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Cyclic feed restriction on growth compensation of *Penaeus monodon* (Fabricius): science meets practice

Rajeeb K. Mohanty[1*]& Anil Mohapatra[2]

[1]Indian Institute of Water Management (Indian Council of Agricultural Research), Bhubaneswar - 751023, Odisha, India
[2]Marine Aquarium & Regional Centre, Zoological Survey of India, Digha 721 428, India

*[E-mail address: rajeebm@yahoo.com]

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Effects of cyclic feed restriction on compensatory growth (CG) performance of *Penaeus monodon*, sediment loading and water productivity in a grow-out production system were examined in 119 days of culture duration. Among different feed management protocols (T_1: Regular feeding, 4-times a day; T_2: 2-weeks feeding followed by 1-week no feed; T_3- 4-weeks feeding followed by 1-week no feed), overall crop performance was in the similar line in both T_1 and T_2 except significantly ($P<0.05$) low AFCR and higher FE in T_2. This was probably due to the prevailing optimal salinity (19.1 ± 1.8 psu), DO (6.1±0.7 ppm) and water pH (7.54±0.13). Among T_2 and T_3, there was no significant ($P<0.05$) variation in overall crop performance except in SGR and MBW. This was probably due to the longer refeeding periods after cyclic food deprivation that successfully triggered full CG response in T_3(CGI, 98-105%) and partial CG in T_2 (89-96%).Shrimp on the cyclic feed restriction may have better used pond resources by increasing the consumption of natural productivity that increased the feed efficiency (71.6-73.5).

[**Keywords:** compensatory growth, *Penaeus monodon*, feeding management, water quality, water productivity]

Introduction

Black tiger shrimp *Penaeus monodon* is one of the most important penaeidspeciescurrently being cultured commercially in many parts of the world. In India, coastal shrimp aquaculture is mainly dominated by this species due to its high growth rate, unique taste, high nutritive value and persistent demand in the global market. The Marine Products Export Development Authority (MPEDA, India) reported that, the tiger shrimp production in India (73155 MT in 2014-15) is around 12% of global production of *P.monodon*. The success of shrimp aquaculture depends heavily on ensuring cost effectiveness during the production process. It is well known that inapt feeding management may lead to over feeding, higher production cost and contamination of aquatic environment[1], while inadequate feeding leads to poor growth that result in decreased yield. Therefore, an important approach to reduce feed cost in shrimp aquaculture is to develop proper feed management and husbandry strategy. One potential way of reducing feed cost is to take advantage of the phenomenon of compensatory growth (CG). There is sound evidence that some animals are capable of increasing their growth rates after the periods of food deprivation, compared to those of non-deprived individuals[2-6].If CG can completely make up for growth lost during starvation, there could be an opportunity to save on shrimp feed by starving the shrimp and making up for lost growth when feeding resumes. Many aquatic species have the ability to actively regulate their growth as a strategy against negative environmental changes and have the potential to elicit above normal growth rate in recovery periods following stress[7]. CG may follow a period of reduced growth resulting from food restriction or some other unfavorable environmental condition and requires an adaptation period whose duration varies from species to species[8-9]. In other words, the degree of recovery seems dependent upon the duration and severity of growth depression[10-11].

The role of energy reserve dynamics during starvation and CG only recently been brought into focus[12-13]. Fish and prawn deplete their energy reserves during starvation and replenish them during hyperphagia[7,14]. Since the replenishment happens on short time-scales, it may constitute a significant part of the CG when weight is considered. Till date, few but appreciable works on compensatory growth performance of fish and prawn have been carried out outside India[11,15-21], showing great scope of implementing this practice in commercial aquaculture for minimizing the feed input, water quality deterioration and enhancing water productivity[22]. However, no work on compensatory growth performance of black tiger shrimp *P. monodon* in grow-out culture has been reported so far.In this backdrop, an attempt was made to study the effects of cyclic food deprivation and re-feeding on the CG performance of *P. monodon*, sedimentation rate, water productivity and economic efficiency in a grow-out system under recommended package of practice.

Materials and Methods

This study was carried out at Balasore (21^0 28' 44" N, 87^0 02' 15" E), Odisha, India, during 2011-2012. During the experiment, feeding management was taken as treatment with 3 replications each [T_1: Regular feeding, 4-times a day, T_2: 2-weeks feeding followed by 1-week no feed, T_3- 4-weeks feeding followed by 1-week no feed]. Water exchange was carried out on 'requirement' basis depending on water quality variables (if the daily variation in average water pH > 1.0 or if dissolved oxygen (DO) < 3.0 ppm or if transparency < 10cm). Amount of water exchange was decided on the basis of Kg. shrimp m^{-2} × (100 × EF), where EF= exchange factor i.e., 0.1-0.25 for stocking density of 10-35 post-larvae m^{-223}. Culture duration was 119 days. Pond size was 5000m^2 each.

Pre-stocking pond preparation for monoculture of *P. monodon* included horizontal ploughing followed by application of lime ($CaCO_3$) at the rate of 300 kg ha^{-1} followed by longitudinal ploughing and application of lime ($CaCO_3$) at the rate of 200 kg ha^{-1}. After liming, ponds were filled with dechlorinated water[23] from the reservoir followed by fertilizer (Urea & Single Super Phosphate - 1:1) application at the rate of 4 ppm. Seven days after pond preparation, stocking was carried out with proper acclimatization procedure. To maintain plankton population in the eco-system, periodic liming and fertilization was carried out. Pond aeration (4-8 hours) mainly in the evening hours, using four 1-hp paddle wheel aerators per pond was a regular practice, after 60 days of culture (DOC). Recommended stocking density of 100,000 Post-Larvae (PL_{22}) of *P. monodon* ha^{-1} were maintained[24]. Management practices and inputs were same for all treatments and replications.

Recommended minimum water depth[24] of 1.0 m for monoculture of *P.monodon* was maintained for each treatment. Required depth was maintained on weekly basis either adding or withdrawing water from the experimental ponds. Major physico-chemical parameters of pond water, e.g., Temperature, pH, Dissolved oxygen (DO) and transparency were recorded daily during 0700-0800 hours and 1500-1600 hours using a Multi-parameter Water Analyzer (YK-611, Yeo-Kal Electronics Pty. Ltd., Australia). Total alkalinity, total suspended solids, dissolved organic matter and CO_2 were monitored *in-situ* every week between 0700-0800 hours and 1500-1600 hours using standard methods[25-26]. Salinity was measured daily using a refractometer (ATAGO S-10, Japan). NH_4^+ was determined spectrophotometically with the indophenol blue method, while chlorophyll-*a* was determined using the acetone extraction method[27]. Primary productivity was analyzed using the "Oxygen method"[25], while nutrient analysis following standard methods[26]. The shrimp pond water quality suitability index (WQSI) that expresses the overall water quality in a given place and time based on different hydro-biochemical variables were calculated[22].Plankton samples were collected at fortnightly intervals by filtering 50 l of pond water through a silk net (No. 25, mesh size 64 µm), preserved in 4% formaldehyde and later analyzed for quantitative estimation.

Surface sediment samples were collected twice from the pond during the crop period (i.e. before stocking and after harvesting) and analyzed for pH, available nitrogen[28], available phosphorus[29] and organic carbon[30]. Estimation of sedimentation rate (m^3 m^{-2} $crop^{-1}$) and sediment load (m^3 t^{-1} biomass) was carried out[1].

High-energy (38% protein and 5% fat) supplemental feed (NOVO feed of C.P. Group, Thailand) was used during the experimental periods. The adopted site-specific feeding schedule[22] and feeding management[1]was mainly for proper utilization of feed, minimal wastage and better growth of shrimp. Feed adjustment was carried out after observing the meal to meal check tray feeding performance, average body weight and weather condition. Keeping the size of pond and position of aerator in view, four check trays per pond were used[31]. During the feeding phase, feeding frequency of four times a day was adopted throughout the experimental periods. Daily feed quantity was estimated based on feed percentage starting from 60.0% to 2.0% was followed for mean body weight (MBW) of shrimp starting from 0.02g (at the time of stocking, Day-1) to 35.0g size, respectively.Similarly, lift net % (2.4-4.2) and time control (2.5 h-1.0 h) to monitor the daily check tray feeding performance was followed for mean body weight (MBW) of 0.02-35.0g, respectively. To study the food preference and feed intake pattern, gut content analysis, average percentage of individual gut content volume (frequency) and percentage of analyzed sample in which different food components were found (abundance) were carried out[32]. Daily feed requirement, % feed used, amount of check tray feed, and feed increment per day was estimated using formulas[31]. Apparent feed conversion ratio (AFCR) and feeding efficiency (FE) was estimated as follows:

AFCR = Total feed used in kg / Net biomass gain in kg ……………………..……….…..……..(1)
FE = Biomass gain in kg / feed used in kg × 100 ……………….…………..………….……. (2)

Weekly growth study was carried out by sampling prior to feeding, so that complete evacuation of gut was ensured. Weekly mean body weight (MBW in g), mean total length (cm), condition factor (Kn), average daily growth or per day increment (PDI in g), absolute growth (g), survival rate (SR%), and biomass (kg) was estimated using formulas[31]. Other growth parameters such as performance index (PI), production-size index (PSI) and specific growth rate (SGR, in % d^{-1}) were estimated as follows:

PI = Per day increment (PDI in g) × Survival rate in % ………..……………………..…..……..(3)
PSI = Production in kg ha^{-1} × MBW in g / 1000 ….…………………………………………..(4)
SGR = ln final weight - ln initial weight / Days of culture (DOC) ×100 ……………..………..(5)

Quantification of compensatory growth (CG) was estimated[7]using the compensatory growth index (CGI = A–B / A * 100). This was calculated as the ratio of the difference between weight variation at the end of restricted (A) and compensatory growth periods (B), respectively, relative to the variation at the end of the restricted growth alone[7]. Generally, among different species the index value range between 50 and 100%. A value of 100% indicates full recovery or compensation.

To evaluate the efficiency of water management, the gross total water productivity (GTWP), net total water productivity (NTWP) and net consumptive water productivity (NCWP) was calculated (USD m^{-3}) keeping the total volume of water used in to account[22]. The ratio of the output value to the cost of cultivation (OV-CC ratio) was estimated. The cost of excavated pond, considering the life span up to 15 years, which is a fixed cost, was added (depreciated cost) to the yearly variable cost of cultivation. The cost of excavated pond was estimated to be \$3000 ha^{-1}. The operational cost mainly includes: the cost of feed (\$ 0.7 kg^{-1}), shrimp seed (\$ 0.01 PL^{-1}), labour (\$ 2.7 man day^{-1}), lime (\$0.17 kg^{-1}), diesel (\$ 0.9 l^{-1}), and fertilizer (\$ 0.2 kg^{-1}). Similarly, the on-site selling price of *P. monodon*was \$ 5.7 kg^{-1} respectively.

Since the experiment was conducted at a particular location without much difference in the physico-chemical and microclimatic characteristics indicating homogeneity among the replications, the one-way analysis of variance (ANOVA) was carried out using the SAS, Version 9[33]. The significant ($P < 0.05$) differences of all possible pairs of the treatment means, using the Duncan's multiple range test[34], have been discussed.

Results

Treatment-wise variations in the water and sediment quality parameters in mono-culture of *P. monodon* under different feed management protocols are presented in Table 1. In most cases, higher values of dissolved organic matter, total suspended solids, chlorophyll-a, nitrite, nitrate, ammonia and total alkalinity were recorded towards the later part of the experiment. At any given point in time, except the total alkalinity and total suspended solids, the remaining water quality parameters and plankton population did not register any specific trend significantly ($P<0.05$) between the treatments. Diatoms and green algae mainly dominated the phytoplankton population while the zooplankton population was dominated by copepods and rotifers. Under different feed management treatments, average primary production in the first month of rearing ranged between 91.7 to 138 mg C m^{-3} h^{-1}, which improved further (341.5 $\underline{+}$41.3 mg C m^{-3} h^{-1}) with the advancement of rearing period. In this experiment, fluctuating trends in plankton density (3.6 x 10^{4} to 4.6 x 10^{4}) were recorded in different treatments (Table 1), which ultimately reflected the overall water quality and production performance (Table 1 and 2).

Table 1- Treatment-wise variations in the water and sediment quality parameters under varied feeding management protocols in monoculture of *P.monodon*

Parameters	T_1	T_2	T_3
Water quality parameters			
Water pH	7.22±0.11^{b}	7.54 ±0.13^{a}	7.41 ±0.17^{ab}
Dissolved Oxygen (ppm)	4.9 ±1.2^{b}	6.1 ±0.7^{a}	5.2 ±1.1^{b}
Salinity (psu)	17.4 ±2.1^{b}	19.1 ±1.8^{a}	17.6 ±1.9^{b}
Temperature (^{0}C)	28.7 ±0.6^{a}	28.5 ±0.3^{a}	28.6 ±0.5^{a}
Total alkalinity (ppm)	96 ±8^{c}	118 ±7^{a}	106 ±10^{b}
Dissolved Organic Matter (ppm)	4.9 ±0.2^{a}	3.7 ±0.4^{b}	3.8 ±0.3^{b}
Total Suspended Solids (ppm)	241 ±13^{a}	192 ±13^{c}	224 ±11^{b}
NH_4^+ (ppm)	0.6 ±0.03^{b}	0.7 ±0.03^{a}	0.67 ± 0.02^{ab}
Chlorophyll-a (mg m^{-3})	44.3 ±5.3^{a}	37.7 ±4.2^{b}	43.1 ±3.2^{a}
Total plankton (nos. l^{-1})	4.6x10^{4} ±1.4x10^{3a}	3.8x10^{4} ±1.1x10^{3b}	3.6x10^{4}± 1.3x10$^{3\,b}$
Nitrite – N (ppm)	0.04 ±0.00^{a}	0.04 ±0.01^{a}	0.03 ±0.01^{a}
Nitrate – N(ppm)	0.37 ±0.07^{a}	0.37 ±0.06^{a}	0.36 ±0.09^{a}
Phosphate–P (ppm)	0.25 ±0.04^{a}	0.21 ±0.03^{b}	0.2 ± 0.04^{b}
Sediment quality parameters			
Available-N (mg 100 g^{-1})	22.6 ± 0.2^{a}	21.1 ± 0.3^{c}	21.8 ± 0.2^{b}
Available-P (mg 100 g^{-1})	2.21 ±0.06^{a}	2.23 ±0.07^{a}	2.11 ± 0.07^{b}
Organic carbon (%)	0.65 ±0.01^{a}	0.66 ±0.01^{a}	0.62 ± 0.01^{b}
Soil pH	6.97 ±0.07^{a}	7.01 ±0.08^{a}	7.04 ± 0.09^{a}

All values are mean ± SD. Values with different superscripts in a row differ significantly (*P*<0.05).

The recorded minimum and maximum range of average total alkalinity was 96 ppm to 118 ppm under different treatments. The shrimp pond water quality suitability index (WQSI) up to 90 DOC, range between 7.5-9.0 in T_2 was very good, needs little management while in the last month of rearing it was good with moderate management requirements (Fig. 1 and 2). Higher the feed input lower was the WQSI as in the case of T_1 followed by T_3. The estimated TWU (total water use) was 2.52, 2.44 and 2.41 ha-m in T_1, T_2 and T_3, respectively.

Table 2 - Growth and production performance of *P. monodon* under different feeding management protocols

Parameters	T_1	T_2	T_3
MBW (g)	27.56±0.25^{b}	27.43±0.37^{b}	29.1±0.17^{a}
PDI (g)	0.23±0^{a}	0.23±0^{a}	0.24±0^{a}
SGR (% d^{-1})	6.07±0.005^{b}	6.07±0.011^{b}	6.12±0.005^{a}
SR %	78.76±4.36^{a}	79.5±2.94^{a}	79.13±3.1^{a}
Yield (t ha^{-1})	2.17±0.13^{a}	2.18±0.085^{a}	2.30±0.078^{a}
PI	18.11±1.00^{a}	18.29±0.68^{a}	18.99±0.74^{a}
PSI	59.86±3.95^{a}	59.83±2.74^{a}	66.96±1.97^{a}
AFCR	1.47±0.04^{a}	1.36±0.02^{b} (7.5%)	1.39±0.02^{b} (5.5%)
FE (%)	67.7±1.86^{b}	73.5±1.41^{a}	71.56±1.44^{a}

All values are mean ± SD. Values with different superscripts in a row differ significantly (*P*<0.05). Initial MBW= 0.02g. Figures in parenthesis indicate percentage saves in total feed. Days of culture=119d.

Soils of the experimental ponds were clay, having an acidic pH (6.7-6.9). The composition of sand, silt and clay was 31.1%, 19.9%, and 49.0 %, respectively. Organic carbon (%), available N and P in soil (mg 100 g^{-1}) varied between 0.19-0.28, 7.7-9.6 and 1.05-1.23, respectively at the beginning of the experiment which was improved later (Table 1). No distinct trends between the treatments were observed. Under different feeding management protocols, treatment-wise sediment load ranged between 48.3-55.7 m^{3} t^{-1} biomass in monoculture of *P.monodon*. Higher the AFCR, higher was the sedimentation rate (Table 3) as in the case of T_1 followed by T_3 and T_2.

Table 3- Treatment-wise sediment load (dry volume) under different feeding management protocols

Treatment	Yield, (t ha^{-1})	AFCR	Sedimentation rate, m^{3} m^{-2} crop^{-1}	Sediment load, m^{3} t $^{-1}$ biomass
T_1	2.17± 0.13^{a}	1.47± 0.04^{a}	0.012± 0.001^{a}	55.7^{a}
T_2	2.18± 0.08^{a}	1.36± 0.02^{b}	0.01± 0.0006^{a}	47.2^{b}
T_3	2.30± 0.07^{a}	1.39± 0.0^{b}	0.011± 0.003^{a}	48.3^{b}

Values are mean ± SD. Values with different superscripts in a column differ significantly (*P*<0.05).

Table 4- Average % of individual gut content volume (abundance) and % of analyzed *P.monodon* in which mentioned food components were found (frequency)

Food component	Abundance (%)		Frequency (%)	
	F	FR	F	FR
Supplemental feed	>61	-	94	-
Phytoplankton	<2	<6	56	83
Zooplankton	<2	<2	44	72
Detritus+Mud	<15	>62	72	100
Benthos	<8	<11	61	83

F- during feeding phase, FR - during feed restriction phase; > more than; < less than

Table 5- Treatment-wise GTWP, NTWP and NCWP under different feeding management protocols

Treatment	GTWP (USD m^{-3})	NTWP (USD m^{-3})	NCWP (USD m^{-3})
T1	0.49	0.22	0.34
T2	0.51	0.26	0.42
T3	0.56	0.29	0.48

1 USD = 55 INR during the experimental period. GTWP- gross total water productivity, NTWP- net total water productivity, NCWP- net consumptive water productivity.

During the experiment, at a fixed population density, higher growth rate was recorded in T_3 (Table 2). Among different feed management protocols, overall crop performance was similar in both T_1 and T_2 (Table 2). Among T_2 and T_3, there was no significant ($P<0.05$) variation in overall crop performance except in SGR and MBW (Table 2). Longer re-feeding periods after cyclic food deprivation successfully triggered compensatory growth response in T_3 (CGI, 98-105%) followed by shorter re-feeding period in T_2 (CGI, 89-96%). It was also recorded that longer the re-feeding period, higher was the growth performance [MBW (29.1g), PDI (0.24g), SGR (6.12 %d^{-1}), PI (18.99), PSI (66.96) and yield (2.3 t ha^{-1})] as in the case of T_3 (Table 2). However, cyclic food deprivation and re-feeding (T_2& T_3) showed no significant impact on the survival rate, but significantly enhanced ($P<0.05$) the feed efficiency of the cultured species as well as the apparent feed conversion ratio. Shorter the duration of re-feeding higher was the FE (73.5%) and lower was the AFCR (1.36) in $T_2$and similar trend was followed by T_3 and T_1. Condition factor (Ponderal index) of *P. monodon* was less than 1.0 (0.87-0.98) at the initial three weeks of rearing and improved thereafter (1.04-1.16). The gut contents analysis of *P. monodon* infers that supplemental feed was most preferred food item during the feeding phase while mud and detritus was highly preferred during the feed restriction phase followed by benthos and phytoplankton (Table 4). Food preference did not change with time of the day. Up to 6th week, most feeding activity occurred at night, later, feeding activity shifted to day-time. Present study also showed poor feed consumption during night times (last meal of the day), when dissolved oxygen, pH and temperature was low.

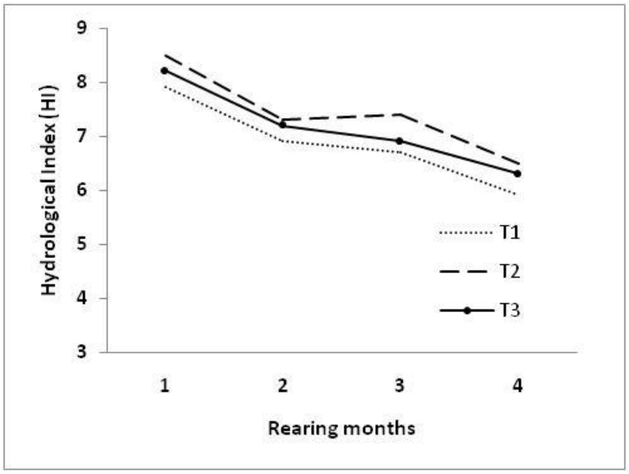

Fig. 1- Month-wise water quality suitability index (WQSI) under different feed management treatments in *P. monodon* culture.

In this experiment, treatment-wise gross total water productivity (GTWP), net total water productivity (NTWP) and net consumptive water productivity (NCWP) in monoculture of *P. monodon* are presented in Table 5. Cyclic food deprivation with longer re-feeding protocol (T_3) performed well (higher NTWP and NCWP) against the shorter re-feeding protocol (T_2) and regular feeding protocol (T_1). Higher OV-CC ratio, also infers that cyclic food deprivation with longer refeeding protocol outclass the regular feeding protocol (Table 6).

Table 6. Treatment-wise ratio of the output value (OV) to the cost of cultivation (CC).

Treatment	OV (\$ ha^{-1})	CC (\$ ha^{-1})	Net return (\$ ha^{-1})	OV-CC ratio
T1	12399^{b}	6971.7^{a}	5427.3^{c}	1.78^{b}
T2	12526^{b}	6239.8^{b}	6286.2^{b}	2.01^{a}
T3	13371^{a}	6344.4^{b}	7026.6^{a}	2.11^{a}

1 USD = 55 INR during the experimental period. The farm gate selling prices of *P.monodon* was INR 285.00 kg^{-1} respectively.Values with different superscripts in a column differ significantly ($P<0.05$).

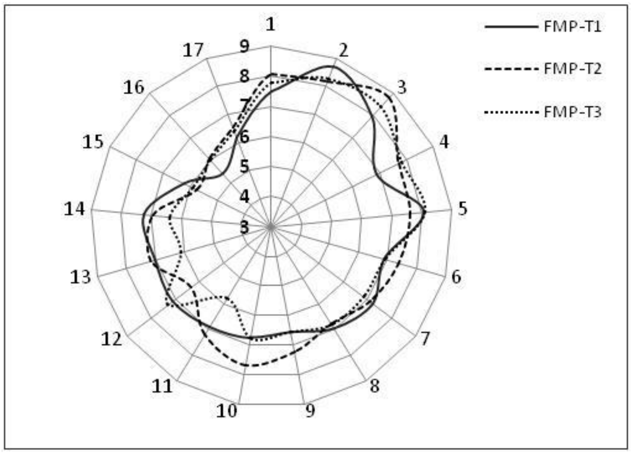

Fig. 2- Weekly water quality suitability index (WQSI) under different feed management protocols (FMP) in monoculture of *P. monodon*.

Discussion

The feeding strategy used in the commercial culture of shrimp has a significant impact on pond water quality and hence growth and survival of the shrimp, as well as the efficiency of feed utilization (Table 2). In this study, various hydro-biological parameters prevailing in the different treatments were within the optimum ranges and did not fluctuate drastically, probably due to the similar levels of inputs in all the treatments in the forms of inorganic fertilizer and periodic liming. The culture of *P. monodon* in salinities closer to the iso-osmotic point (25 psu), where osmotic stress will be the lowest, would result in decreased metabolic demands and therefore increased growth[35]. In this study, average salinity however, ranges between 17.4-19.1psu. The decreasing trend in DO in all the treatments with the advancement of the shrimp rearing period, attributed to the fluctuations in plankton density and a gradual increase in biomass, resulting in higher oxygen consumption. Most warm water species require a minimum DO of 1 ppm for survival and 5 ppm for ideal growth and maintenance[36]. During the study period, necessity of water exchange was not there up to 63-DOC. Later, water exchange was carried out three times T_1 and once each in T_2 and T_3, as daily morning DO fall below 3.0 ppm. However, in this study the weekly average morning DO level did not drop below 3.7 ppm in any treatments. The stable level of dissolved oxygen in this study could be attributed to proper aeration that raised the dissolved oxygen level to allow aerobic bacteria to reduce biochemical oxygen demand and thus improve water quality. Further, higher the feed input, higher was the water exchange requirement (0.45 ha-m) and TWU (total water use) as in T_1 (2.52 ha-m). Evaporation (5.06 mm d^{-1}) and seepage losses (4.4 mm d^{-1}) contribute significantly to consumptive water use (CWU). In the present study, evaporation loss range between 2.6-2.8 m^3 water kg^{-1} productions in brackish water monoculture of *P. monodon*.

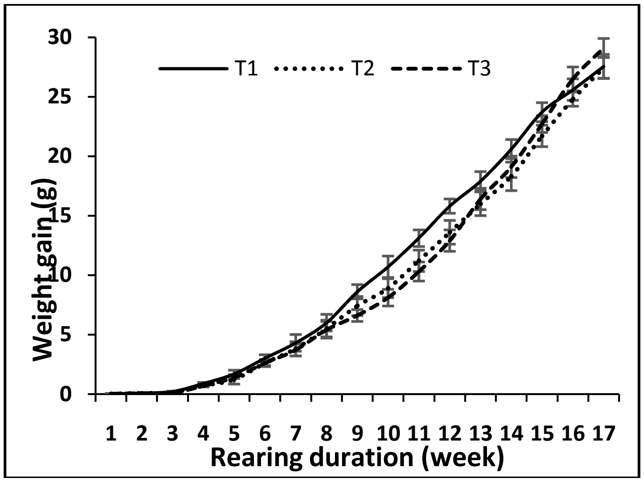

Fig. 3- Growth performance of *P. monodon* under different feed management protocols (FMP).

Cyclic food deprivation and re-feeding also helped in maintaining water quality due to the restricted feed input (7.5% in T_2 and 5.5% in T_3), thus minimizes the input cost and improve production efficiency[18-19]. Significantly better water quality parameters ($P<0.05$) were recorded in T_2 (Table 1) where frequency of feed restriction was higher (less feed input) followed by T_3 and T_1. Apart from being an unnecessary expense, unconsumed feed contributes to the deterioration of pond water quality when subjected to microbial activity. Excess feeding can result in an increase in organic material and a decrease in DO as in T_1 followed by T_3, probably due to oxidation by bacteria and an increase in metabolic wastes[37]. The shrimp pond water quality suitability index (WQSI) that expresses the overall water quality in a given place and time (Fig.1 and 2) also infers that lower the feed input (T_2) higher is the overall suitability of water quality.

Gradual increase of organic carbon (%), available N and P in soil (mg 100 g^{-1}) towards later part of the culture was likely due to (1) a large fraction of the input nutrients that ends up in the sediment[38-39], (2) shrimp grazing on the photosynthetic aquatic biomass and other components of the system, thereby aiding in nutrient cycling[40]. No distinct trends between the treatments were observed and the sediment characteristics of the different treatments were indicative of a medium productive soil group[41].Nutrients, organic matter and suspended solids generally cause sedimentation in shrimp ponds. Sediment quality and quantity reflect pond output and play an important role in the mineralization process of organic matter, absorption and release of nutrients to water, influencing water quality and survival rate of the cultured species[1]. AFCR plays a key role in sediment loading[1.] Higher the AFCR, higher is the sedimentation load (Table 3) as in T_1 (55.7 m^3 t^{-1} biomass) followed by T_3 and T_2. Boyd and Tucker[42] reported that the pollution potential of feed-based aquaculture systems usually is much greater than that of fertilized ponds. In feed-based aquaculture, shrimp consume only 60 to 80%[43] and about 20% of feed consumed is excreted as feces. These factors along with water management protocols and duration of culture determined the treatment-wise sediment quantity, in this study.

P. monodon is a continuous-intermittent feeder. This feeding behavior dictates the feed management strategy. Among different feed management protocols, overall crop performance was similar in both T_1 and T_2 (Table 2). However, significantly ($P<0.05$) low AFCR and higher FE in T_2 over T_1, was probably due to the prevailing optimal salinity (19.1 ± 1.8psu), DO (6.1±0.7 ppm) and water pH (7.54±0.13). The optimal range of salinity (15-25psu) and water pH (7.5-8.5) plays a key role in growth, survival and yield of *P.monodon*[44]. The low AFCR value obtained in this study may be ascribed to the strict control of feeding by trays and site specific feeding schedule. Among T_2 and T_3, there was no significant ($P<0.05$) variation in overall crop performance except in SGR and MBW (Table 2). This was probably due to the longer refeeding periods after cyclic food deprivation that successfully triggered compensatory growth response (CG Index: 98-105% in T_3 and 89-96% in T_2). It was also recorded that longer the refeeding period, higher was the growth performance (MBW, PDI, SGR, PI and PSI) and yield (Table 2) as in the case of T_3. However, cyclic food deprivation and refeeding (T_2 & T_3) showed no significant impact on the survival rate, but significantly enhanced ($P<0.05$) the feed efficiency of the cultured species as well as the apparent feed conversion ratio.

Hyperphagia (an increase in appetite) or improved feed efficiency, or both[2-3] and changes in endocrine status and nutrient availability[16,45] contribute to CG. Fishes and shrimp have different responses for CG either complete or partial[7]. In the case of partial compensation as in T_2, the deprived animal was not successful in achieving the same size at the same age as non-restricted contemporaries. However, they do show increased feed efficiency (73.5±1.41), probably shrimp on the cyclic feed regimen may have better used pond resources by increasing the consumption of natural productivity. In full compensation as in T_3, the deprived animal attains the same size at the same age as non-restricted contemporaries. Usually, specific growth rate (SGR), which assumes exponential growth over the examined growth interval, is often used to estimate the rate of weight increase. If the animal from feed restricted (manipulated) groups have a higher SGR than the control group, they are said to exhibit full CG[7] as in the case of T_3 (Fig. 3). The results in the present study indicate that *P. monodon* have the ability to with stand and recover from periodic starvation after cyclic feeding periods. Similar findings were also recorded for *Fenneropenaeus chinensis*[46] and *P. semisulcatus*[47].

In this experiment, the gut contents of *P. monodon* had supplemental feed, plant and animal materials, detrital matter, rotifers, copepod, diatoms, and green algae that contributed to the increase in shrimp growth. Supplemental feed was most preferred food item for *P. monodon,* during the feeding phase while mud and detritus was highly preferred during the feed restriction phase followed by benthos and phytoplankton (Table 4). Planktons are the richest source of protein, lipid, and essential amino acids that also act as feed supplement in enhancing the growth and survival of *P. monodon*[48] during the feed restriction phase. Food preference did not change with time of the day. Up to 6th week, most feeding activity occurred at night, later, feeding activity shifted to day-time. Reduction of the maximum gut content at dissolved oxygen levels below 4 ppm at night indicated a cessation of feeding in which case shrimp fed during the day-time, when dissolved oxygen levels were higher [49]. Poor feed consumption during night times (last meal of the day) was probably due to low DO, pH and temperature. Feed management should therefore be regulated by feed consumption and demand as shrimp appetite vary with the environmental conditions, i.e, weather, water quality, physiological conditions such as moulting, stress, disease and gut evacuation rate[1].

Aquacultural water productivity (the ratio of the net benefits from aquacultural systems to the amount of water used), reflects the objectives of producing more food, income, livelihood and ecological benefits at less social and environmental cost per unit of water consumed[50]. Further, water productivity is an index of the economic value of water used[51] and a useful indicator of efficient water management[52]. Higher water productivity not only reduces the need for additional water, but also minimizes the operational cost.Cyclic food deprivation with longer refeeding protocol (T_3) performed well (higher NTWP and NCWP) against the shorter refeeding protocol (T_2) and regular feeding protocol (T_1). Higher OV-CC ratio, also infers that cyclic food deprivation with longer refeeding protocol outclass the regular feeding protocol (Table 6). This was probably due to the excess feed input and increased cost of cultivation in T_1 and compensatory growth response of cultured species under regulated feed input and enhanced net return in T_3 (Table 6). Keeping the growth performance (Table 2), water productivity (Table 5) and economic efficiency (Table 6) in view, T_3 is considered the best feed management protocol followed by T_2 and T_1.

Conclusions

Compensatory growth has been reported in many fish and prawn species under various feeding regimes. *P. monodon* also have the ability to withstand and recover from cyclic food deprivation. Cyclic feed protocol of 4-weeks feeding followed by 1-week no feed can significantly improve the overall growth and crop performance mainly due to the longer refeeding periods that successfully triggered compensatory growth response. Minimizing feed input and taking advantage of the compensatory growth response, also perceived as a way to increase water productivity and profits in aquaculture operations. Cyclic food deprivation and refeeding also helped in maintaining water quality due to the restricted feed input, thus minimizes the input cost and improves production efficiency. The knowledge derived from this study may be a basis to optimize pond rearing efforts in shrimp culture and the feeding strategies can be tailored to minimize environmental impact of aquaculture and production costs.

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