0 mg/ℓ could sustain appetite. In 200 g fish, the 2 and 3% rations brought the best growth and conversion rates at 3.5−4.5 mg/ℓ oxygen level ; from 3 till 6% (the last tested ration at 200 g fish) oxyge groups over 4.5 mg/ℓ were matchable with animal's appetite. In 400, 600, and 800 g fish, all the rations above 2% had to be generally supported with oxygen levels above 4.5 mg/ℓ.

요 약

食慾에 부합되는 適正量의 먹이 섭취는 잉어의 成長을 增加시키고, 同時에 먹이의 허비를 막으며, 그로 인해서 飼育水質의 汚染을 막는 附隨的인 効果도 가지게 된다. 이 目的을 達成하기 위하여 食慾 유발과 그에 따른 빠른 成長의 중요한 요인으로서 溶存酸素에 관한 精密한 硏究가 필요하다.

水溫 25℃ 下에서 잉어(이스라엘계)의 未成魚, 67g, 200g, 400g, 600g 및 800g 되는 實驗群으로서, 溶存酸素를 2.0−6mg/ℓ 사이에서 飼料를 體重의 1%부터 먹을 수 있는 양까지에 걸쳐서 飼育實驗硏究를 하였다.

魚體가 작을수록 同一한 溶存酸素 조건에서는 보다 높은 食慾과 보다 많은 먹이 摂取量을 나타내었다. 어체가 클수록 낮은 溶存酸素量에서는 生活 能力이 약해지고, 먹이 攝取量이 增加하면 耐性은 더욱 줄어졌다.

成長率(日間 成長率)은 낮은 溶存酸素에 의해서 影響을 받지 않는한, 먹이의 攝取量이 많을수록 增加하였다. 最高成長率은 67 g 魚에서는 D.O. 5.0 mg/ℓ에서 1日 먹이량이 體重의 7%일때 日間成長率 5.05%였고, 200 g 魚에서는 D.O. 5.5 mg/ℓ에서 먹이량 6%일때 1日 成長率이 3.75%였다. 400g 魚에서는 D.O. 6.0 mg/ℓ에서 먹이량이 5%일때 1日 成長率 3.37%였으며, 600g 魚에서는 D.O. 5.5 mg/ℓ에서 먹이량이 1일 4%였을 때 1日 成長率 2.82%였다. 800g 魚에서는 D.O. 5.0mg/ℓ에서 먹이량이 1일 3%였을 때 1일 성장율이 1.95%였다.

正常的인 生活 및 成長 機能發揮 가능 D.O. 濃度로부터 最高 먹이 攝取可能量에 부합되는 D.O. 濃度까지 사이에서 먹이 轉換效率(사료가 어체로 바뀌는 효율)은 처음 D.O.가 증가함에 따라 높아지고, 最高値에 이른 뒤, D.O.가 더욱 더 높아짐에 따라 먹이 轉換效率은 다시 감소하기 시작한다. 이 최고 飼料效率은 작은 어체에서는 큰 어체 보다 높은 먹이 섭취량에서 나타난다 (물론 먹이 攝取量에 부응하는 D.O.량이 갖춰졌을때). 즉 最高 먹이 轉換效率은 67g 魚에서 D.O. 3.0−4.0 ㎎/ℓ에서 먹이 섭취량 4% 때 였으며, 200g 魚에서는 D.O. 3.0−4.5 ㎎/ℓ에서 먹이 攝取量 3% 때였고, 400 g 魚에서는 D.O. 4.0−4.5㎎/ℓ에서 먹이 섭취량 2% 때였다. 600g 및 800 g 魚에서는 가장 낮은 D.O.에서 먹이 攝取量 1% 때였다.

적절하지 못한 낮은 D.O. 함량에서는 정상적인 조건하의 個體보다 먹이 攝取量이 감소하며, 또 먹이가 消化管을 빨리 통과하고, 똥의 양이 증가하는 것을 관찰할 수 있었다. 그리고, 견디지 못할 만큼 낮은 D.O.하에서는 먹이를 토하고, 體色이 열은 黃色으로 변하거나, 또는 灰色의 얼룩진 반점으로 변하기도 했다. 이 모든 현상들이 먹이 轉換效率의 감소로 이어졌다.

반면에 아주 높은 D.O.하에서는 강한 活動을 하였으며, 어체 크기가 같고 먹이의 양도 같았지만 D.O.가 약간 낮은 群에 비교하여 먹이 轉換效率이 떨어지는 경향이 나타났다.

모든 크기에서 먹이량을 體重의 1%만 주었을 때는 D.O. 량이 2.0−2.5㎎/ℓ 이면 적절하였다. 먹이량을 증가시키면 魚體의 正常活動을 유지시키기 위하여 보다 높은 D.O.가 필요하였다.

67g 魚에서는 D.O. 2.0−2.5 ㎎/ℓ이면 체중의 2%이상 먹이량을 충분히 지탱할 수 있었으나, 먹이를 5%로 증가시키면 D.O. 3.0−4.0 ㎎/ℓ일 때 식욕이 보다 왕성하고 높은 成長을 가져왔다. 먹이량이 5−7%에서는 4.0 ㎎/ℓ 이상의 D.O.라야 식욕을 유지시킬수 있다.

200 g魚에서는 먹이량이 체중의 2−3% 일때는 D.O. 3.5−4.5 ㎎/ℓ에서 가장 높은 成長率을 보였으나 먹이량이 체중의 3−6%로 올라가면 D.O. 함량이 4.5 ㎎/ℓ을 넘어서야만 어류의 生活機能 發揮에 부응될 수 있었다.

400 g, 600 g 및 800 g 魚에서는 먹이량이 체중의 2%를 넘을 때는 (4% 및 5%까지 실험) 모두 D.O. 함량이 4.5 ㎎/ℓ를 넘어야 했다.

INTRODUCTION

Dissolved oxygen (DO) should be regarded as the most common and important factor of the many pollutional changes of water quality. When it falls below certain levels it can adversely affect fish culture to a great extent. The realization of such adverse effects has prompted many investigators to focus their efforts towards establishing the limits of oxygen requirements for the normal growth of cultural species. The findings were as varied as the number of species and methods of conducting the experiments involved.

Since the oxygen requirements are related to several other parameters, the study of their relationship can be carried out only when the attempted parameters could be controlled in the laboratory. An important factor that determines such requirements is the amount of food supplied. It has been demonstrated that the appetite and growth of fish go down as DO concentrations decline below certain levels (Adelman and Smith, 1970 ; Brett and Blackburn, 1981 ; Chiba, 1966 ; Fisher, 1963 ; Herrmann et al., 1962 ; Kim and Kim, 1986 ; Stewart et al., 1967 ; Swift, 1963). A wide variety of studies on the influence of DO upon metablic activity of fish, its relation to aquatic respiration, and the limits below which normal metabolism is impaired have been established in a number of species : yet, perhaps not much work on its relation to food consumption rate and the practical fesibility of the interactions between these factors have been carried out (Doudoroff and Shumway, 1970). Herrmann et al. (1962) found that food consumption and growth rates of juvenile coho salmon, *Oncorhynchus kisutch,* declined with reduction of oxygen concentration.

Similar methods have also been conducted by other workers whose results on different species show the same trend as that of Herrmann et al. (1962). For instance, Fisher(1963) found that the food consumption and growth rates of underyearling coho salmon on unrestricted ration decreased with reduction of oxygen from levels near air saturation. Chiba(1966) observed that the growth, feeding, and food efficiency rates of *ad libitum* fed juvenile common carp decreased when oxygen concentration was less than 3 cc/ℓ (4.3 mg/ℓ). Stewart et al. (1967) reported that the growth of juvenile largemouth bass, *Micropterus salmoides,* fed unrestricted ration increased with increase in oxygen concentration up to the air saturation level. Similar trend was observed on *ad libium* fed northern pike, *Eosx lucius,* (Adelman and Smith, 1970).

All the above-mentioned works are in harmony with one another, except for some differences in specification of thresholds. These somewhat similar observations have made the fact clearly established that the higher oxygen concentrations near the air saturation levels are generally associated with higher rates of food consumption and growth. However, when we take intensive culture systems, particularly recirculating water systems into consideration, there are generally limits to maintaining oxygen concentrations near the air saturation levels, and in some instances even above 5 mg/ℓ most of the times (personal observations). Therefore, it is very important to fully exploit the prevalent oxygen ranges within a culture system. Though the effect of reduced DO or its fluctuations on the food consumption, hence growth, have been the subject of many investigations, the attempts seem to have been mainly on defining the already known concept of DO—food consumption—growth, without much efforts towards elaborating the thresholds of the prevalent DO concentrations, within which appropriate level of feed for economically feasible growth could be supplied. To pursue this idea, the concept of *ad libitum* feeding should be substituted for appropriate level proportional to the ambient oxygen concentrations. If DO can be maintained at certain concentrations within narrow fluctuations—that is, nearly constant levels—then the idea of *ad libitum* feeding strategy can be a good method to bring about healthy and fast growth. But, since DO in conventional culture systems highly fluctauates, a certain amount of *ad libitum* supplied feed that might have already been consumed under a certain oxygen level might prove to be too high when the DO decreases beyond the fish metabloic requirement. Such circumstances are well indicated by letheargy and regurgitation, whose severity depends on the margin of the fluctuation and exposure duration. In serious cases the fish become highly stressed, normal color may change and the animal refuses food with ultimate loss of weight and health, until the required oxygen level is restored. However, the same reduced level may bring about some degree of growth without any stress smyptoms, if the supplied ration is proportional to the oxygen levels with insight to its likely fluctuation margins. It is, thus, not unusual to observe a period of active feed consumption followed by another of less active feeding in systems with limited oxygen generating capacity to sustain the metabolically required levels. This phenomenon may partially have its reason in DO levels which might initially be normal, but as the fish consume more feed the demand for oxygen also increases to the level that is beyond the system's capacity to furnish it. The process is generally accompanied with gradual reduction in oxygen to the level that is below the metabolic requirement of the fish, which results into oxygen deficiency and its inducing stress symptoms, if left uncontrolled.

The purpose of the present investingations is to deal with laboratory observations on the relation of different DO concentrations and feed levels to the growth of young common carp reared in recirculating water system, so as to suggest appropriate rations proportional to prevalent oxygen concentrations which could sustain economic ratio of feed to the growth of Israeli strain common carp which is the most popular among fish farmers in Korea (Gov. Rep. Korea, 1988)

MATERIALS AND METHODS

EXPERIMENTAL FISH

Totally five series of experiments were conducted to cover five size groups of 67, 200, 400, 600, and 800 grams in average weight. Juveniles of Israeli strain of common carp, hatched at the fish culture facility in the National Fisheries University of Pusan, were selected. Depending on the availability of enough number of suitable specimens, attempts were made to conduct as many intended experiments with juveniles within a single population as possible, in order to reduce errors that might have been caused by genetical inheritance.

Efforts were made to select the fish of uniform size. They were treated with potassium permanganate soultion (4 ppm) against any possible presence of protozoan or helminth parasites of gills. After the treatment they were transferred into indoor aquaria having had the same thermostatically—controlled temperature as the preceding one ; the temperature was gradually adjusted to the desired experimental level (25℃). The fish were subjected to conditioning periods of 15 days in case of 67 g size group and 5 days in the other size groups. After conditioning, the intended amount of healthy and uniform size stock was carefully hand—selected and evenly redistributed into another set of aquaria of the same dimensions and temperature for the commencement of the experiments. To let them recover from the stress endured during handling, they were supplied only a little feed equivalent to their maintenance ration for three days before the beginning of the experiments. The same procedure was followed in all the experiments undertaken.

EXPERIMENTAL APPARATUS

The details of the experimental system is schematically shown in Fig. 1.

a) Aquaria Sets

Aquaria sets used in this study were designed to maintain a constant but adjustable flow of recirculating water. Two sets of basically the same design and functions were employed. In one set, used for the fish of 67 and 200 gram size ranges, 10 individual aquaria were connected with the gravel filled filter chamber through an inlet ; dimensions of each was 60×30×40(D) cm. The other set, used for the fish above 200 g size range, consisted of 6 independent units ; in each unit 4 individual aquaria, of 60×45×45(D) cm dimensions, were connected with the filter chamber. All the aquaria were covered with net mesh to prevent the fish from jumping out.

b) Aeration System

It consisted of small air pumps connected with the main airpipe ; smaller branches from the main pipe connected with air stones were, via control valves, supplied to each aquarium. A supplementary liquid oxygen cylinder (not shown in the figure) was, via outlet, connected with the filter chamber of the set with 10 aquaria. It was used, though occasionally, when the oxygen generated by the aeration did not match with the desired levels.

c) Heating System

Thermostatically controlled stainless steel immersion heaters were put in the filter chambers to maintain the temperature at the desired levels.

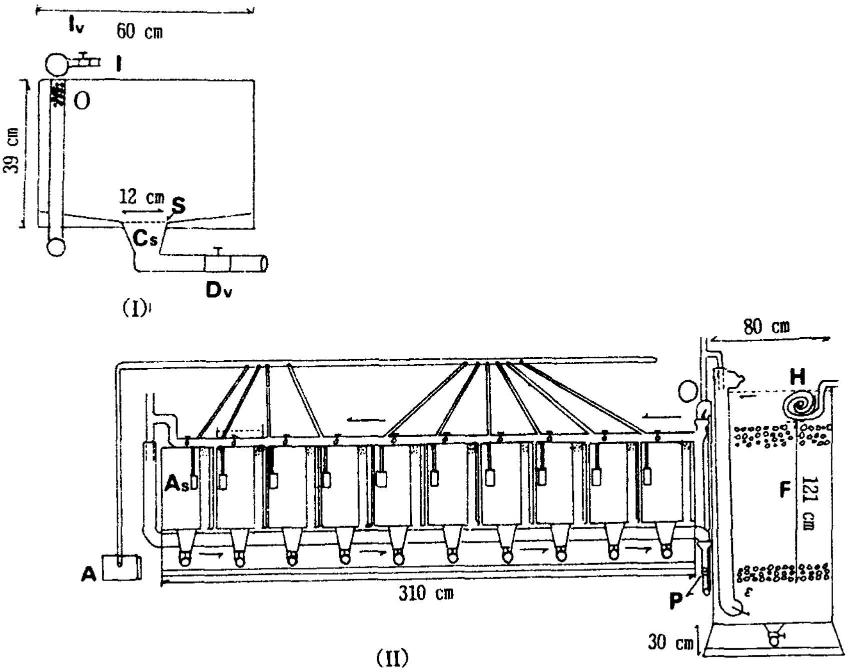

Fig. 1. Schematic drawing of a single experimental aquarium (I), and the whole set (II).

A—air pump, As—air stone, I—inlet, O—outlet overflow, Iv—inflow valve, Dv—drain valve for solid waste, P—pump for water circulation, H—heater immersed, F—gravel filled filter chamber, S—screen, Cs—Chamber for solid waste collection

d) Oxygen Measuring Instrument

Oxygen measurement was conducted with a DO−meter of OXI 91 (made in West Germany.)

e) Autofeeders

Specially designed autofeeders (Kim, 1987) were used to supply feed at desired frequencies with constant feed drops.

The experiments were carried out in a room illuminated with fluorescent light, making night feeding quite possible and observable.

EXPERIMENTAL PROCEDURES

To focus on the study of the main topic of interest, that is the interactions between DO and feed levels, the other parameters, such as temperature, pH, etc. were all kept at constant rates through all the experiments the range of oxyen concentrations to be studied was 2.0 to 6.0 ㎎/ℓ which includes all the DO levels. The are most likely to be encountered in highly intensive culture systems. The reason for selecting the 2.0 ㎎/ℓ as the lowest test level was its background in earlier works (Kim and Kim, 1986 ; Jafar, unpublished) undertaken in our laboratory which clearly rejected the economic feasibility of DO at 2.0 ㎎/ℓ for growth. Practically, in intensive recirculating warm water culture systems, DO generally remains far below saturation level ; and in our case and many others in Korea, DO hardly exceeds 4.5 ㎎/ℓ (personal observations). The adjustment of oxygen concentrations was so that the difference between two adjacent aquaria was 0.5 ㎎/ℓ in every series. When the suitability of the lowest concentration for a tested ration towards comparatively feasible growth was disproved, it was neglected in the subsequent tests of the higher ration and a higher concentration was added instead. Oxygen measurement was routinely conducted at 2 hours interval. Oxygen adjustement was performed by putting or removing airstones into or from the filter chamber and also, though occasionally, by manipulating the air valves through which air in each aquarium was individually supplied. Attempts were made to minimize sharp fluctuations during the course of the test, particularly at the time of feeding. Fluctuations did not stay long and were soon adjusted to the range of designated levels. About 12 hours was required to adjust the DO to the desired levels at the beginning of each experiment.

The intended experimental stock was carefully selected and distributed into the the test vessels (denoted by the DO concentrations in ㎎/ℓ). The first experiment of any series started with a ration of 1% of the body weight and increased−by 1% −to as many percent as could be consumed, under the experimental circumstances, subsequently.

The feed used was commercially available pellets for common carp ; its major ingredients are given in Table 1. The arrangement order of the tested feed rations (% initial body weight) under the designated DO concentrations in different series are given in Table 2.

Daily ration was formulated using the method suggested by Stickney (1979) as follow :

$W_t = W_o + (W_o \times F/C)$, where

W_t' = weight of animals on day t

W_O = weight of animals on day o

F = feeding rate percentage

C = food conversion ratio

Table 1. Major ingredients of the feed used (%)

Ingredients	%
Soybean meal	46
Wheat flour	36
Fish meal	12
$NaH_2PO_4 \cdot 2H_2O$	2.5
Vitamin mix	1.7
Minerals	1.3
Yeast	0.5

Table 2. The arrangement order of the tested rations(%) specified in the columns under designated DO concentrations at different size series of 67, 200, 400, 600 and 800g average weights. Blank spaces in DO columns indicated that no ration tests were carried out in the respective DO levels.

DO (mg/l)	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
	1	1	1	1	1				
	2	2	2	2	2	2			
	3	3	3	3	3	3			
First series		4	4	4	4	4			
(67 g)		5	5	5	5	5	5		
			6	6	6	6	6	6	
				7	7	7	7	7	
	1	1	1	1					
	2	2	2	2	2	2			
		3	3	3	3	3			
Second series		4	4	4	4	4			
(200 g)				5	5	5	5	5	
				6	6	6	6	6	
	1	1	1	1	1				
	2	2	2	2	2	2			
Third series		3	3	3	3	3	3		
(400 g)					4	4	4	4	4
					5	5	5	5	5
	1	1	1	1	1				
Fourth series	2	2	2	2	2	2			
(600 g)			3	3	3	3	3	3	3
				4	4	4	4	4	4
Fifth series	1	1	1	1	1				
(800 g)	2	2	2	2	2	2	2		
			3	3	3	3	3	3	3

Feeding frequency was periodically adjusted, depending on feeding regimes under different tests. Under any frequency, feed drop rate was proportionally well-regulated at the same feeding group of each experiment. The fish were allowed to consume as much part of the ration as they could within 15 hours feeding period ; the uneaten amount, if any, will be mentioned in the respective tables.

Specific growth rate as the expression of growth per day as a percentage of body weight was measured using the equation suggested by Kim (personal communication), as follow :

$$g = \left\{ \left| \frac{W_t}{W_o} \right|^{1/t} - 1 \right\} \times 100, \text{ where}$$

g = specific dailygrowth rate in %
w_t = weight of animals on day t
w_o = weight of animals on day o
t = duration (number of days between t and o)

The duration was 20 days for the first series (67 g size category) ; it was reduced to 10 days for the subsequent series (200, 400, 600 and 800 g). To remove solid wastes the water was partially drained off and replaced with pre-heat-adjusted well water every morning before the scheduled feeding.

RESULTS

Table 3 shows the constant experimental conditions at every dissolved oxygen group throughout the five size series of experiments undertaken.

Table 3. Constant experimental conditions at every dissolved oxygen group through the five size series.

Size	Temperature (℃)	Initial Weight (g)	# of Fish[a]	Average Weight (g)	Duration (days)
		14			
First	25+0.5	1000	15	67± 5	20
Second	25+0.3	1000	5	200± 22	10
Third	25+0.4	2000	5	400± 36	10
Fourth	25+0.5	2400	4	600± 46	10
Fifth	25+0.4	2400	3	800± 61	10

a) No mortallity occurred throughout the course.

b) Standard deviation of the mean weight calculated based on randomly collected specimens, 45, 27, 16, 10 and 10 samples, form each population, respectively.

I. First series (67 g size groups)

Table 4 shows the tested DO concentrations, amount of feed supplied, and the resultant growth and food conversion efficiency for the first size series.

a) Appetite

The 1% ration was easily consumed at all the tested oxygen levels ; so was the 2%. The 3% ration was consumed at ease by all the DO groups, though with some degree of strain at 2.0 mg/ℓ. The 4% was readily consumed. The 5% ration was partially accepted by 2.5 mg/ℓ group ; the 3.0 mg/ℓ group consumed it, though not comfortably. The 6% ration was partially taken by the the 3.0 mg/ℓ, and not comfortably by the 3.5 mg/ℓ. All the DO groups at the 7% ration consumed the feed less readily than their sister groups at lower rations, because the supply was pretty high which always kept the fish at satiation, so no higher DO could likely enhance the appetite further. The slowness at feeding was the clear feature of the 3.5 mg/ℓ group.

The appetite was a clear function of oxygen regimes ; the ease at which the rations were consumed visibly increased as DO upgraded.

b) Growth and Food Conversion Efficiency

The growth was directly dependent on the amount of feed consumed (Fig. 2). The results indicated that as long as the fish could consume—with relative ease—it proportionally grew well at any DO level. At the low ration of 1%, the growth rate and food conversion efficiency were superior in 2.0 mg/ℓ DO group ; above 2.0 mg/ℓ, they showed a declining trend. At 2% ration the lower DO levels of 2.0 and 2.5 mg/ℓ were better performers ; above 2.5 mg/ℓ, the same declining tendency in growth and conversion efficiency was also observed. At 3% ration, the growth in 2.0 mg/ℓ group was lower than the other groups, in dircet connection with the suppressed appetite ; above 2.0 mg/ℓ it improved, though not much differences were observed. At 4% ration, the growth rates and conversion efficiency were equally good at all the DO groups, though better performances were seen at DO levels above 2.5 mg/ℓ. At 5% ration, the growth rate and conversion efficiency in 2.5 mg/ℓ were far inferior, in direct connection with its highly suppressed appetite ; it improved at DO levels above 2.5 mg/ℓ, though at similar rates above 3.0 mg/ℓ. At 6% ration, the 3.0 mg/ℓ showed the poorest growth and conversion, followed by 3.5 mg/ℓ above which they improved, though with a slight decreasing trend towards 5.0 mg/ℓ. The same trend was also observed at 7% ration in which the growth rates increased as the DO increased from 3.5 to 5.5 mg/ℓ, though not much differences above 4.0 mg/ℓ observed.

As for the food conversion efficiency, it shows an increasing trend from the lowest ration (1%) up to 4%, above which it decreases with further increase in ration (Fig. 3) ; besides, it exhibited better rates at lower DOs, when their concentrations did not suppress the feeding activities. The best conversion efficiency was recorded at the 4% ration in 3.5—4.5 mg/ℓ range(Fig. 4, 5).

II. Second series (200 g size groups)

Data for the tested rations, DO concentrations, and the resultant growth and food conversion efficiency are shown in Table 5.

a) Appetite

The 1% ration was readily accepted by all the tested DO groups ; the 2% ration was also accepted but somewhat reluctantly consumed by 2.0 mg/ℓ followed by 2.5 mg/ℓ. The 3% ration was consumed, though at a much reduced appetite in the 2.5 and 3.0 mg/ℓ DO groups ; the 4% ration

Table 4. Records of growth, food conversion, and related data for the first series 67g size of the experiments under the influence of different oxygen concentrations (20 days duration)

Food Level[a] (% initial body weight)	Dissolved Oxygen Level (mg/ℓ)[b] Designated	Range	Mean	Feed Supplied (g)	Final Weight (g)	Increment (g)	Increment (%)	Food Conversion (ratio)[c]	Food Conversion (%)	Specific Growth Rate (percent per day)
1	2.0	1.4−2.8	2.0	232	1196	196	20	1.18	85	0.90
	2.5	1.6−3.2	2.6	232	1142	142	14	1.63	61	0.67
	3.0	1.9−3.7	2.9	232	1142	142	14	1.63	61	0.67
	3.5	2.3−4.2	3.4	232	1131	131	13	1.77	51	0.62
	4.0	2.7−4.6	3.9	232	1118	118	12	1.97	51	0.56
2	2.0	1.3−2.6	2.0	471	1422	422	42	1.12	90	1.78
	2.5	1.7−2.9	2.5	471	1398	398	40	1.18	85	1.69
	3.0	2.3−3.6	3.0	471	1375	375	38	1.26	80	1.61
	3.5	2.7−4.3	3.5	471	1377	377	38	1.25	80	1.61
	4.0	2.8−4.9	4.1	471	1355	355	36	1.33	75	1.53
	4.5	3.3−5.3	4.4	471	1357	357	36	1.32	76	1.54
3	2.0	1.4−2.9	2.1	720*	1540	540	54	1.33	75	2.18
	2.5	1.7−3.2	2.5	734	1640	640	64	1.15	87	2.50
	3.0	2.2−3.6	3.1	734	1628	628	63	1.17	86	2.47
	3.5	2.5−4.3	3.5	734	1610	610	61	1.20	83	2.41
	4.0	3.0−4.8	4.0	734	1605	605	61	1.21	82	2.39
	4.5	3.3−5.2	4.4	734	1615	615	62	1.19	84	2.42
4	2.5	1.3−3.5	2.6	1062	1960	960	96	1.11	90	3.42
	3.0	1.6−3.7	3.2	1062	2050	1050	105	1.01	99	3.65
	3.5	2.8−4.1	3.5	1062	2103	1103	110	0.96	104	3.79
	4.0	3.2−4.5	4.1	1062	2090	1090	109	0.97	103	3.75
	4.5	3.6−4.9	4.4	1062	2060	1060	106	1.00	100	3.68
5	2.5	1.5−3.3	2.4	1200*	1926	925	93	1.30	77	3.33
	3.0	2.3−3.8	3.0	1425	2209	1209	121	1.18	85	4.04
	3.5	2.5−4.2	3.5	1425	2338	1338	134	1.06	94	4.34
	4.0	3.4−4.7	4.0	1425	2316	1316	132	1.08	92	4.29
	4.5	3.4−5.2	4.5	1425	2348	1348	135	1.06	95	4.36
	5.0	3.9−5.6	5.0	1425	2327	1327	133	1.07	93	4.31
6	3.0	2.1−3.6	3.0	1720*	2210	1210	121	1.42	70	4.04
	3.5	2.4−4.4	3.5	1780	2284	1284	128	1.40	72	4.22
	4.0	3.1−4.9	4.0	1780	2473	1473	147	1.20	83	4.63
	4.5	3.7−5.4	4.5	1780	2447	1447	145	1.23	81	4.57
	5.0	4.1−5.8	5.0	1780	2415	1415	142	1.26	79	4.50
7	3.5	2.6−4.5	3.5	2242	2464	1464	146	1.53	65	4.61
	4.0	3.3−5.1	4.0	2242	2616	1616	161	1.40	72	4.92
	4.5	3.3−5.1	4.5	2242	2670	1670	167	1.34	74	5.03
	5.0	3.9−6.1	5.0	2242	2681	1681	168	1.33	75	5.05
	5.5	4.3−6.6	5.5	2242	2661	1661	166	1.35	74	5.01

a) Actual consumption rates calculated at the terminations are lower than the mentioned values.
b) Range of observed values only.
c) Dry feed supply / wet increment.
*) The fish could not consume the whole designated ration ; the substracted uneaten amounts were the leftovers from the autofeeders and did not include the quantity which had already been rejected in the test vessels.

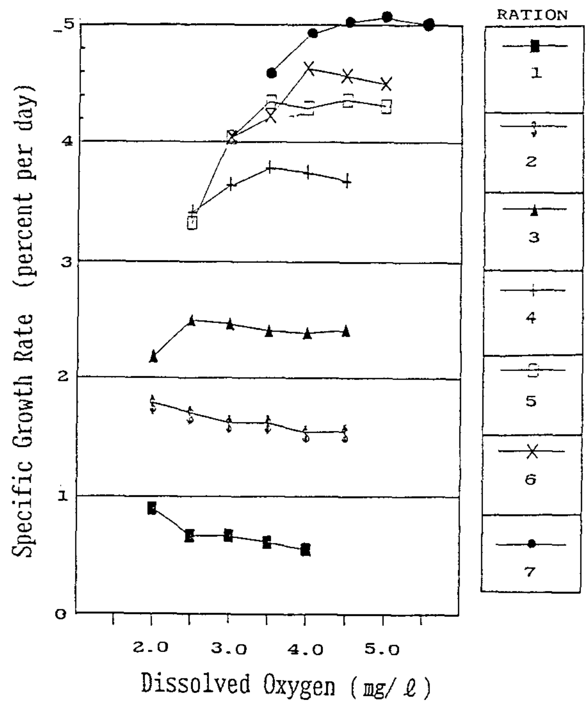

Fig. 2. Comparative trends of specific growth rates at different rations (% initial body weight) in relation to dissolved oxygen concentrations, in 67 g size groups.

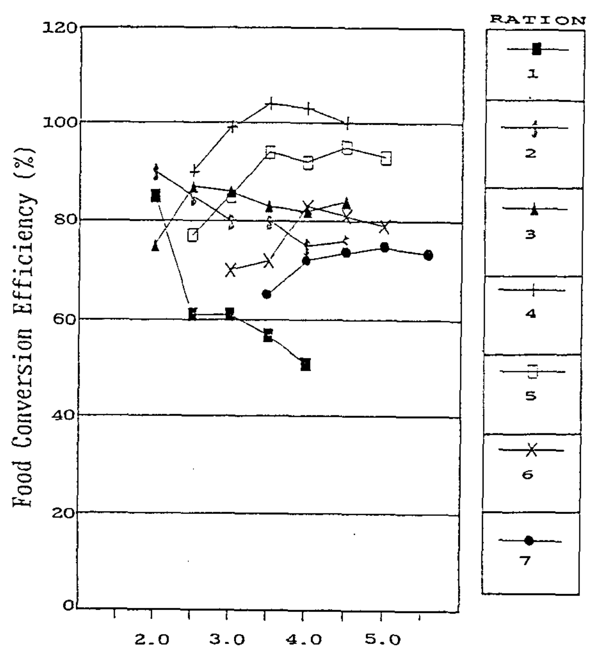

Fig. 3. Comparative trends of food conversion efficiency (percent amount of feed converted into the fish tissue) at different rations (% initial body weight) in relation to dissolved oxygen concentrations, in 67 g size groups.

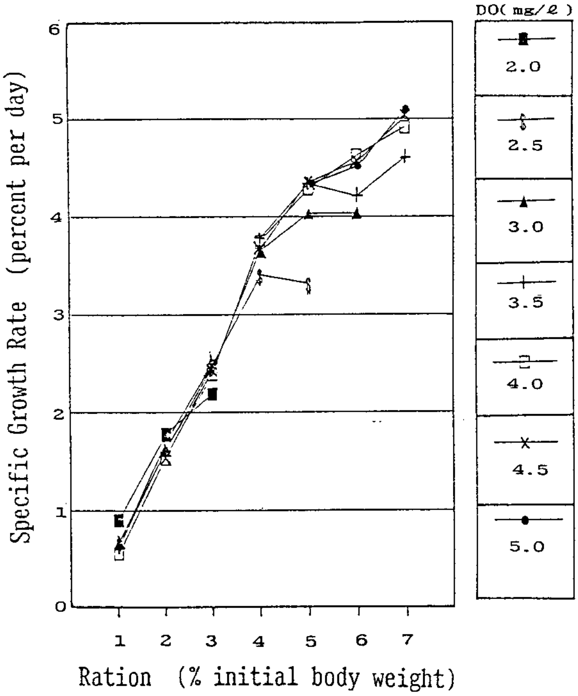

Fig. 4. Comparative trends of specific growth rates at different oxygen concentrations (mg/ℓ) in relation to different rations, in 67 g size groups.

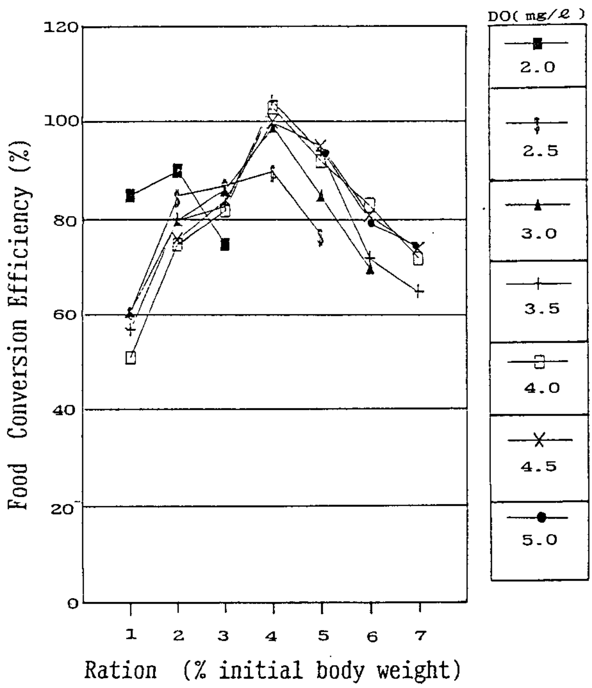

Fig. 5. Comparative trends of food conversion efficiency at different oxygen concentrations (mg/ℓ) in relation to different ratios, in 67 g aize groups.

Table 5. Records of growth, food conversion, and related data for the second 200g size series of the experiments under the influence of different oxygen concentrations. (20 days duration)

Food Level[a] (% initial body weight)	Dissolved Oxygen Level (mg/ℓ)[b] Designated	Range	Mean	Feed Supplied (g)	Final Weight (g)	Increment (g)	Increment (%)	Food Conversion (ratio)[c]	Food Conversion (%)	Specific Growth Rate (percent per day)
1	2.0	1.4－2.7	2.0	104	1078	78	8	1.33	75	0.75
	2.5	1.9－3.1	2.6	104	1075	75	8	1.39	72	0.73
	3.0	2.3－3.9	3.1	104	1073	73	7	1.42	70	0.71
	3.5	2.3－4.5	3.6	104	1075	75	8	1.39	72	0.73
	4.0	3.0－4.9	4.0	104	1070	70	7	1.49	67	0.68
2	2.0	1.3－2.6	1.9	254	1185	185	19	1.37	73	1.71
	2.5	1.5－3.3	2.5	254	1200	200	20	1.27	79	1.84
	3.0	2.1－3.7	3.0	254	1215	215	22	1.18	85	1.97
	3.5	2.5－4.2	3.6	254	1220	220	22	1.15	87	2.00
	4.0	3.1－5.5	4.0	254	1210	210	21	1.21	83	1.92
	4.5	3.3－5.8	4.5	254	1210	210	21	1.21	83	1.92
3	2.5	1.7－3.1	2.3	328	1220	220	22	1.49	67	2.00
	3.0	1.9－3.4	2.9	328	1255	255	26	1.29	78	2.30
	3.5	1.9－4.1	3.5	328	1280	280	28	1.17	85	2.50
	4.0	3.2－4.9	4.1	328	1290	290	95	1.13	88	2.58
	4.5	3.3－5.3	4.5	328	1295	295	30	1.11	90	2.62
4	2.5	1.9－3.3	2.6	297*	1115	115	12	2.58	39	1.09
	3.0	1.8－3.6	2.9	381*	1175	175	18	2.18	46	1.63
	3.5	2.4－4.3	3.5	448	1315	315	32	1.42	70	2.78
	4.0	3.1－5.2	4.2	448	1340	340	34	1.32	76	2.97
	4.5	3.3－5.7	4.8	448	1365	365	37	1.23	81	3.16
5	3.5	2.3－4.6	3.5	546	1336	336	34	1.63	62	2.94
	4.0	2.8－5.1	4.0	546	1365	365	37	1.50	67	3.16
	4.5	3.6－5.6	4.5	546	1365	365	37	1.50	67	3.16
	5.0	4.1－5.9	4.9	546	1410	410	41	1.33	75	3.50
	5.5	4.5－6.5	5.7	546	1400	400	40	1.37	73	3.42
6	3.5	2.4－4.8	3.6	584	1291	291	29	2.00	50	2.59
	4.0	2.7－5.3	3.9	667	1370	370	37	1.80	55	3.2
	4.5	3.5－6.0	4.5	667	1425	425	43	1.57	64	3.60
	5.0	4.1－5.8	4.9	667	1418	418	42	1.60	63	3.55
	5.5	4.8－6.3	5.6	667	1445	445	45	1.50	67	3.75

a) Actual consumption rates calculated at the terminations are lower than the mentioned values.
b) Range of observed values only.
c) Dry feed supply / wet increment.
*) The fish could not consume the whole designated ration ; the substracted uneaten amounts were the leftovers from the autofeeders and did not include the quantity which had already been rejected in the test vessels.

was partially taken by the 2.5 and 3.0 mg/ℓ. The 5% ration was accepted by all the groups which were higher subjected to oxygen levels than the formers, though at reduced appetite in the lower DO categories ; the same trend was also observed at 6% ration where the 3.5 mg/ℓ took feed partially. The 6% ration appeared to keep the fish at complete satiation.

b) Growth and Food Conversion Efficiency

Similar to the results of the first series, growth was a function of consumption (Fig. 6). At the lowest ration(1%), the growth and conversion efficiency in the lower DOs were as good as or even better than the higher oxygen. As the ration was upgraded, the growth was enhanced with higher oxygen concentrations within some limits above which it remained constant or even depressed with further oxygen increase. Food conversion efficiency (Fig. 7) shows an increasing tendency from the lowest ration (1%) up to 2%, above which it gradually decreased ; further, it shows the best record at 2% ration in 3.5−4.0 mg/ℓ(Fig. 8, 9).

III. Third Series (400 g size groups)

Rate for the tested rations, DO concentrations, and the resultant growth and food conversion efficiency are given in Table 6.

a) Appetite

The 1% ration easily consumed by all the tested DOs. At 2% ration, the 2.0−2.5 mg/ℓ and to some extent 3.0 mg/ℓ DO groups failed to consume the scheduled feed supply. At 3% ration, the 2.5 mg/ℓ group started eating normally in the first, but gradually lost the appetite and in the third day completely ceased feeding. Some parts of the supplied feed of both the 2% and 3% rations in 2.0− 3.0 mg/ℓ groups were wasted through regurgitation. The 4 and 5% rations were consumed by all the tested DO groups, with higher degree of appetite at higher oxygen concentrations. The 5% ration appeared to be the maximum limit to feed supply under the experimental conditions, because the fish looked completely satiated at this ration.

b) Growth and Food Conversion Efficiency

No differences in growths and conversion ratios was observed at 1% ration (Fig. 10 and Fig. 11). At 2% ration, growth in 2.0−2.5 mg/ℓ was negligible ; a considerable amount of wasted food, through rejection and vomiting, from the supplied ration contributed greatly to getting too poor food conversion results. At 3% ration, the 2.5 mg/ℓ group ceased feeding in the third day up to the end of the course, thus lost weight. In general, better food conversion results were recorded at the lower rations(Fig. 12, 13).

IV. Fourth Series (600 g size groups)

Table 7 shows the tested rations, DO concentrations, and the resultant growth and food conversion rates.

a) Appetite

The 1% ration was comfortably consumed by all the tested DO groups. The 2% ration was partially consumed by the 2.0−2.5 mg/ℓ groups. The 3% ration seemed to have been consumed by all the tested groups, however a considerable part of the supplied feed was observed to be regurgitated by the 3.0−3.5 mg/ℓ groups. The 4% ration was partially taken by the 3.5 mg/ℓ group. Higher DO concentrations were assossiated with higher degree of appetite.

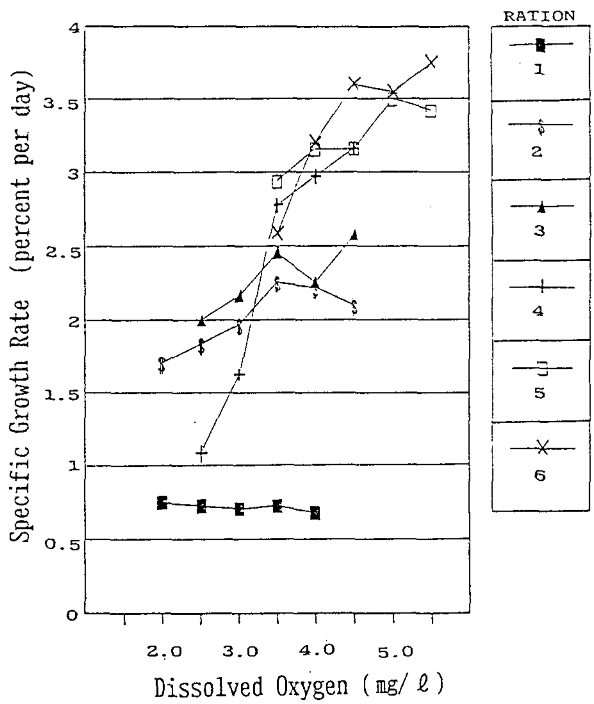

Fig. 6. Comparative trends of specific growth rates at different rations (% initial body weight) in relation to dissolved oxygen concentrations, in 200 g size groups.

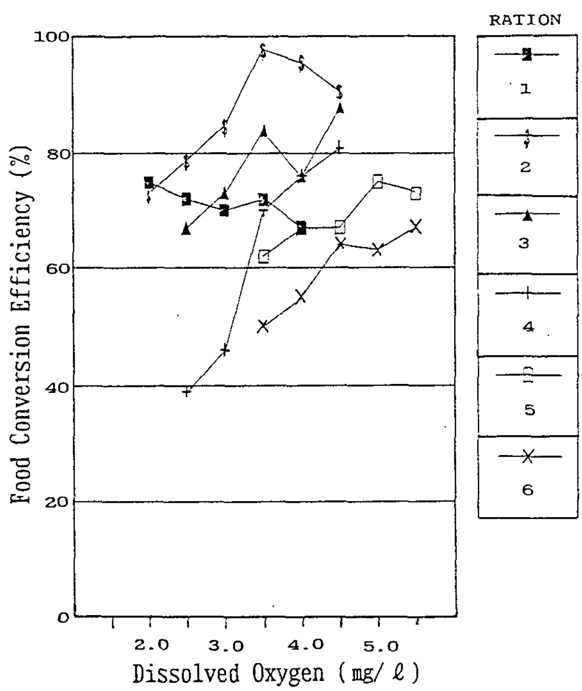

Fig. 7. Comparative trends of food conversion efficiency (percent amount of feed converted into the fish tissue) at different rations (% initial body weight) in relation to dissolved oxygen concentrations, in 200g size groups.

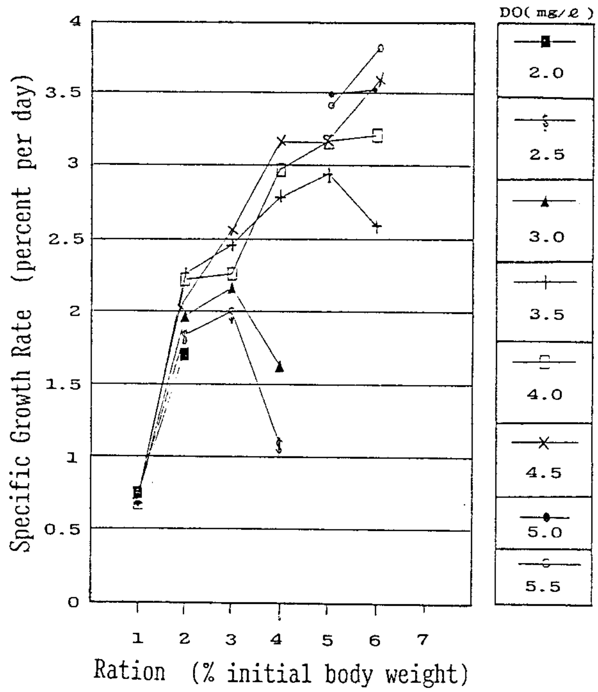

Fig. 8. Comparative trends of specific growth rates at different oxygen concentrations (mg/ℓ), in relation to different rations, in 200 g size groups.

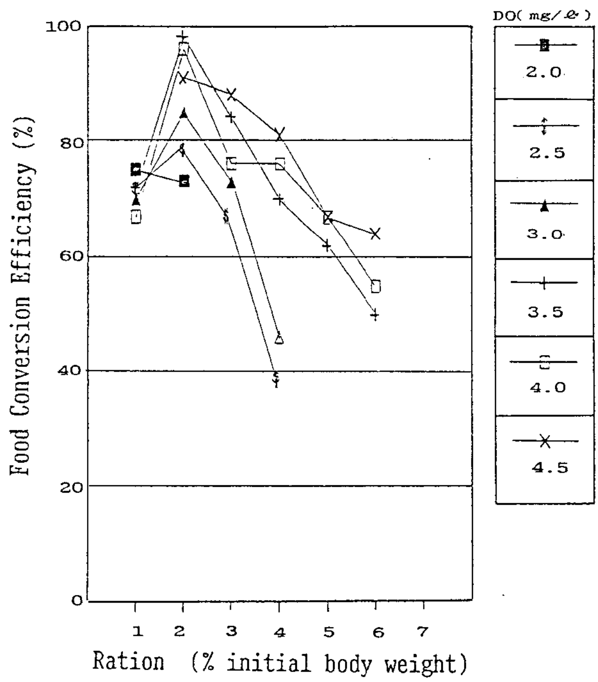

Fig. 9. Comparative trends of food conversion efficiency at different oxygen concentrations (mg/ℓ) in relation to different rations, in 200 g size groups.

Table 6. Records of growth, food conversion, and related data for the third series (400g size) of the experiments under the influence of different oxygen concentratrions (10 days duration)

Food Level[a] (% initial body weight)	Dissolved Oxygen Level (mg/ℓ)[b]			Feed Supplied (g)	Final Weight (g)	Increment		Food Conversion		Specific Growth Rate (percent per day)
	Designated	Range	Mean			(g)	(%)	(ratio)[c]	(%)	
1	2.0	1.2−2.7	2.1	208	2170	170	9	1.22	82	0.82
	2.5	1.8−2.9	2.5	208	2165	165	8	1.26	79	0.80
	3.0	2.1−3.7	2.9	208	2165	165	8	1.26	79	0.80
	3.5	2.3−4.7	3.4	208	2163	163	8	1.28	78	0.79
	4.0	2.9−5.1	3.9	208	2165	165	8	1.26	79	0.80
2	2.0	1.1−2.5	1.9	205*	2030	30	2	6.83	15	0.15
	2.5	2.3−3.3	2.7	271*	2020	20	1	13.55	7	0.10
	3.0	2.4−3.7	3.1	367*	2175	175	9	2.10	48	0.84
	3.5	2.9−4.6	3.6	422	2310	310	16	1.36	73	1.45
	4.0	3.6−4.5	4.1	422	2355	355	18	1.19	84	1.65
	4.5	3.8−5.4	4.7	422	2362	362	18	1.17	86	1.68
3	2.5	2.1−3.0	2.6	321*	1980	−20	−1			−0.10
	3.0	2.4−3.9	3.1	562*	2249	249	12	2.26	44	1.18
	3.5	3.0−4.3	3.5	655	2329	329	16	1.99	50	1.53
	4.0	3.3−4.6	4.0	655	2414	414	21	1.58	63	1.90
	4.5	3.5−5.1	4.5	655	2515	516	26	1.27	79	2.32
	5.0	3.9−5.9	5.0	655	2510	510	26	1.28	78	2.30
4	4.0	3.2−5.0	4.0	890	2523	523	26	1.70	59	2.35
	4.5	3.9−5.3	4.5	890	2585	585	29	1.52	66	2.60
	5.0	4.4−5.7	5.0	890	2570	570	29	1.56	64	2.54
	5.5	5.2−5.8	5.5	890	2605	605	30	1.47	68	2.68
	6.0	5.6−6.5	5.9	890	2623	623	31	1.43	70	2.75
5	4.0	3.3−5.2	4.1	1142	2495	495	25	2.31	43	2.24
	4.5	3.8−5.1	4.5	1142	2675	675	34	1.69	59	2.95
	5.0	4.5−5.5	4.9	1142	2775	775	39	1.47	68	3.33
	5.5	4.9−5.8	5.5	1142	2743	743	37	1.53	65	3.21
	6.0	5.4−6.4	6.0	1142	2785	785	39	1.45	69	3.37

a) Actual consumption rates calculated at the terminations are lower than the mentioned values.
b) Range of observed values only.
c) Dry feed supply / wet increment.
*) The fish could not consume the whole designated ration ; the substracted uneaten amounts were the leftovers from the autofeeders and did not include the quantity which had already been rejected in the test vessels.

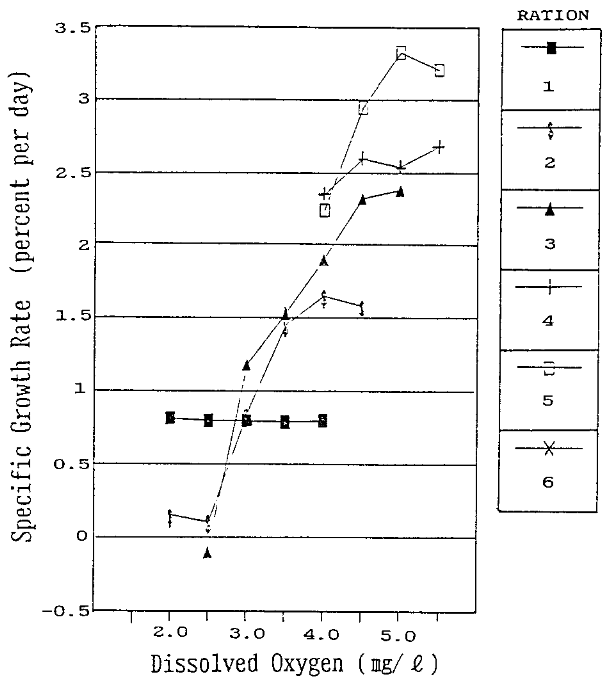

Fig. 10. Comparative trends of specific growth rates at different rations (% initial body weight) in relation to dissolved oxygen concentrations, in 400 g size groups.

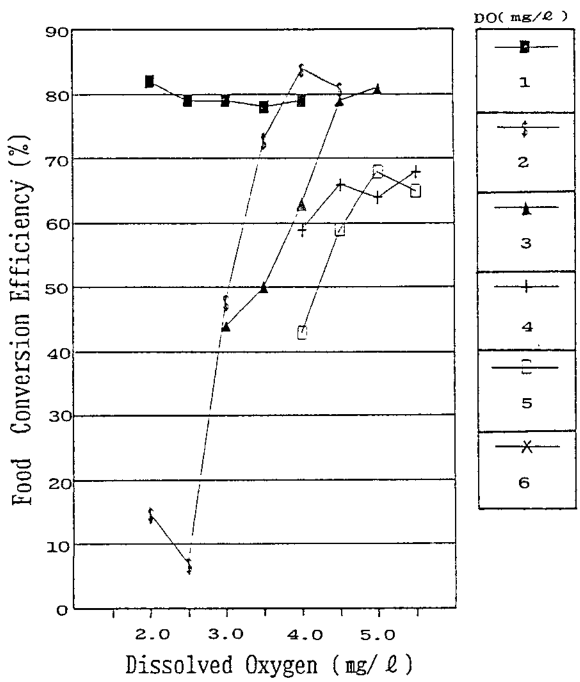

Fig. 11. Comparative trends of food conversion effeciency (percent amount of feed converted into the fish tissue) in relation to dissolved oxygen concentrations, in 400 g size groups.

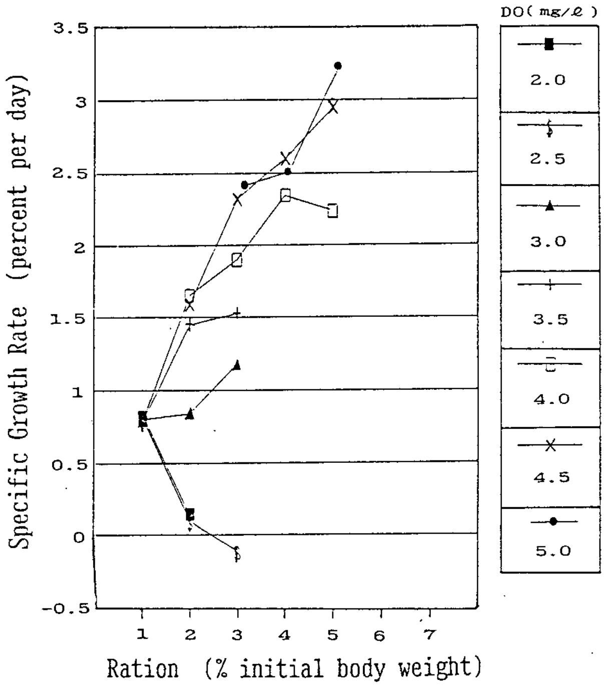

Fig. 12. Comparative trends of specific growth rates at different oxygen concentrations (mg/ℓ), in relation to different rations, in 400 g size groups.

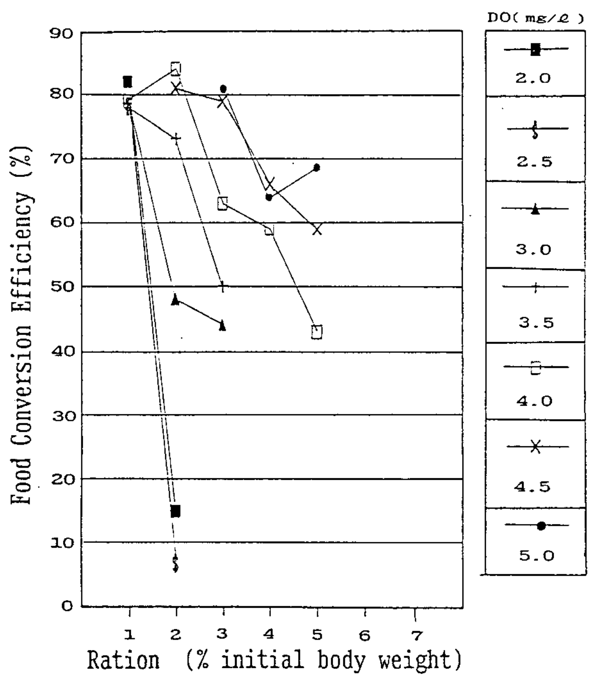

Fig. 13. Comparative trends of food conversion efficiency at different oxygen concentrations (mg/ℓ) in relation to different rations, in 400g size groups.

Table 7. Records of growth, food conversion, and related data for the fourth series(600g size) of the experiments under the influence of different oxygen concentrations (10 days duration)

Food Level[a] (% initial body weight)	Dissolved Oxygen Level (mg/ℓ)[b]			Feed Supplied (g)	Final Weight (g)	Increment		Food Conversion		Specific Growth Rate (percent per day)
	Designated	Range	Mean			(g)	(%)	(ratio)[c]	(%)	
1	2.0	1.6−2.5	2.1	249	2575	175	7	1.42	70	0.71
	2.5	1.7−2.3	2.5	249	2577	177	7	1.41	71	0.71
	3.0	2.4−3.6	2.9	249	2550	150	6	1.66	60	0.61
	3.5	2.6−4.0	3.4	249	2580	180	8	1.40	72	0.73
	4.0	3.3−4.6	4.1	249	2562	162	7	1.54	65	0.66
2	2.0	1.6−2.7	2.1	255*	2460	60	3	4.25	24	0.25
	2.5	1.9−3.3	2.6	325*	2505	105	4	3.10	32	0.43
	3.0	2.6−3.6	3.1	515	2620	220	9	2.34	43	0.88
	3.5	2.6−3.8	3.4	515	2760	360	15	1.43	70	1.41
	4.0	3.5−4.4	3.9	515	2750	350	15	1.47	68	1.37
	4.5	4.1−5.0	4.4	515	2770	370	15	1.39	72	1.44
3	3.0	2.3−4.3	3.1	794	2650	250	10	3.18	31	1.00
	3.5	2.8−4.4	3.5	794	2710	310	13	2.56	39	1.22
	4.0	3.3−4.6	4.1	794	2815	415	17	1.91	52	1.61
	4.5	3.9−5.1	4.5	794	2860	460	19	1.73	58	1.77
	5.0	4.9−5.3	5.1	794	2835	435	18	1.82	55	1.68
	5.5	4.9−5.8	5.5	794	2930	530	22	1.50	67	2.01
	6.0	5.8−6.9	6.4	794	2920	520	22	1.53	65	1.98
4	3.5	3.2−4.5	3.6	859*	2700	300	13	2.86	35	1.18
	4.0	3.3−4.6	4.1	1075	2950	550	23	1.95	51	2.08
	4.5	4.2−5.1	4.5	1075	2980	580	24	1.85	54	2.19
	5.0	4.8−5.5	5.1	1075	3015	615	26	1.75	57	2.31
	5.5	5.3−5.9	5.6	1075	3090	690	29	1.56	64	2.56
	6.0	5.9−6.6	6.3	1075	3100	700	29	1.54	64	2.59

a) Actual consumption rates calculated at the terminations are lower than the mentioned values.

b) Range of observed values only.

c) Dry feed supply / wet increment.

*) The fish could not consume the whole designated ration ; the substracted uneaten amounts were the leftovers from the autofeeders and did not include the quantity which had already been rejected in the test vessels.

b) Growth and Food Conversion Efficiency

No sharp differences in growth and food conversion rates were observed at 1% ration (Fig. 14 and Fig. 15). The 2% ration brought about comparatively poor growth and conversion rates in 2.0−2.5 mg/ℓ groups in direct connection with the appetite. As the DO concentrations increased, growth and food conversion were enhanced at 3% ration ; so was the case at the 4% ration which appeared to be the maximum limit to the food supply. Higher oxygen concentrations up to the maximum tested limit showed to enhance both growth and conversion rates at rations above 1%. Better conversion efficiency was generally recorded at lower rations(Fig. 16, 17).

V. Fifth Series (800 g size groups)

Table 8 shows the tested rations, DO, and the resultant growth and food conversion rates.

a) Appetite

The 1% ration was comfortably consumed by all the tested DO groups, down to the 2.0 mg/ℓ group. The 2% designated ration was not consumed by the 2.0 and 2.5 mg/ℓ groups.

The 3% ration was not consumed by the 3.0 mg/ℓ gorup.

b) Growth and food Conversion Efficiency

No significant difference in growth rate was observed between DO levels at 1% ration (Fig. 18, 19). At 2% ration, both the food conversion and growth rate were considerably poor for 2.0 and 2.5 mg/ℓ also significantly poorer for 3.0 and 3.5 mg/ℓ groups than 4.0 mg/ℓ~5.0 mg/ℓ groups. At 3% ration, food conversion and growth rate were very poor for 3.0 mg/ℓ group, and significantly poor for 3.5 and 4.0 mg/ℓ gorups compared to 5.0~6.0 mg/ℓ groups.

General Condition and Behavior of the Fish

Under any ration, the uncomfortable oxygen concentrations were indicated by surfacing and aggregation around the inflow ; also, the amount of fecal excretion was observed to be higher than those of comfortable oxygen ranges, indicating poorer digestion and assimilation of feed ; the medium had a higher degree of turbidity due to the rejected feed (such symptoms appeared in those DO groups indicated by comparatively poorer growth and conversion rates). When DO was unbearably lower than the metabolically required level, the animal passed much larger than the normal amount of feces and ceased feeding which contributed to high degree of turbidity ; they became too lethargic, the normal body color changed into whitish−yellow or grey patches (such symptoms appeared in all the size groups indicated by failing to consume the supplied ration and also comparatively too poor growth and conversion rates). The severity of such symptoms depended on the DO concentrations and exposal period. Under very serious conditions normal color deeply changed and the fish ceased feeding even for days with subsequent loss of weight (such symptoms did appear in 2.5 mg/ℓ of the 400 g size series under 3% ration)

An interesting observation was that the hungry fish initially began consuming feed even at the lowest tested DO concentration ; as the feeding went on, naturally the metabolic demand for oxygen increased ; when the desired tested levels were too low to satisfy the demand ; the beginning of the low DO stress symptoms appeared. The condition was aggravated by unavoidable decrease of the DO. When such decrease below the required level occured not long after the feed ingestion, the animal regurgitated the feed particles through the mouth ; and when it happened somewhat long after ingestion, the regurgitation was in the form of particulated substances (probably semidigested

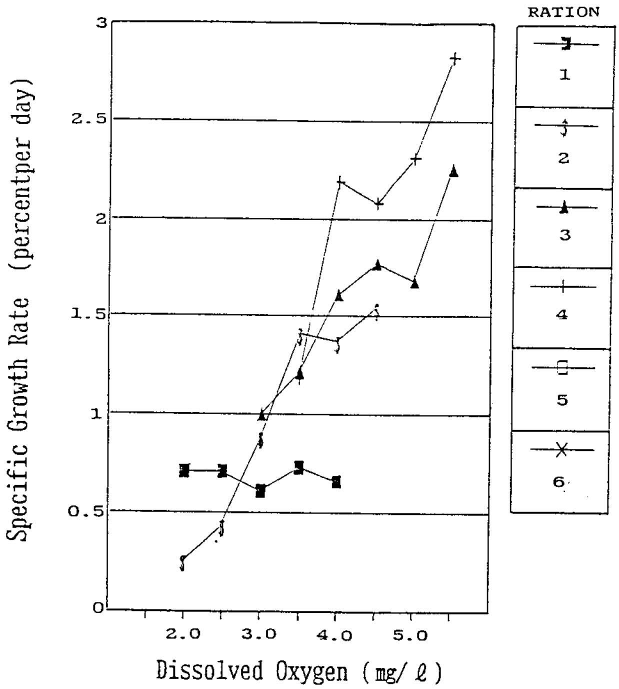

Fig. 14. Comparative trends of specific growth rates at different rations (% initial body weight) in relation to dissolved oxygen concentrations, in 600 g size groups.

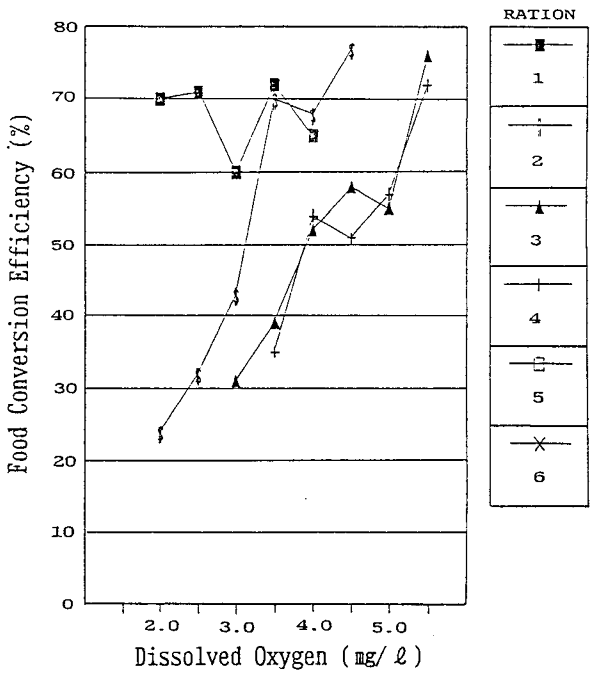

Fig. 15. Comparative trends of food conversion efficiency (percent amount of feed converted into the fish tissue) at different rations (% initial body weight) in relation to dissolved oxygen concentration, in 600 g size groups.

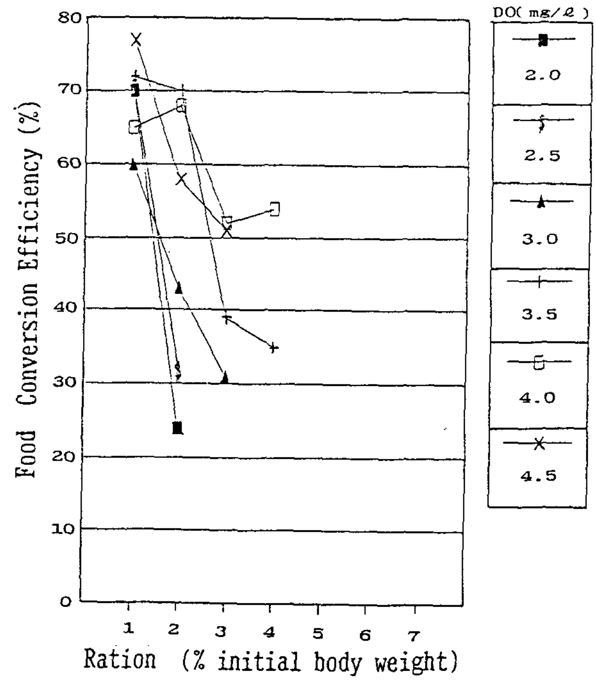

Fig. 16. Comparative trends of specific growth rates at diffeent oxygen concentrations (mg/ℓ), in relation to different rations, in 600g size groups.

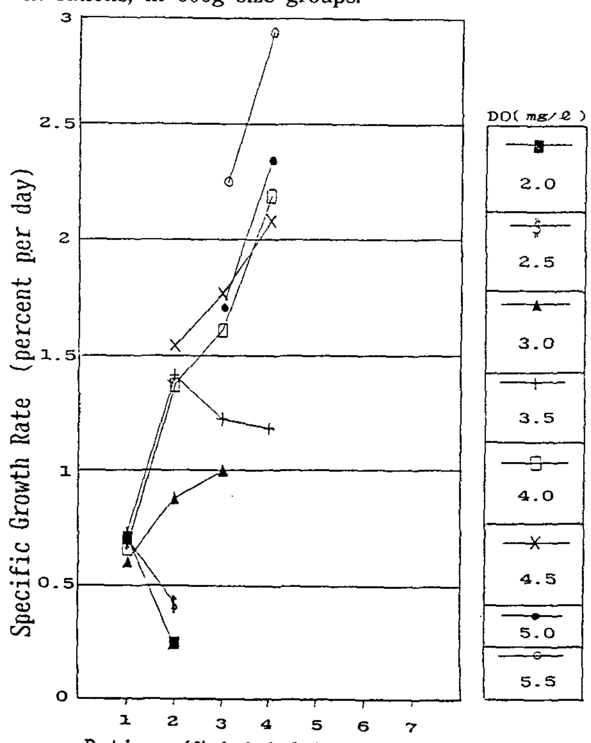

Fig. 17. Comparative trends of food conversion efficiency at different oxygen concentrations (mg/ℓ), in relation to different rations, in 600 g size groups.

Table 8. Records of growth, food conversion, and related data for the fifth series(800g size) of the experiments under the influence of different oxygen concentrations (20 days duration)

Food Level[a] (% initial body weight)	Dissolved Oxygen Level (mg/ℓ)[b]			Feed Supplied (g)	Final Weight (g)	Increment		Food Conversion		Specific Growth Rate (percent per day)
	Designated	Range	Mean			(g)	(%)	(ratio)[c]	(%)	
1	2.0	1.5−2.6	2.0	249	2570	170	7	1.46	68	0.69
	2.5	1.6−3.1	2.5	249	2585	185	8	1.35	74	0.75
	3.0	1.9−3.5	2.9	249	2568	168	7	1.48	67	0.68
	3.5	2.6−3.9	3.4	249	2560	160	7	1.56	64	0.65
	4.0	3.1−4.7	4.1	249	2552	152	6	1.64	61	0.62
2	2.0	1.8−2.8	2.1	330*	2475	75	3	4.40	23	0.31
	2.5	1.9−2.9	2.5	350*	2520	120	5	2.92	34	0.49
	3.0	2.3−3.7	3.2	515	2605	205	9	2.51	40	0.82
	3.5	2.7−3.8	3.6	515	2655	255	11	2.02	50	1.01
	4.0	3.2−4.9	4.0	515	2725	325	14	1.58	63	1.28
	4.5	3.4−5.2	4.5	515	2748	348	15	1.48	68	1.36
	5.0	4.4−5.8	5.0	515	2735	335	14	1.54	65	1.32
3	3.0	2.9−3.6	3.0	620*	2620	220	9	2.82	28	0.88
	3.5	3.2−4.5	3.5	794	2800	400	17	1.99	50	1.55
	4.0	3.5−4.6	3.8	794	2810	410	17	1.94	52	1.59
	4.5	3.8−5.2	4.4	794	2865	465	19	1.71	59	1.79
	5.0	4.5−5.5	5.1	794	2910	510	21	1.56	64	1.95
	5.5	4.8−5.7	5.5	794	2906	506	21	1.57	64	1.93
	6.0	5.0−6.9	6.5	794	2890	490	20	1.62	62	1.88

a) Actual consumption rates calculated at the terminations are lower than the mentioned values.

b) Range of observed values only.

c) Dry feed supply / wet increment.

*) The fish could not consume the whole designated ration ; the substracted uneaten amounts were the leftovers from the autofeeders and did not include the quantity which had already been rejected in the test vessels.

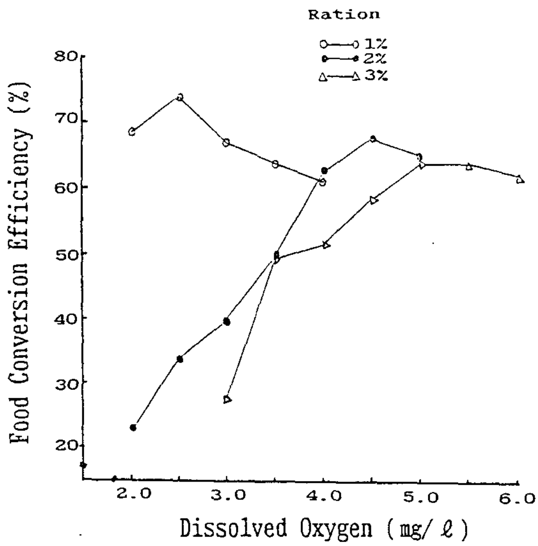

Fig. 18. Comparative trends of food conversion efficiency at different rations in relation to dissloved oxygen in 800 g size groups.

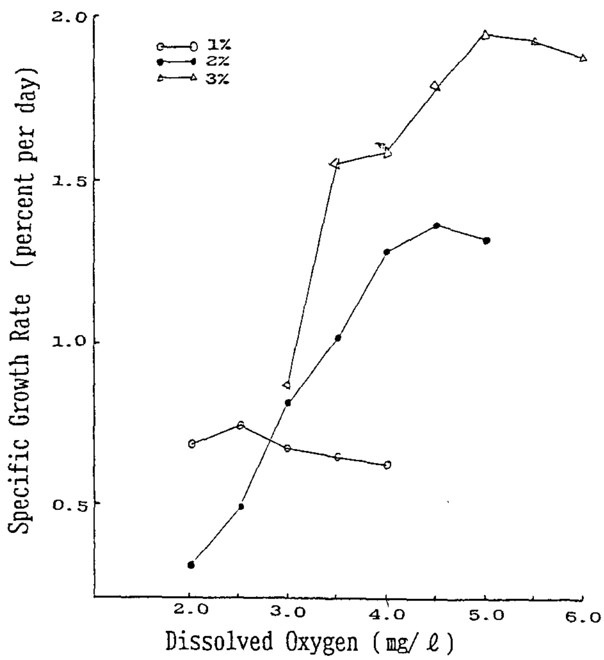

Fig. 19. Comparative trends of growth rate at different rations in relation to dissloved oxygen in 800 g size groups.

food from the upper part of the intestine) through the opercular chambers. When the DO dropped long after the ingestion, the animal passed stool earlier and in larger proportion than those in comfortable DO concentrations.

Another observed feature was the response of differnt size groups to different rations and oxygen concentrations. It was found that the larger the fish the less tolerant they became to the low DOs, and the degree of their tolerance aggravated as the ration was increased. This trend is well indicated by comparing the data for the same rations and DOs in different size groups.

DISCUSSION

The results of the present works indicate that higher oxygen level enhances appetite, which is in accordance with the results of northern pike, *Esox lucius* (Adelman and Smith, 1970) ; coho salmon, *Oncorhynchus kisutch* (Fisher, 1963 ; Herrmann et al., 1962) ; Common carp (Kim and Kim, 1986) ; largemouth bass, *Micropterus salmoides* (Stewart et al., 1967) ; channel catfish, *Ictalurus punctatus* (Andrews et al., 1973) ; sweet smelt (ayu), *Plecoglossus altivelis* (Chiba, 1988). These works, demonstrate that low concentrations of oxygen generally restrict feed consumption. Since there are generally limits to maintaining high DO in intensive culture systems, the thresholds of feed consumption should be roughly drawn in relation to the prevalent DO ranges, that is, to rationize the feed according to the DO-induced appetite.

The results of the present investigations show that the larger fish are less tolerant to the lower DO ranges tested, particularly 2.0-3.0 mg/ℓ. This trend is indicated by reduced appetite and growth-within the same ration and DO concentrations-as size increases. The 1% ration was fully consumed by all the size and DO groups with visibly higher degree of appetite in smaller groups than the larger ones within the same low DO ranges tested. For the 400 and 600 g fish the DO range of 2.0-3.0 mg/ℓ was observed to be too low to sustain normal feeding at or above 2% ration, so poor growth. Likewise, as the ration incresed the lower tested DO ranges became more intolerable to the extent that the animal became lethargic and ceased feeding with subsequent loss of weight in one instance. There were one or two exception to this trend which would be attributed to the individual's characteristics such as the degree of tolerance to low oxygen level. Above 3.0 mg/ℓ no sign of low DO-induced symptom appeared, yet, the fish exhibited better appetite and growth as DO increased to the maximum tested level. Opposite to the larger fish, the smaller ones exhibited higher degree of growth and tolerance for a given ration at low DO ranges. In 67 g size groups the 2.0 mg/ℓ limited the appetite and growth as the ration increased to 3% ; no appetite and growth limiting effect in 2.5 mg/ℓ was observed until the ration reached the 4% level.

When the food consumption was associated with strain, an indication of inadequate DO concentrations, growth and food conversion rates were adversely affected, the degree of which was dependent on the extent of stress ; the severity of the case showed itself by changes in normal skin color that has also been reported by Scherer (1971). The fish that endured uncomfortable DO levels regurgitated and were observed to pass higher amount of fecal waste ; this phenomenon may well indicate that at intoloerably reduced DO the digestion and assimilation processes are adversely affected. The fish in higher DO levels had a higher degree of movements and appetite ; growth and conversion performance by such fish were depressed when compared with the corresponding size and ration groups with less degree of movements. This trend was more conspicuous in lower rations and smaller fish. The reason for this trend is maybe that lower oxygen concentrations reduces the animal's spontaneous activity (Herrmann et al., 1962), so less energy is required for the maintenance, which results in a greater net efficiency (Brown, 1957).

An interesting trend of food conversion efficiency in these studies is that it tended to increase as the ration was increased from the lowest level until some points above which further increase in ration pushed down the conversion efficiency (Tables 9, 10 ; Fig. 20). Such trend which has also been observed on several occasions (Huisma, 1976 ; Hung and Lutes, 1987 ; Johnson, 1966) is explained to be due to the maintenance requirement of the animal which absorbs part of the food energy ; as the ration increases, more energy goes into maintenance process. Above certain points further increase in ration resulted in decreasing conversion efficiency. The reasons for this trend have been explained to be due to a decrease in digestive assimilatory efficiency, and an increase of energetic

Table 9. Records of food conversion efficiency rates(%), arranged according to the subsequent size groups within similar rations, under the influence of oxygen concentrations.

Ratio (%)	Size Groups(g)	DO (mg/l)	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	7.0
	67		85	61	61	57	51				
	200		75	72	70	72	67				
1	400		82	79	79	78	79				
	600		70	71	60	72	65				
	800		68	74	67	64	61				
	67		90	85	80	80	75	76			
	200		73	79	85	98	96	91			
2	400		15	7	48	73	84	81			
	600		24	32	43	70	68	77			
	800		23	34	40	50	63	68	65		
	67		75	87	86	83	82	84			
	200			67	73	84	76	88			
3	400			–	44	50	63	79	81		
	600				31	39	52	58	55	76	69
	800				28	50	52	59	64	64	62
	67			90	99	104	103		100		
4	200			39	46	70	76	81			
	400						59	66	64	68	70
	600					35	54	51	57	72	65
	67			77	85	94	92	95	93		
5	200					62	67	67	75	73	
	400						43	59	68	65	69
6	67			77	85	94	92	95	93		
	200					50	55	64	63	67	
7	67					65	72	74	75	74	

Table 10. Records of food conversion efficiency rates, arranged according to the subsepuent increase in the tested ration within similar size groups, under the influence of oxygen concentration.

Size Groups	Ration (%)	DO (mg/l) 2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	7.0
60 g	1	85	61	61	57	51				
	2	90	85	80	80	75	76			
	3	75	87	86	83	82	84			
	4		90	99	104	103	100			
	5		77	85	94	92	95	93		
	6				70	72	83	81	79	
	7				65	72	74	75	74	
200 g	1	75	72	70	72	67				
	2	73	79	85	98	96	91			
	3		67	73	84	76	88			
	4		39	46	70	76	81			
	5				62	67	67	75	73	
	6				50	55	64	63	67	
400 g	1	82	79	79	78	79				
	2	15	7	48	73	84	81			
	3		—	44	50	63	79	81		
	4					59	66	64	68	70
	5					43	59	68	65	69
600 g	1	70	71	60	72	65				
	2	24	32	43	70	68	77			
	3	24	32	43	70	68	77			
	4				35	54	51	57	72	65
800 g	1	68	74	67	64	41				
	2	23	34	40	50	63	68	65		
	3			28	50	52	59	64	64	62

cost of opercular movements, which tended to increase along with higher ration, and also elevated metabolic activity (Degani and Gallagher, 1985 ; Fisher, 1963 ; Kelso, 1972 ; Kramer, 1987 ; Stewart et al., 1967 ; Swenson and Smith, 1973). For the 67 g fish of this experiments the conversion efficiency reaches maximum at 4% in 3.5 mg/ℓ DO level ; no sharp DO influence above 3.5 mg/ℓ is indicated. For the 200 g fish groups conversion efficiency reaches maximumm at 2% ration in 3.5−4.0 mg/ℓ DO levels. As the fish size increases the more efficient conversion rates occur in the lower rations and higher DO levels. Poor conversion rates in untolerably low DO levels is connected with reduced appetite, digestive and assimilatory efficiency as well.

Another trend of food conversion efficiency is indicated by its gradually decreasing rate as the fish size increases. This trend may have its reason in the digestive and assimilatory efficiency which tend to decrease as the animal grows bigger.

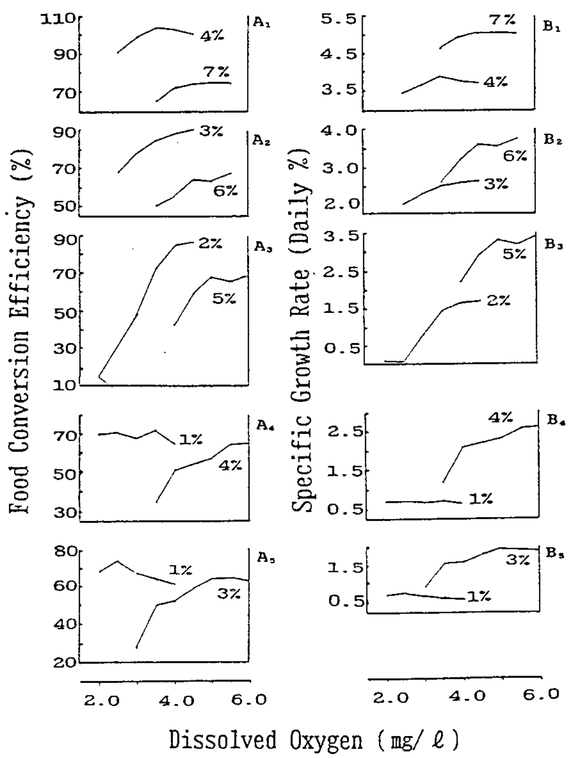

Fig. 20. Trends of food conversion efficiency (A) and growth rate (B) at rations as shown in the figure for 67 g fish (A_1, B_1), 200 g fish (A_2, B_2), 400 g (A_3, B_3), 600 g (A_4, B_4), and 800 g fish (A_5, B_5).

Although the maximum growth will be obtained at *ad libitum* food supply, it has invariably been reported to reduce food conversion efficiency in all the concerned species (Andrews and Stickney, 1972 ; Brett et al., 1969 ; Chua and Teng, 1978 ; Paloheimo and Dickens, 1966). Also, there is some limit in feed consumption, irrespective of oxygen concentraion, above which the speed of growth slows down (Goolish and Adelman, 1984). Besides, the risk of adverse effect of polluting the culture medium, caused by *ad libitum* feed supply, should not be over looked (New, 1987). Tucker et al., (1979) reported that the channel catfish treated with low and medium amount of ration (34 and 56 kg/ha) enjoyed a better water quality and conversion efficiency than high ration treatment (78 kg/ha) ; the net economic gains were $1136, $1303, and $671 per ha for low, medium, and high feeding rates, respectively, though the net production increased as were feeding rates (2990, 4100, and 4860 kg/ha).

In these investigations, food conversion efficiency reaches maximum at 4% ration (optimum ration) in the 67 g fish size (Fig.5) within 3.0−4.5 mg/ℓ DO levels, with slight advantage in 3.5−4.0 mg/ℓ ; reduced conversion efficiency below 3.0 mg/ℓ should be attributed to suppressed appetite, while the slight disadvantage above 4.0 mg/ℓ is believed to be due to the loss of energy by spontaneous activites (Herrmann et al., 1962). In the 200 g fish the best conversion efficiency is found at 2% ration within 3.5−4.0 mg/ℓ (Fig. 9). In the 400 g fish, due to the individual's different response, no clear distinction for conversion rate between 1 and 2% ration is apparent (Fig. 13). In the 600 g fish the most efficient conversion lies in 1% ration in 2.0 mg/ℓ DO (Fig. 17). This trend indicates that as the fish increases in size its optimum food level (the amount of food for the highest food conversion efficiency) decreases, so is the DO level. Since the determination of the maintenance requirements for food and DO were beyond the scope fo these investigations, the 'optimum term' is used for the tested levels.

Unavoidable contradictions arise when the the overall outcome of these experiments are compared with similar works by others. The sources of these problems are too many and maybe alreddy clear to workers. Involvement of different species under various parameters, feeding regimes, density, and ages are only a few to mention. Owing to differences of experimental methods, disagreement of results even for the same species is inevitable (Doudoroff and Shumway, 1970).

Chiba (1966) reported that the feeding rate, growth rate, and food conversion efficiency of the juvenile common carp decreased with reduction of oxygen concentration below 4.3 mg/ℓ. He concluded that 3.0 cc (4.3 mg/ℓ) DO at 20−33 ℃ might be considered the critical level for the carp, and active feeding and fast growing could not be expected below 3.0 cc/ℓ. Taking all the parameters of Chiba's experiment into consideration, the result of this study for the same oxygen level disagrees with his highly variable ones. His data provide little evidence for his conclusion (Doudoroff and Shumway, 1970) ; besides, in several instances quite contradictory. Lack of uniformity in methods, occurrence of mistakes in calculations of data, and questionable supply of adequate level of food upon which conversion efficiency is derived casts heavy doubts on the reliability of Chiba's results and conclusion. Chiba's idea was also supported by Itazawa and Takeda (1979) who, through estimating the oxygen requirement for the maintenance of the arterial oxygen content of, concluded the minimum level of DO for healthy life of the carp to be 45−55% in saturation.

Kim and Kim (1986) observed the 3.5 mg/ℓ to be best among five DO groups in 2.0−4.0 mg/ℓ range. In their experiments feeding and growth rates and food conversion efficiency in *ad libitum* fed common carp increased as the mean oxygen concentration was upgraded. Although the fish 3.5

and 4.0 ㎎/ℓ had almost consumed the same amount of feed, the overall growth performance was in favour of the former ; this corresponds with the results of the present investigations that show better growth in lower DO when the ration is consumed with ease. The poorest performance was at 2.0 followed by 2.5 ㎎/ℓ which consumed the least amont of feed, which is in harmony with the present result under the corresponding inital fish size of 200 g. Comparatively poorer results by Kims' fish may find its reason in reprotedly high ammonia concentration and probably other unfavorable emvironmental parameters that are believed to show their adverse effects more on the animals maintaind in not so favorable oxygen concentrations (Herrmann et al., 1962 ; Moss and Scott, 1961). A similar work was conducted (Jafar, unpublished) for the same DO levels as those of Kims' in duplicates, one for restricted and the other for unrestricted feeding. The result for the latter was not different from Kims' ; for restricted feeding the growth performance was similar in all DO groups, however relatively poorer at 2.0 ㎎/ℓ.

The number of works on other species, particularly on salmon family dominates the field. For instance, food consumption and growth rates of juvenile coho salmon, *Oncorhynchus kisutch* were reported (Herrmann et al., 1962) to decline slightly with reduction of oxygen concentrations from a mean of about 8.3 to 6 and 5 ㎎/ℓ, and declined more sharply with further reduction. Comparable results on sockeye salmon, *O. nerka* and coho salmon (Brett and Blackburn, 1981) ; brown trout, *Salmo trutta,* (Swift, 1963) show the trend in the present work is in harmony with their's ; that the higher DO does not necessarily encourage the growth, unless a proportional amount of feed matchable with the appetite is supplied ; also, there is a threshlold of oxygen above which the growth is not radically affected even if substantial amount of feed is consumed.

Perhaps the most comparable work with the present studies is that of Fisher's (1963), because his experiment of coho salmon was under uniformly restricted ration. The growth did not differ much in six different DO concentrations (3.0 to 18.1 ㎎/ℓ), though slightly lower at 3.0 ㎎/ℓ. His results are similar to the ones of these experiments that when, under any DO, a ration is easily consumed a further increase in DO did not enhance the growth. His conclusive statement 'reduction of food consumption probably can have a favorable effect of the food conversion efficiency only when it is not a reduction that is necessitated by adverse dissolved oxygen conditions' is the best that can define the role of oxygen concentrations for growing fish.

Among the most prominent works on non-salmonidae species worth mentioning is that of Stewart et al. (1967) on largemouth bass, *Micropterus salmoides.* Their well elaborated data give the impression that the feeding and growth rates sharply increased as the mean constant oxygen concentrations reached 5.8-8.2 ㎎/ℓ range, above which they reversed or remained constant. However, food conversion does not show marked increase with increase of DO above 4.0 ㎎/ℓ. Somewhat similar pictures have been reported on channel catifish, *Ictalurus punctatus* (Andrews et al., 1973) ; northern Pike, *Esox lucius* (Adelman and Smith, 1970) ; sweet smelt, *Plecoglossus altivelis* (Chiba, 1988). A report on young silver bream, *Sparus sarba* (Chiba, 1983) indicated the same trend, too.

All the above- mentioned authors directly specified the growth as a function of food consumption rate which is enhanced by higher oxygen concentrations near air saturation level. However, the lower thresholds are either not so much considered or show different points of views. The differences are mostly unavoidable due to variability inherent among different species and even the same species, let alone different conditions and experimental methods ; nevertheless, some could at least be reduced, if the animals were allowed to get adapted to the new circumstances before and during the course of testing. The importance of adaptations to different parameters and the differences that can be brought as the result have been demonstrated (Moss and Scott, 1961 ; Brett, 1962 ; Shepard, 1955). Although the adverse effects of the lower thresholds of oxygen on the feeding rate and growth are a known fact, the role of other adversaries that have been stated to be more deleterious at untolerably low oxygen concentrations. One of these burdens was the turbidity of the medium that was observed to be due to the relatively higher amount of fecal wastes excreted by the fish in unfavorably low DO ; regurgitated feed, also observed by Bouck and Ball (1965), was an exclusive feature by the low oxygen-stressed fish. The toxicity of ammonia and other nitrogen byproducts (Kawamoto, 1961 ; Robinette, 1976 ; Soderberg et al., 1983 ; Yashouy, 1958), CO_2, pH, and the extent of their adverse interactions (Dhalberg et al., 1968 ; Davis, 1975 ; Doudoroff, 1957 ; Eddy and Morgan, 1969 ; Emerson et al., 1975 ; Fry, 1957 ; Hampson, 1976 ; Kossakowski and Jezierska, 1984 ; Takeda and Itazawa, 1979) have been reported to be more prominently defined in fishes which enduerd unfavorably DO regimes.

Though advocating very low DO is beyond the present works, it was observed that concentrations far below the air saturation level can be used as efficiently as the higher ones in the smaller size groups (67 and 200 g).

The first step towards fully exploiting the available range of oxygen in a system is to apply appropriate level of feed matchable with the fish appetite under its ambient circumstances (Itazawa, 1971). The results of these investigations indicate that for the small fingerling of 67 g size the DO range of 2.0−2.5mg/ℓ could sustain the normal apetite at 1 and 2% ration with better growth and conversion outcomes ; for 3% ration, the 2.5−3.0 mg/ℓ, for 4% the 3.0−4.0 mg/ℓ, and for 5% ration 3.5−4.0 mg/ℓ ranges were found suitable enough to sustain efficient growth ; above 5% ration the DO levels over 4.0 mg/ℓ are recommended (Fig. 4). For the 200 g fish the 2.0−2.5 mg/ℓ at 1% ration, 3.5−4.5 mg/ℓ range at 2 and 3% and above 3% ration DO ranges above 4.5 mg/ℓ were found to be the matchable levels with the fish normal metabolic activites (Fig. 8). For the 400 g fish the 2.0−2.5 mg/ℓ at 1% ration, and above this ration the DO range above 4.0 mg/ℓ could support the fish normal growth and activities (Fig. 12). The same trend was also observed in 600 g fish groups (Fig. 16) and 800 g fish groups (Fig. 19).

The second step is to establish a well scheduled feeding programming. The daily feeding rate is related to the capacity of the stomach and rate of digestion (Brett, 1971) ; therefore, the frequency of feeding plays an important role (Ishiwata, 1969). The absence of digestive storage stomach makes carp non−voracious (Huet, 1973). The ingested feed has to undergo mastication before it is pushed into the intestine, which acts as digestive and abosrptive organs both. For the very same reason feed should be supplied in small amounts but continually at regular periods to increase the efficiency of mastication and digestion ; it is also a good measure to make the animal adapted to the feeding regimes under the ambient parameters. Therefore, I deem not to agree with the idea of less feeding frequency (Charles et al, 1984) which does seem to suit the physiological need of the fish. Frequent feeding strategy is also supported by New (1987). Kono and Nose (1971) demonstrated that the daily ration nearly maximized with 12 feedings for gold fish which is similar to carp in digestive anatomy. Prolonging the duration of feeding of carp on a prescribed ration was found to be more effctive than satiating the animal in short duration (personal ovservation). Shelbourn et al, (1973) reported that the continuous feeding of sockeye salmon for 15 hr/day at 20℃ resulted in a significantly greater growth rate than feeding to satiation three times daily. The feeding schedule should be so adjusted to make sure the fish are never satiated at any frequency. This measure was found to be more important, both in term of productivity and water quality, than to attempt increasing ration and oxygen level beyond the capacity of the system (personal ovservation). During the course of these experiments it was observed that the fish supplied with a surfeit feed were more susceptible to any adverse influence of the ambient parameters, particularly low DO. On the other hand those fed with less than ample amount, characterized by high movements, had their growth not as efficient as the amply-fed ones.

Finally, efforts should be made not to allow sharp drops below the average existing DO concentrations within which the animal has already adapted itself to a prescribed feed, particularly at the height of feeding activity. This measure should particularly be taken at 2.0-2.5 mg/ℓ. Intolerably sharp falls make the stressed fish vomit which in turn deteriorates the water quality so that encourages other unfavorable factors into the scene. Doudoroff and Shumway (1970) concluded that no impairment of the food resources for fish ascribable to dissolved oxygen insufficiency will occur, as long as oxygen concentrations guarantee the satisfaction of fish.

CONCLUSIONS

These studies were undertaken to come to a broader understanding on disssolved oxygen, with particular interest in the ranges that are most likely to be encountered in highly intensive culture systems. This will help to have a more elaborate picture on feeding strategy and management. Such works can particularly interest the fish farmers who are involved in raising their animals under intensive recirculating water systems where oxygen becomes a limiting factor.

The results of different oxygen concentrations (2.0-6.0 mg/ℓ) indicate that the smaller fish of the five tested sizes (67, 200, 400, 600 and 800 g) were more tolerant to low DO levels. The degree of tolerance was reduced as the fish increased in size, particularly when the feed level increased.

Growth was a direct function of appetite and feeding rate. The smaller fish exhibited high degree of appetite even in low DO levels (2.0-3.0 mg/ℓ) at 1 to 3.0% ration, while the bigger the fish the less appetie it showed at the corresponding DOs and rations. The fish at too comfortable DO levels exhibited a higher degree of movements and had their growth and conversion efficiency depressed. The higher feeding rate resulted in higher growth rate, however the degree of weight increment decreased as the ration approached maximum level ; this trend was also the feature as the fish size increased.

Food conversion efficiency increased from the lowest ration up to a level then it started decreasing (in smaller fish) ; it also showed a decreasing trend from the smaller to the bigger fish. Under the same ration and size, it was decreased only when the fish appetite was supressed by unfavorably low DO, or when the fish exhibited high degree of spontaneous activity. Digestion process was apparantly affected by untolerably low DO and the stressed fish were observed to pass the feces quicker and in higher quantity than usual pace in normal individuals ; also the stressed fish were seen to vomit ; these processes contributed further to reducing the conversion efficiency in the stressed fish.

The results of the interactions of different rations and size groups under the influence of different oxygen concentrations are summarized as follow :

-for the 67 g fish at rations of 1 and 2% the DO 2.0-2.5 mg/ℓ was enough to sustain the normal appetite and growth ; as the ration increased to 5% higher range of 3.0−4.0 ㎎/ℓ resulted in better growth and conversion performance ; above 5% ration the DO levels of over 4.0 ㎎/ℓ were observed to sustain appetite and growth.

−for the 200 g fish the 2.0−2.5 ㎎/ℓ at 1% ration, 3.5−4.5 ㎎/ℓ at 2 and 3%, and above 3% ration at DO ranges over 4.5 ㎎/ℓ were found to be the matchable levels with animals normal metabolic activity.

−for at the 400, 600 and 800 g fish the 2.0−2.5 ㎎/ℓ at 1%, and above this ration at the ranges above 4.0 ㎎/ℓ could support the fish normal activity.

In order to increase the production efficiency, feed supply should be very frequent but in small amount to make sure the animals are never satiated at any frequency. A practical method is to observe the animal behavior ; they should neither remain too sluggish nor too mobile, as both states cause the reduction in gross efficiency ; the former indicates that the ambient DO does not match with the fish oxygen requirement which results in inefficient digestion and loss of appetite, the latter wastes much metabolic energy that could otherwise go to the growth process.

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