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Water quality suitability and water use indices: Useful management tools in coastal aquaculture of *Litopenaeus vannamei*

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ABSTRACT

Attempts were made to study the effect of stocking density and water saving approach on water and sediment quality, growth and production performance of shrimp (*Litopenaeus vannamei*). The experiment was carried out with three stocking density of post-larvae i.e. 400,000 per ha (T_1), 500,000 per ha (T_2) and 600,000 per ha (T_3). Water exchange was carried out depending on water quality parameters. Water quality suitability index (WQSI) was lower at higher stocking density as was evident in T_3 followed by T_2 and T_1. A very good WQSI (7.5–9.0) was recorded up to 13th, 12th and 9th week of culture in T_1, T_2 and T_3, respectively; which was ascribed to stocking density, smaller shrimp size and less initial feed input. In *L. vannamei* culture, optimum stocking density of 50 post-larvae per m^2 (T_2) led to total water use of 3.42×10^4 m^3 and water exchange of 0.80×10^4 m^3. It was perceived as a way to improve shrimp productivity (10.31 t ha^{-1} 120 d^{-1}), consumptive water use index (1.93 m^3 kg^{-1} biomass), total water footprint (1426 m^3 t^{-1} biomass), net consumptive water productivity (USD 1.13 m^{-3}) and ratio of output value to the cost of cultivation (1.99). Further, farming systems with low to moderate water exchange as in T_2, helped maintain water quality suitable for the shrimp growth, improved water use efficiency (518 g biomass m^{-3} water), minimized quantity of sediment load (41.7 m^3 t^{-1} biomass) and effluent outputs (0.8×10^4 m^3). The knowledge derived from this study could provide the basis to optimize pond rearing efforts in shrimp culture and the water management strategies can be tailored to minimize production costs.

Statement of relevance: This paper presents findings and analysis, from a methodologically rigorous investigation and provides insight regarding density-dependent optimum water use, its effect on pond water quality, sedimentation rate, growth performance, water productivity and water footprint. The knowledge derived from this study may be a basis to optimize pond rearing efforts in shrimp culture and the water management strategies can be tailored to prevent wasteful use of water and enhance water use efficiency and water productivity.

1. Introduction

Rapid expansion of coastal shrimp aquaculture in many countries may pollute the coastal water and interest of other users. The extent of environmental impacts associated with coastal aquaculture largely depends upon the intensity and technology adopted. Due to the disposal of organic and nutrients rich shrimp pond effluent, coastal environments can suffer from oxygen depletion, reduction of transparency, changes in benthic population structure and eutrophication (Casillas-Hernández et al., 2007; Páez-Osuna, 2001). Deteriorating water quality is a major factor that affects shrimp production performance (Ferreira et al., 2011; Ma et al., 2013). As water quality affects reproduction, growth and survival of aquatic organisms (Table 1), its monitoring and assessment play an important role in controlling harmful crisis in aquaculture. In order to evaluate the water quality of aquatic systems, many countries have introduced water quality monitoring plan and even predict the occurrence of unfavorable conditions for rearing (Zampella et al., 2006; Simoes et al., 2008), thus avoiding risks of environmental damage.

There are several Water Quality Indices (WQIs) using different parameters depending on the water quality objectives for the classification of surface waters or the assessment of beneficial use (Said et al., 2004), water pollution assessment and environmental impacts assessment of aquacultural activities (Ferreira et al., 2011; Kocer and Sevgili, 2014; Ma et al., 2013). The WQI method has been widely applied to assess water quality (Hou et al., 2016; Mohanty et al., 2016; Simoes et al., 2008), that expresses the overall water quality in a given place and time based on different hydro-biochemical variables. This method allows the quantitative classification into representative classes of

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Table 1
Major water quality parameters and its importance in coastal shrimp farming.

Water quality parameter	Importance
pH	Extremely low or high pH stresses shrimp and causes soft shell and poor survival. pH in the range of 6.0 to 9.0 is suitable for optimal growth of shrimp in general (Boyd, 1990).
Salinity	High salinity reduces dissolved oxygen in water. Fluctuations in salinity and significant decrease in water alkalinity creating conditions unfavorable to the growth of marine shrimp (Atwood et al., 2003). Salinity in the range of 15 to 25 ppt is suitable for optimal growth of *L. vannamei* (Bett and Vinatea, 2009).
Water temperature	Temperature influences the metabolism of the crustacean (Allan et al., 2006), growth and survival (Guan et al., 2003), oxygen consumption and molt cycle (Guan et al., 2003), and immune response (Cheng et al., 2005). Water temperature in the range of 25 to 30 °C is suitable for optimal growth shrimp in general (Bett and Vinatea, 2009).
Dissolved oxygen	Suitable DO for growth of marine shrimp is $>$ 5.0 ppm (Cheng et al., 2003). Growth restriction and mortality occurs with values below 2.0 ppm (Páez-Osuna, 2001).
Ammonia	Ammonia increases tissue oxygen consumption, damages gills, affects growth, molt, and reduces the ability of blood to transport oxygen (Chen and Kou, 1992). $NH_3 < 1.0$ ppm is suitable for optimal growth of shrimp in general (Boyd, 1990).
Nitrate and nitrite	If the ammonia conversion to nitrate is prevented, significant concentrations of nitrite accumulate in the environment and may cause a decrease in immune ability of *L. vannamei*, leading to a higher susceptibility to infection of vibrios (Tseng and Chen, 2004). A safe level of $<$ 0.8 ppm for nitrate and $<$ 1.0 ppm for nitrite (Boyd, 1990) is recommended.
Total suspended solids	High values negatively interfere with the photosynthetic process and promote changes in the composition of aquatic community. According to Gaona et al. (2011), the recommended upper limit of total suspended material for marine shrimp is 500 mg/L.
Transparency/turbidity	Turbidity is a measure of the degree in which the water loses its transparency due to the presence of suspended particles. Transparency of 35 to 45 cm (close to 20–15 NTU) is suitable for optimal growth of marine shrimp species (Boyd, 1990)
Alkalinity	Alkalinity affects daily variation of pH in the pond, molting and growth. Alkalinity concentrations should not exceed 140 mg/l for shrimp in general (Ferreira et al., 2011).
Hydrogen sulfide	In water, hydrogen sulfide in unionized (H_2S) form is considered toxic to aquatic organisms. Unionized H_2S concentration is dependent on pH, temperature and salinity, and it is mainly affected by pH. Optimal range for H_2S is below 0.1 mg/l for marine shrimp (Carbajal-Hernández et al., 2013).

conditions ranging from very poor to excellent. Thus, one can either obtain statistical comparisons between different water bodies/ponds, as well as assessments of its developmental trend over time (Ferreira et al., 2011; Ma et al., 2013).

In shrimp aquaculture, WQI is used to transform large amounts of water quality data into a single number and provide a whole interpretation of the behavior of the water quality parameters (Carbajal-Hernández et al., 2013). Apart from water quality monitoring and assessment using WQI, aquaculture water management also aims at quantification and minimization of water use in coastal shrimp culture. The future development of shrimp farming requires responsible practices to improve operational efficiency and help prevent wasteful use of water, effluent discharge and environmental degradation of coastal ecosystems through water use minimization. Water budgeting and density-dependent water use are therefore, two major requirements in improving coastal aquaculture performance (Mohanty et al., 2014a) mainly of the penaeid shrimp, the fastest growing aquaculture sector.

Shrimp farming plays an important role in the economic development of many countries because of the high economic returns. Shrimp farming was synonymous with the mono culture of black tiger shrimp, *Penaeus monodon* in India, till 2009. Commercial producers mainly adopt semi-intensive shrimp culture in the coastal belt of India including Odisha. However, wasteful use of water through exchange and large-scale effluent discharge resulted in increased operational cost and environmental degradation. Further, during the last few years, white spot disease (WSD) caused large-scale mortalities, leading to massive economic losses. So the farmers were seriously looking for alternative species for culture and gradually shifted to *Litopenaeus vannamei*, commonly known as the Pacific white shrimp (FAO, 2012). Since 2009–10, *L. vannamei* production from brackish water ponds in India has shown steady increase and reached the present peak of 4.06 lakh MT (metric tonnes) during 2015–16, increasing the overall shrimp production to about 5 lakh MT (MPEDA, 2017). Usually, majority farmers in India practice commercial aquaculture of *L. vannamei* in earthen brackish water ponds of 0.4–1.0 ha with a stocking density of 35–60 post-larvae m^{-2} and average production of 6.5–9.5 t ha^{-1} in 100–110 days of culture (Balakrishnan et al., 2011; Ravuru and Mude, 2014).

Although several studies have also been conducted on the growth (Bett and Vinatea, 2009; Sookying and Allen, 2011), water quality (Ray et al., 2011; Ma et al., 2013; Brito et al., 2014), feeding management (Carvajal-Valdes et al., 2012; Patnaik and Samocha, 2009) and rearing density (Schveitzer et al., 2013; Ravuru and Mude, 2014; Casillas-Hernández et al., 2007; Sookying and Allen, 2011) of *L. vannamei*, no study has been reported so far on density-dependent water use in grow-out culture of this species. Keeping in view the importance of water budgeting for development of best management protocols, the broad objective of this study was to assess the effect of various shrimp (*L. vannamei*) densities on water and sediment quality, growth and production performance. Moreover, we investigated different aspects of water budgeting to quantify total water requirement (TWR), consumptive water use (CWU) and consumptive water use index (CWUI) through hydrological water balance study to minimize wasteful use of water, production cost and enhancing the water productivity and water footprint.

2. Material and methods

2.1. Pre-stocking pond preparation and management

This study was carried out at Balasore district (21° 28′ 44″ N, 87° 02′ 15″ E), Odisha, India, during 2015–2017. In this experiment, “stocking density of *L. vannamei*” was taken as treatment [T_1: 400,000 post-larvae (PL_{20}) ha^{-1}, T_2: 500,000 PL_{20} ha^{-1}, T_3: 600,000 PL_{20} ha^{-1}] in randomized block design with three replications. Management practices and inputs were similar for all the treatments and replications. Three crops (one crop in a year) were undertaken during the experimental period. This study was conducted only in brackish water. Culture duration of each crop was 120 days. Size of each earthen pond was 5000 m^2. Water exchange (WE) was carried out depending on water quality variables (if the daily variation in average water pH $>$ 1.0 or if dissolved oxygen $<$ 3.0 ppm or if water quality suitability index (WQSI) $\leq$ 5.5). The quantity of WE was decided on the basis of kg·shrimp $m^{-2} \times (100 \times \text{EF})$, where EF = exchange factor i.e., 0.15–0.25 for stocking density of 40–60 $PL_{20–22}$ m^{-2}. Pre-stocking pond preparation included longitudinal ploughing (length-wise) followed by application of lime ($CaCO_3$) at the rate of 400 kg ha^{-1} followed by horizontal ploughing (cross ploughing, width-wise) and application of lime at the rate of 200 kg ha^{-1}. After liming, pond was filled with dechlorinated reservoir water followed by combined fertilizer application (Urea:Single Super Phosphate: 1:1) at the rate of 4 ppm. Two weeks after pond preparation, stocking operation was carried out. Stocking was carried out with proper acclimatization procedure (Mohanty, 1999), during the early morning hours. To maintain plankton density in the pond eco-system, periodic liming and fertilization was carried out. Ten hours aeration in a day up to 50 days of culture (50-DOC), 14 h per day aeration during 51–90 DOC and 18 h per day aeration thereafter till harvesting (91–120 DOC), using four 2-hp paddle wheel aerators per pond, was a regular practice.

2.2. *Environmental variables and water budgeting*

Water depth of 1.2 m was maintained for monoculture of *L. vannamei* up to 30-DOC and 1.5 m thereafter till harvesting (31–120 DOC) in each pond. Prerequisite depth was maintained on weekly basis either adding or withdrawing water from the ponds. Water temperature, pH, dissolved oxygen (DO) and transparency were recorded in-situ daily between 0700–0800 h and 1500–1600 h using a Multi-parameter Water Analyzer (YK-611, Yeo-Kal Electronics Pty. Ltd., Australia). Daily salinity level was measured using ATAGO S-10 refractometer, Japan. Other major physico-chemical parameters e.g., total alkalinity, total suspended solids, dissolved organic matter and CO_2 were monitored weekly, using standard methods (APHA, 1995). Ammonium (NH_4^+) was determined spectrophotometrically using the indophenol blue method, while chlorophyll-*a* was determined using the acetone extraction method (Strickland and Parsons, 1972). Primary productivity using the "Oxygen method" and nutrient analysis following standard methods (APHA, 1995) were carried out. Collection of plankton samples at fortnightly intervals by filtering 50 L of pond water through a silk net (No. 25, mesh size 64 μm) was carried out, preserved in 4% formaldehyde and later analyzed for qualitative and quantitative estimation (Dash and Pattanaik, 1994).

Water quality suitability index (WQSI) was estimated to evaluate the suitability of water quality for shrimp culture in ponds. Four critical water quality variables were chosen and weighted: salinity, turbidity, pH, and DO. The allocation of weights (from 1 to 5) was based on Analytical Hierarchy Process (Saaty and Vargas, 2001). Salinity received a greater weight as it is indispensable to shrimp culture. In opposite, turbidity, pH and DO got the smaller weights because they can be easily corrected during pond management. Once the variable weight (VW) and the variable weight range (WR) are defined (Table 2), VW is multiplied by WR to obtain the score of the variable for each sampling station (SVS)/pond (Eq. (1)). The final score of the sampling station (FSS) or pond is obtained by multiplying the score of each of the four variables (Eq. (2)).

Table 2
Range set classification for the selected variables and their weights to estimate water quality suitability index (WQSI) and classes of suitability for *L. vannamei* farming.

Weight range	Salinity (PSU)	Turbidity (NTU)	pH	DO (ppm)
5	30	< 10	8.0	> 7.0
4–5	20–30 or 30–35	10–20	7.5–8.0 or 8.0–8.5	6.0–7.0
3–4	15–20 or 35–40	20–35	7.0–7.5 or 8.5–9.0	5.0–6.0
2–3	10–15 or 40–45	35–60	6.5–7.0 or 9.0–9.5	4.0–5.0
1–2	5–10 or 45–50	60–100	6.0–6.5 or 9.5–10	3.0–4.0
0–1	0–5	100–150	5.5–6.0 or 10–10.5	2.0–3.0
Variable weight	*5*	*3*	*2*	*1*

WQSI range and classes of suitability (source: Beltrame et al., 2006): > 9.0 - suitable without restriction (excellent water quality), 7.5 to 9.0 - suitable with low restriction (very good, needs little management), 5.5 to 7.5 - suitable with medium restriction (good, needs moderate management), 3.0 to 5.5 - suitable with high restriction (acceptable, needs intensified management approach), < 3.0 - unsuitable (unacceptable). PSU (Practical Salinity Unit, ‰ or g kg^{-1}); NTU (Nephelometric Turbidity Unit).

$$\mathrm{SVS_{var}} = \mathrm{VW_{var}} \times \mathrm{WR_{var}} \tag{1}$$

$$\mathrm{FSS} = \mathrm{SVS_{salinity}} \times \mathrm{SVS_{pH}} \times \mathrm{SVS_{turbidity}} \times \mathrm{SVS_{dissolved\ oxygen}} \tag{2}$$

Applying the Eqs. (1) and (2), the FSS may vary between 0.0 and 18,750. To facilitate the understanding of the index, these values were recalculated to values from 0 to 10 as follows (Ferreira et al., 2011):

$$\mathrm{WQSI} = 0.8546 \times (\mathrm{FSS})^{0.25} \tag{3}$$

WQSI values were grouped into 5 classes of suitability for shrimp farming (Table 2) as suggested by Beltrame et al. (2006) and Ferreira et al. (2011).

To make precise estimates of water use in ponds, hydrological water balance equation, inflow = outflow ± change in volume (ΔV), was used. Water use in aquaculture may be categorized as either total water use (TWU) or consumptive water use (CWU). TWU (probable inflows to ponds) = initial water filling (W_f) + management additions or regulated inflows (I) + precipitation (P) + runoff (R). CWU (possible outflows) = intentional discharge or regulated discharge (D) + overflow (O_f) + evaporation (E) + seepage (S_o) + transpiration (T) + water content in the harvested biomass (W_b). The difference between the total and consumptive water use, refers to non-consumptive water use (NWU). Commercial shrimp ponds rarely receive direct inflow from streams/creeks. Further, aquatic weeds are disallowed from growing in and around edges of ponds and water is rarely used for activities other than aquaculture. Therefore, creek inflow, and transpiration are seldom major factors. As embankment shrimp ponds are small watersheds, runoff is therefore, negligible and groundwater inflow is also seldom a factor (Boyd and Gross, 2000). Water content in the harvested biomass which is a negligible amount (about 0.75 $m^3\ t^{-1}$, Boyd et al., 2007) that can be ignored. Thus the appropriate water balance equation is:

$$P + I = E + S_o + O_f + D \pm \Delta V \tag{4}$$

Details of water balance study such as estimation of seepage and evaporation loss, regulated outflow, regulated inflow has been described in Mohanty et al. (2014b) and Mohanty (2015). The consumptive water use index (CWUI) that specifies the amount of water used per unit shrimp production was estimated as shown below:

$$\mathrm{CWUI} = \mathrm{CWU}\ (m^3)/\mathrm{shrimp\ production\ (kg)} \tag{5}$$

2.3. *Pond sediment quality and quantity*

During each crop period, surface sediment samples up to a depth of 3 cm from the pond bottom were collected twice (before stocking and after harvesting), using a spatula and analyzed for available organic carbon (Walkley and Black, 1934), nitrogen (De, 1962), phosphorus (Troug, 1930) and pH. Estimation of sedimentation rate ($m^3\ m^{-2}$ $crop^{-1}$) and sediment load ($m^3\ t^{-1}$ biomass) was carried out as described by Mohanty (2001).

2.4. *Feed and feeding management*

Artificial high-energy supplemental feed (MANAMEI feed, Avanti feeds Ltd., India) was used throughout the experimental period. Protein, fat, fiber and moisture content of the feed were 35, 5, 4 and 11%, respectively. For proper utilization of feed, minimal wastage and better growth of shrimp, site-specific feeding schedule (Table 3) was adopted. Feed supply was regulated after observing the check tray feeding performance, time control in relation to shrimp weight, and prevailing weather condition (Mohanty, 2001). Keeping in view the size of pond and position of aerator, four check trays (1.0 m × 1.0 m) per pond were used. Feeding frequency of four times a day was

Table 3
Feeding programme for monoculture of *L. vannamei*.

(A) Blind feeding programme (initial 30 days)

DOC (days of culture)	Feed increase/day/ 100,000 PL	Feed/day/100,000 PL	Feed type
1	–	1.2 kg	Crumble-1
2–10	200 g	1.4–3.0 kg	Crumble-1 & 2
11–20	250 g	3.25–5.5 kg	Crumble-2
21–30	300 g	5.8–8.5 kg	Crumble-2 & 3

(B) Detailed feeding programme

MBW (g)	% feed	Feed type/code	Feeding frequency	% lift net	Time control
0.02–2.2	60.0–8.0	Crumble-1,2 & 3	4	2.4–2.5	3.0 h
2.3–5.0	7.0–4.5	Crumble-3 & Pellet-3P	4	2.5–2.6	3.0 h
5.0–7.5	4.5–3.5	Pellet-3P & Pellet-3S	4	2.6–2.9	2.5 h
7.5–12.5	3.5–2.8	Pellet-3S & Pellet-3M	4	2.9–3.3	2.0 h
12.5–18.0	2.8–2.4	Pellet-3M	4	3.3–3.7	2.0 h
18.0–20.0	2.4–2.0	Pellet-3M & Pellet-3L	4	3.7–3.9	1.5 h
20.0–26.5	2.0–1.9	Pellet-3L	4	3.9–4.0	1.5 h
26.5–30.0	1.9–1.8	Pellet-3L	4	4.0–4.2	1.0 h

N.B.: from 25th day, check trays are immersed in to the ponds with some amount of feed for every meal up to 30th day, so that baby shrimps are made to learn their check tray feeding habit. From 31st day onwards till harvesting, meal to meal feed adjustment is done on the basis of check tray feed consumption. PL: post-larvae; MBW: mean body weight.

implemented throughout the experimental periods. Feeding performance was monitored based on the mean body weight (MBW) of shrimp, starting from 0.02 to 30.0 g. Initially feed percentage was maintained at 60% when the body weight was 0.02 g, and gradually reduced to 1.8% at 30 g MBW; accordingly, lift net percentage was raised from 2.4 to 4.2, and time control was reduced from 3.0 h to 1.0 h to monitor the check tray. Daily feed requirement, % feed used, amount of check tray feed, and feed increment per day was estimated using formulas as described by Mohanty (1999). Apparent feed conversion ratio (AFCR) and feeding efficiency (FE) was estimated as described by Mohanty (2015). Waste production ratio (WPR), which is the ratio of waste to live weight production of the culture species and dry matter ratio (DMR) which is an indicator of the efficiency with which nutrients in feed are converted to animal biomass were estimated as follows:

$$\mathrm{WPR} = (\mathrm{DMR} - 1) \times \%\mathrm{DM\ in\ culture\ species}/100 \qquad (6)$$

$$\mathrm{DMR} = \mathrm{FCR} \times \%\mathrm{DM\ in\ feed}/\%\mathrm{DM\ in\ culture\ species} \qquad (7)$$

Dry matter (DM) estimation was carried out using standard procedure (Mohanty et al. 2014). The estimated DM of feed and *L. vannamei* was 89 and 25.5%, respectively.

2.5. *Growth and yield parameters*

Weekly growth study of *L. vannamei* was carried out by cast net sampling prior to feeding, so that complete evacuation of gut was ensured. Weekly MBW in g, mean total length (cm), average daily growth or per day increment (PDI in g), absolute growth (g), survival rate (%), and biomass gain (kg) was estimated using formulas as described by Mohanty (1999). Other growth parameters such as performance index (PI), specific growth rate (SGR, in % d^{-1}) and production-size index (PSI) were estimated as described by Mohanty (2015).

2.6. *Water productivity, water footprint and economic efficiency*

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 as described by Mohanty (2015). Water footprint was expressed as $\mathrm{m}^3\,\mathrm{t}^{-1}$, i.e. cubic metre of consumptive water per tonne of shrimp produced. As per the methods described by previous researchers (Kar et al., 2016; Ercin and Hoekstra, 2014), all four components of water loss have been taken into consideration such as evaporation and/or evapotranspiration, water incorporated in harvested biomass, contaminated water, and non-returned water to the same area from where it was withdrawn. All these four losses refer to water loss to the catchment, while seepage and percolation loss are not a loss to the catchment and can be reused in the same area. Therefore, seepage and percolation loss was not included in this study for estimation of water footprint. Usually, blue (surface and groundwater) and green (precipitation) water contribute to water footprint in aquaculture. Thus the appropriate equation is:

$$\text{Total water footprint } (\mathrm{WF}_t, m^3\ t^{-1}) = D + O_f + E + W_b/E_{\mathrm{cy}} \qquad (8)$$

where, D = intentional discharge or regulated discharge (m^3), O_f = overflow or other losses (m^3), E = evaporation (m^3), W_b = water content in the harvested biomass (m^3) and E_{cy} = Economic crop yield ($\mathrm{t\ ha}^{-1}$).

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 shrimp feed (\$1.1 kg^{-1}), shrimp seed (\$0.01 PL^{-1}), labour (\$3.33 man d^{-1}), lime (\$0.25 kg^{-1}), diesel (\$0.9 l^{-1}), and fertilizer (\$0.3 kg^{-1}). Similarly, the on-site selling price of *L. vannamei* was \$4.38 kg^{-1}.

2.7. *Statistical analysis*

We used the Generalized Linear Model (GLM) for data analysis using SAS 9.2 (SAS Institute, 2002). Two multiple comparison tests, namely Duncan's Multiple Range Test (DMRT) and Tukey's test were employed to assess the differences among the treatment means at the 5% significance level (i.e., $p < 0.05$). As both the tests yielded similar results, we described the significance of means based on the DMRT comparison.

3. Results

3.1. *Environmental variables under varying intensity levels*

In shrimp monoculture of *L. vannamei* under varying intensity levels, the treatment-wise variations in water and sediment quality parameters are presented in Table 4. At any given point of time, except the total alkalinity and total suspended solids, the remaining water quality variables and plankton density did not register any specific trend between the treatments. The recorded minimum and maximum range of average total alkalinity was 101 ppm to 123 ppm under different stocking density treatments. Total plankton density (numbers l^{-1}) ranged between $4.1 \times 10^4 \pm 1.1 \times 10^3$, $3.9 \times 10^4 \pm 1.3 \times 10^3$ and $4.9 \times 10^4 \pm 1.4 \times 10^3$ in T_1, T_2 and T_3, respectively (Table 4). Out of the total plankton density, green algae and diatoms together dominated the phytoplankton population (73–79%) while the zooplankton was dominated mainly by copepods and rotifers (21–27%). Under varying intensity levels, average primary production in the first month of rearing ranged between 86.6 and 120.8 $\mathrm{mg\,C\,m}^{-3}\,\mathrm{h}^{-1}$, which improved further (168 ± 10.4 to 182.2 ± 14.6 $\mathrm{mg\,C\,m}^{-3}\,\mathrm{h}^{-1}$) towards later part of rearing period. In this study, fluctuating tendencies in plankton density ($3.9 \times 10^4 \pm 1.3 \times 10^3$ to $4.9 \times 10^4 \pm 1.4 \times 10^3$) were

Table 4
Treatment-wise variations in the water and sediment quality parameters in monoculture of *L. vannamei* under varying intensity levels.

Parameters	T_1	T_2	T_3
Water quality parameters			
Water pH	7.56 ± 0.1^a	7.43 ± 0.14^{ab}	7.24 ± 0.08^b
Dissolved oxygen (ppm)	6.0 ± 0.6^a	5.1 ± 1.0^b	4.8 ± 1.1^b
Salinity (‰)	20.1 ± 1.7^a	18.6 ± 1.8^b	18.4 ± 2.0^b
Turbidity (NTU)	21.2 ± 3.4^c	24.6 ± 2.6^b	28.8 ± 1.6^a
Temperature (°C)	28.9 ± 0.3^a	29.0 ± 0.5^a	28.9 ± 0.6^a
Total alkalinity (ppm)	123 ± 8^a	111 ± 11^b	101 ± 9^c
Dissolved organic matter (ppm)	3.9 ± 0.4^b	4.0 ± 0.3^b	5.1 ± 0.2^a
Total suspended solids (ppm)	206 ± 14^c	238 ± 12^b	255 ± 14^a
NH_4^+ water (ppm)	0.63 ± 0.03^b	0.69 ± 0.02^{ab}	0.72 ± 0.03^a
Chlorophyll-*a* (mg m^{-3})	38.9 ± 4.1^b	44.3 ± 3.1^a	45.5 ± 5.2^a
Total plankton (units l^{-1})	$4.1 \times 10^4 \pm 1.1 \times 10^{3b}$	$3.9 \times 10^4 \pm 1.3 \times 10^{3b}$	$4.9 \times 10^4 \pm 1.4 \times 10^{3a}$
Nitrite – N (ppm)	0.04 ± 0.01^a	0.03 ± 0.01^a	0.04 ± 0.00^a
Nitrate – N (ppm)	0.37 ± 0.06^a	0.36 ± 0.09^a	0.37 ± 0.07^a
Phosphate – P (ppm)	0.21 ± 0.02^b	0.2 ± 0.03^b	0.25 ± 0.03^a
Sediment quality parameters			
Available-N in soil (mg 100 g^{-1})	21.9 ± 0.3^c	22.6 ± 0.2^b	23.4 ± 0.2^a
Available-P in soil (mg 100 g^{-1})	2.26 ± 0.08^a	2.16 ± 0.08^b	2.27 ± 0.07^a
Organic carbon in soil (%)	0.68 ± 0.01^a	0.64 ± 0.01^b	0.67 ± 0.01^a
Soil pH	7.03 ± 0.07^a	7.06 ± 0.08^a	6.99 ± 0.06^a

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

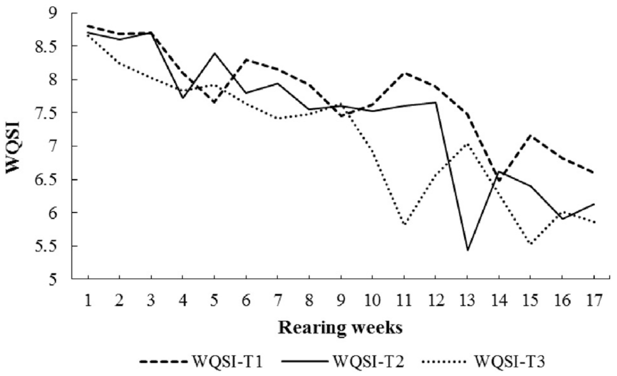

Fig. 1. Weekly water quality suitability index (WQSI) under varying intensity levels in *L. vannamei* culture [T_1: 400,000 post larvae (PL) ha^{-1}, T_2: 500,000 PL ha^{-1}, T_3: 600,000 PL ha^{-1}].

recorded in different treatments, which ultimately reflected the production performance (9.15–11.36 t ha^{-1}) and overall water quality (Table 4) in the T_1 and T_3. Lesser shrimp biomass at low density resulted in higher WQSI as in T_1 compared to higher biomass obtained in T_2 and T_3 (Fig. 1). A very good rating of WQSI (7.5–9.0) was recorded in T_1, T_2 and T_3 up to 13th, 12th and 9th week of culture respectively, thus required little management; while the rating was good (5.5–7.5) in all treatments for the rest of the period, hence required moderate management (Fig. 1). Four critical water quality parameters (pH, DO, salinity and turbidity) considered for WQSI under varying intensity levels in *L. vannamei* culture is presented in Fig. 2. Based on WQSI value close to 5.5, water exchange was carried out once in T_2 and twice in T_3 during the study period (Fig. 1).

Soils of the experimental ponds were clayey. During the experimental period, the composition of sand, silt and clay was 31.3%, 19.9%, and 48.8%, respectively. Organic carbon (%), available N and P in soil (mg 100 g^{-1}) varied between 0.38–0.46, 11.6–13.8 and 1.22–1.38, respectively at the beginning of the experiment. No distinct trends between the treatments were observed except the available-N content during the culture period (Table 4). Treatment-wise sediment load under different stocking densities, ranged between 37.1 and 51.9 $m^3 t^{-1}$ biomass (Table 5). Treatment-wise estimated WPR was 1.16, 1.26 and 1.37 while DMR was 5.58, 5.97 and 6.39 for T_1, T_2 and T_3, respectively (Table 7).

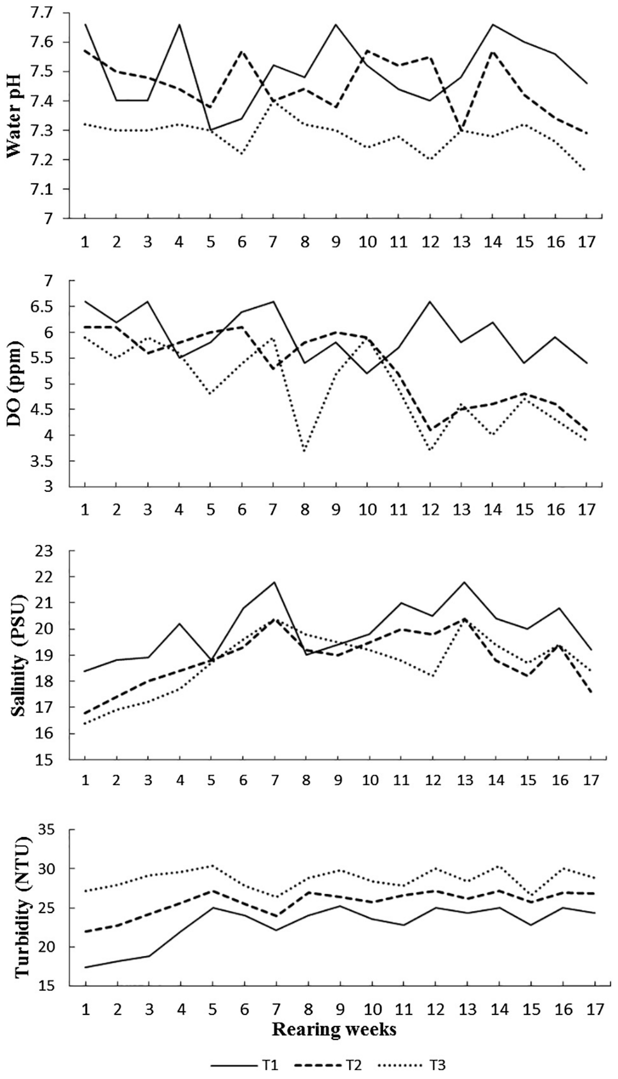

Fig. 2. Four critical water quality parameters considered for WQSI under varying intensity levels in *L. vannamei* culture [T_1: 400,000 post larvae (PL) ha^{-1}, T_2: 500,000 PL ha^{-1}, T_3: 600,000 PL ha^{-1}].

Table 5

Treatment-wise sediment load (dry volume) under varying intensity levels in monoculture of *L. vannamei*.

Treatment	Yield (t ha^{-1})	AFCR	Sedimentation $m^3\ m^{-2}\ crop^{-1}$	Sediment load, $m^3\ t^{-1}$ biomass
T_1	9.15 ± 0.14^b	1.60 ± 0.02^c	0.034 ± 0.001^b	37.1 ± 1.11^b
T_2	10.31 ± 0.09^a	1.71 ± 0.02^b	0.043 ± 0.001^b	41.7 ± 0.82^b
T_3	11.36 ± 0.12^a	1.83 ± 0.04^a	0.059 ± 0.003^a	51.9 ± 1.07^a

Values are mean ± SD. Values with different superscripts in a column differ significantly ($p < 0.05$). Days of culture: 120 d.

3.2. Water budgeting in varying intensity levels

Treatment-wise estimated total water use, TWU (m^3) or total crop water requirement ha^{-1} (culture duration-120d) was 3.13×10^4, 3.42×10^4 and $3.90 \times 10^4\ m^3$ in T_1, T_2 and T_3, respectively while, the computed consumptive water use index (CWUI, $m^3\ kg^{-1}$ biomass) was 1.90, 1.93 and 2.20 in T_1, T_2 and T_3, respectively (Table 6). Higher the amount of water exchange (1.3×10^4, m^3), higher was the TWU (3.9×10^4, m^3) as in the case of T_3. Similarly, lower the amount of water exchange (0.55×10^4, m^3), lower was the TWU (3.13×10^4, m^3) as in the case of T_1. Evaporation (0.61×10^4, m^3) and seepage losses (0.52×10^4, m^3) contributed significantly to CWU (Table 6). Average seepage loss during the crop cycle was 4.3 mm d^{-1}, while the average evaporation loss was 5.08 mm d^{-1}. The estimated evaporation and seepage loss ranged between 0.54–0.66 and 0.46–0.56 m^3 water kg^{-1} shrimp production, respectively during the crop cycles. Treatment-wise other ignored loss including the loss through biomass and over flow ranged between 0.06 and 0.07×10^4, m^3. The non-consumptive water use (NWU) or leftover water in pond amounts to 1.39×10^4–1.43×10^4, m^3 in different treatments (Table 6).

3.3. Shrimp growth and production performance

During the study, higher growth rate was recorded at lower density (Table 7) and there was no significant growth variation ($p < 0.05$) among T_2 and T_3. Although, growth performance was significantly lower ($p < 0.05$) in T_3 and T_2 than T_1 (Table 7), the yield performance was significantly high at higher density ($p < 0.05$). There was no significant yield variation ($p < 0.05$) among T_2 and T_3. Declining trend was recorded in case of PDI, SGR, PI and survival rate (Table 7) at increased stocking density. PSI was low (259.1) at lower density (T_1) and there was no significant variation ($p < 0.05$) at higher density among T_2 and T_3. In this experiment, density-dependent lower rates of water exchange in T_1 (0.55×10^4, m^3) showed improved water quality (Table 4) and growth performance (Table 7). However, yield performance was significantly higher ($p < 0.05$) at high density, with higher water exchange as in T_3 (1.3×10^4, m^3) followed by T_2 (0.8×10^4, m^3) than T_1. Although intensity of water exchange was more in T_3, significant variation ($p < 0.05$) in productivity was not recorded between T_2 and T_3. Treatment-wise average quantity of feed supplied to ponds were 7325, 8819 and 10,398 kg in T_1, T_2 and T_3, respectively. AFCR among treatments varied significantly ($p < 0.05$). Higher the density, higher was the AFCR (Table 7). Significantly higher ($p < 0.05$) FE (%) was recorded at low (61.2 in T_1) and moderate (58.5 in T_2) stocking density than the high density (T_3) with high water exchange scenario. In general, higher survival rate (80.9–80.1%) was recorded in lesser densities and there was no significant difference ($p < 0.05$) between T_1 and T_2.

Table 6

Density-dependent water use under varying intensity levels in monoculture of *L. vannamei*.

	T_1	T_2	T_3
Evaporation losses, ($\times 10^4$, m^3)	0.61 ± 0.01^a	0.61 ± 0.02^a	0.61 ± 0.02^a
Seepage losses, ($\times 10^4$, m^3)	0.52 ± 0.01^a	0.52 ± 0.01^a	0.52 ± 0.02^a
Regulated outflow, ($\times 10^4$, m^3)	0.55 ± 0.00^b	0.80 ± 0.00^{ab}	1.30 ± 0.00^a
Other losses*, ($\times 10^4$, m^3)	0.06 ± 0.00^a	0.06 ± 0.00^a	0.07 ± 0.00^a
Total loss (CWU), ($\times 10^4$, m^3)	1.74 ± 0.01^c	1.99 ± 0.02^b	2.50 ± 0.02^a
Initial water level, ($\times 10^4$, m^3)	1.39 ± 0.01^a	1.43 ± 0.01^a	1.40 ± 0.01^a
Precipitation, ($\times 10^4$, m^3)	0.49 ± 0.02^a	0.49 ± 0.01^a	0.49 ± 0.01^a
Regulated inflow, ($\times 10^4$, m^3)	1.25 ± 0.01^b	1.50 ± 0.02^b	2.01 ± 0.03^a
TWU, ($\times 10^4$, m^3)	3.13 ± 0.02^c	3.42 ± 0.03^b	3.90 ± 0.02^a
NWU, ($\times 10^4$, m^3)	1.39 ± 0.01^a	1.43 ± 0.02^a	1.40 ± 0.03^a
CWUI, $m^3\ kg^{-1}$ biomass	1.90 ± 0.01^b	1.93 ± 0.01^b	2.20 ± 0.01^a
Total water footprint (WF_t, $m^3\ t^{-1}$)	1333 ± 16.6^b	1426 ± 12.4^b	1743 ± 18.3^a

* Other loss mainly includes loss through biomass, overflow and other ignored losses. CWU: consumptive water use, TWU: total water use, NWU: non-consumptive water use (TWU-CWU), CWUI: consumptive water use index, WF_t: total water footprint. Average seepage loss was 4.3 mm d^{-1}. Average evaporation loss was 5.08 mm d^{-1}. Precipitation was 488 mm 120 d^{-1}. All values are mean ± SD. Values with different superscripts in a row differ significantly ($p < 0.05$).

3.4. Economic efficiency and water productivity

Under varying intensity levels, treatment-wise gross total water productivity (GTWP), net total water productivity (NTWP) and net consumptive water productivity (NCWP) in *L. vannamei* culture is presented in Fig. 3. Lesser water exchange (T_2) with moderate stocking density performed well (higher NTWP, NCWP and NCWP) against higher water exchange (T_3) with high stocking density and minimum water exchange (T_1) with low stocking density. Lower NTWP and NCWP in T_3 against T_2 were probably due to excess water exchange at higher density that increased the operational cost. Treatment-wise total water footprint was 1333, 1426 and 1743 $m^3\ t^{-1}$ in T_1, T_2 and T_3, respectively (Table 6). Significantly higher ($p < 0.05$) OV-CC ratio (Table 8) in T_1 (2.08) and T_2 (1.99), also infers that lesser water exchange at lower and moderate stocking density has a distinct edge over T_3 (1.8) with higher rate of water exchange.

4. Discussion

4.1. Water quality

A good water quality condition is essential for any aquaculture practice. Aquatic organisms are susceptible to stress when ecological conditions are not adequate. High stress levels generate low feeding and growth rates (Carbajal-Hernández et al., 2013). Therefore, shrimp pond water quality monitoring at regular interval, helps not only to forecast and control critical conditions for farming, but also evades risks of environmental impairment and breakage of the production process. Hydro-biological parameters prevailing in different treatments were within the optimum ranges and did not fluctuate drastically. This was probably due to the similar levels of inputs in the form of inorganic fertilizer and periodic liming and management in all the treatments. Significantly higher ($p < 0.05$) water pH, DO, total alkalinity and salinity was recorded in T_1 probably due to lesser stocking density, organic load and amount of water exchange (0.55×10^4, m^3). Low primary production in the initial phase of rearing was probably due to the fixation of nutrient ions by suspended soil/clay particles as well as rich organic matter (Mohanty et al., 2014a). Previous studies indicate that salinity has a greater influence on growth rate (Mohanty, 1999; Mohanty, 2001) of marine shrimps. Although, *L. vannamei* is known to inhabit saline water of 1–40‰ and higher, but 15–25‰ is considered as the optimal salinity for culture (Zhang et al., 2006). Water temperature and salinity are considered to be the main abiotic factors influencing oxygen consumption in aquatic animals. At 25–30 °C temperature and 13–25‰ salinities, oxygen consumption remain more stable (Bett and Vinatea, 2009). In this study, average temperature and

Table 7
Growth and production performance of *Litopenaeus vannamei* under varying intensity levels.

Parameters	T_1	T_2	T_3
Mean body weight, MBW (g)	28.3 ± 0.16^a	25.7 ± 0.19^b	24.1 ± 0.14^b
Per day increment, PDI (g)	0.24 ± 0.00^a	0.21 ± 0.00^b	0.20 ± 0.00^b
SGR (% d^{-1})	6.09 ± 0.005^a	6.02 ± 0.011^a	5.96 ± 0.005^b
Survival rate, (SR%)	80.9 ± 3.30^a	80.1 ± 2.12^a	78.7 ± 2.28^b
Yield (kg $pond^{-1}$ 120 d^{-1})	4578.3 ± 34.4^b	5157.3 ± 39.8^a	5682.3 ± 52.2^a
Productivity (t ha^{-1} 120 d^{-1})	9.15 ± 0.14^b	10.31 ± 0.09^a	11.36 ± 0.12^a
Performance index, PI	19.1 ± 0.53^a	17.1 ± 0.36^{ab}	16.00 ± 0.52^b
Production-size index, PSI	259.1 ± 3.91^b	265.8 ± 2.7^{ab}	273.5 ± 1.93^a
Apparent feed conversion ratio, AFCR	1.60 ± 0.02^c	1.71 ± 0.02^b	1.83 ± 0.04^a
Dry matter ratio, DMR	5.58 ± 0.07^c	5.97 ± 0.08^b	6.39 ± 0.08^a
Waste production ratio, WPR	1.16 ± 0.01^c	1.26 ± 0.01^b	1.37 ± 0.02^a
Feed efficiency, FE (%)	61.2 ± 1.84^a	58.5 ± 1.39^a	54.6 ± 1.42^b

All values are mean ± SD. Values with different superscripts in a row differ significantly ($p < 0.05$). Initial MBW = 0.02 g. Days of culture = 120 d. Pond size: 5000 m^2 each. Dry matter in *L. vannamei* is 25.5% and in feed is 89%.

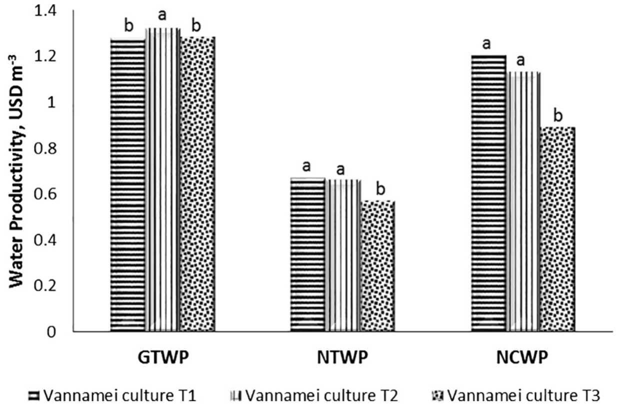

Fig. 3. Gross total water productivity (GTWP), net total water productivity (NTWP) and net consumptive water productivity (NCWP) under varying intensity levels in *L. vannamei* culture [T_1: 400,000 post larvae (PL) ha^{-1}, T_2: 500,000 PL ha^{-1}, T_3: 600,000 PL ha^{-1}]. Values with different letters (a, b, c) indicate significant ($p < 0.05$) difference among water productivity treatments.

Table 8
Ratio of the output value (OV) to the cost of cultivation (CC) under varying intensity levels in monoculture of *L. vannamei*.

Treatment	Output value (USD ha^{-1})	Cultivation cost (USD ha^{-1})	Net return (USD ha^{-1})	OV-CC ratio
T_1	40,148 ± 586^c	19,265 ± 68^c	20,883 ± 48^b	2.08 ± 0.08^a
T_2	45,222 ± 710^b	22,753 ± 76^b	22,469 ± 48^a	1.99 ± 0.05^a
T_3	49,826 ± 494^a	27,672 ± 84^a	22,154 ± 52^a	1.8 ± 0.08^b

1 USD = 65 INR during the experimental period. The farm gate selling prices of harvested *L. vannamei* was USD 4.38 kg^{-1}. Price of shrimp post-larvae (PL) and feed were USD 0.01 per PL and USD 1.1 kg^{-1} respectively. Values are mean ± SD. Values with different superscripts in a column differ significantly ($p < 0.05$). Days of culture: 120 d.

salinity however, ranged between 28.9–29.0 °C and 18.4–20.1‰, respectively (Table 4).

Dissolved oxygen is a major limiting factor in aquaculture. The bottom layer of pond waters, where shrimps spend most of their time, may become hypoxic or even anoxic due to organisms' respiration and decomposition of feed remains and feces, particularly at night time. These hypoxic conditions can certainly threaten shrimps' life. Hence, DO has often been considered an important environmental factor determining the success and intensification of shrimp culture. DO values higher than 5.0 ppm have often been recommended for intensive culture practices (Cheng et al., 2003) while, hypoxia or low DO is defined as DO < 2.8 ppm (Diaz and Rosenberg, 1995). An increase in stocking density also implies an increase in feeding because of biomass increases and consequent rises in particulate organic matter in water that helps in enhancing microorganism population. Microorganisms consume dissolved oxygen (DO) to maintain metabolic activities during the decomposition of organic matter (Avnimelech, 2009). In this sense, the aeration system must be sufficient to supply dissolved oxygen to the target species and microorganisms (De Schryver et al., 2008), which was a regular practice in this experiment. During the study period, water exchange was carried out two times as daily morning DO fell below 3.0 ppm only in T_3. However, in this study the weekly average morning DO level did not drop below 3.9 ppm in all the treatments. The stable level of dissolved oxygen in this study (4.8–6.0 ppm) 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. However, in some studies, the DO concentrations falls, especially in conditions of high concentrations of suspended solids (Ray et al., 2010; Krummenauer et al., 2011) beyond the recommended levels of 500–600 ppm (Gaona et al., 2011). In this study, low levels of total suspended solids (206–255 ppm) and dissolved organic matter (3.9–5.2 ppm) helped in maintaining stable DO level in all the treatments (Table 4).

In general, the poor growth performance of cultured species takes place at pH < 6.5, while higher values of total alkalinity (> 90 ppm) indicates a more productive ecosystem (Mohanty et al., 2016). The effects of feed on water quality and shrimp growth are important factors to be considered; more so when dealing with intensive systems. In an intensive system, feed can directly affect the suspended solids, pH, and alkalinity, requiring careful monitoring and refinement to maximize production (Furtado et al., 2011; Ray et al., 2010). In this experiment meal to meal check tray monitoring of feed helped in restricting the AFCR between 1.6 ± 0.02 and 1.83 ± 0.04 (Table 7). This also helped in maintaining optimal range of water pH (> 7.0), alkalinity (> 100 ppm) and TSS (< 500 ppm) which ultimately played a key role in growth, survival and yield of *L. vannamei* (Zhang et al., 2006; Furtado et al., 2011; Gaona et al., 2011).

Enhanced nutrient input in terms of feed affected plankton density and composition. Phytoplankton and zooplankton make excellent indicators of environmental conditions and aquatic health within ponds because they are sensitive to changes in water quality. In this experiment, fluctuating trends in plankton density (3.9×10^4 to 4.9×10^4) ultimately reflected the overall water quality and shrimp yield in different treatments (Tables 4 and 7). Chlorophyll-*a* concentration (38.9–45.5 mg m^{-3}), indicating that the system never became nutrient limiting, and thus, in turn, sustained high phytoplankton biomass (73–79%). Seemingly, dissolve nutrients together with the high light intensity, and warm temperature supported active growth of phytoplankton. The availability of CO_2 for phytoplankton growth is linked to total alkalinity (Mohanty et al., 2014a), while water having 20 ppm to 150 ppm total alkalinity produced a suitable amount of CO_2 to permit plankton production. In this study, the recorded minimum and maximum range of total alkalinity was 101 ppm to 123 ppm, which was maintained due to periodic liming. In all treatments, alkalinity levels were maintained higher than 100 ppm, which is in agreement with the recommendations reported by Furtado et al. (2011) for growing penaeid shrimp. This also helped in maintaining average CO_2 concentration of surface water (3.5 ± 0.8–4.3 ± 1.1 ppm) and bottom water (4.2 ± 0.7–5.6 ± 1.4 ppm) in the ponds during the rearing period. Bottom water contained a greater carbon dioxide concentration than surface water probably due to greater photosynthesis rate in surface water (Boyd and Tucker, 1998).

An overall suitable water quality was recorded in T_1 followed by T_2 (Table 4, Fig. 1), probably due to the lesser stocking density, feed input and lower amount of water exchange. Regulated or less water exchange also increases the hydraulic retention time (HRT) in ponds. The hydraulic retention time of static shrimp ponds usually is weeks or even months, and in ponds with water exchange, HRT usually is a week or more (Boyd et al., 2007). This allows natural processes to assimilate wastes more completely and reduces loads of potential pollutants in effluent (Boyd, 2005). WQSI (Fig. 1) also infers that high water exchange (T_3) due to increased stocking density and biomass deteriorates the overall suitability of water quality for shrimp culture. Maintenance of very good WQSI (7.5–9.0) up to 13th, 12th and 9th week of culture in T_1, T_2 and T_3, respectively might be attributed to the stocking density, smaller shrimp size and less feed input. Additionally, because of aeration and the high DO concentration, the consumption of the nutrients and organic matter by microorganisms may have accelerated the nutrient turnover in the ponds and reduced waste accumulation, thereby maintaining a better water environment. Similar findings on aeration effect on nutrient turnover and production performance have been reported for *L. vannamei* (Sookying and Allen, 2011). Subsequently, the decreased WQSI after 13th, 12th and 9th week of culture in T_1, T_2 and T_3, respectively which eventually varied between “suitable with medium restriction” was probably due to increased shrimp biomass, WPR (1.16–1.37), organic and sediment load (37.1–51.9 $m^3\ t^{-1}$ biomass). The WQSI could be used to evaluate the water quality synthetically; furthermore, it could also yield results when some or other variables deteriorate significantly. Based on these results, more attention should be given to variables under extreme conditions (Ma et al., 2013). In this study, the use of WQSI was helpful for fast and easy data interpretation, and its application in monitoring the overall water quality. This also helped in deciding the water exchange requirement (once in T_2 and twice in T_3), maintenance of overall water quality (Table 4), and productivity (9.15–11.36 $t\ ha^{-1}$) at varying intensity levels (40–60 $PL\ m^{-2}$).

4.2. Sedimentation rate and quality

Pond bottom conditions are more critical for shrimp, as they spend most of their time on the bottom soil. Aquaculture pond bottom soils are recipient of large amount of nitrogen, phosphorus and organic matter and these substances tend to accumulate in bottom soils (Gunalan et al., 2012). In this study, no distinct trends between the treatments except the available N were observed and the sediment characteristics of the different treatments were indicative of a medium productive soil group (Banerjee, 1967). The concentration of organic carbon (%), available N and P in soil (mg 100 g^{-1}) in all the treatments were gradually increased towards the later part of the culture. This was possibly due to (1) a large fraction of the input nutrients that ends up in the sediment (Boyd, 1985), (2) shrimp grazing on the photosynthetic aquatic biomass and other components of the system, thereby aiding in nutrient cycling (Mohanty et al., 2014b). Pond bottom sediment quality and quantity reflect pond output and play an important role in the mineralization process of organic matter, capture and release of nutrients to water, influencing water quality and survival rate of the cultured species (Mohanty, 2001). In this study, under varying intensity levels, significantly low ($p < 0.05$) sedimentation rate in T_1 was probably due to the lesser stocking density and feed input (Table 5). AFCR also plays a key role in sediment loading. Higher the AFCR, higher is the sedimentation rate (Table 5). A value of acceptable AFCR, contributes to maintain a pond bottom with good quality and minimizes the sediment quantity (Mohanty, 2001). Boyd and Tucker (1998) reported that the pollution potential of feed-based aquaculture systems usually is much greater than that of fertilized ponds where, shrimp bite their food, and consume only 60 to 80%. Moreover, increased levels of stocking density will require more feed inputs and thereby generates more wastes (Mohanty, 2001). These factors at varying intensity levels determined the sediment quantity of the experimental ponds, in the present study.

4.3. Water balance study

Water balance study in different stocking density infers that higher the amount of water exchange, higher is the TWU. On average, 5.2 m^3 water per kg production is consumed through evaporation from ponds (Bosma and Verdegem, 2011). However, in the present study, evaporation loss was much less, 0.54–0.66 m^3 water kg^{-1} shrimp production due to low evaporation rate of 5.08 mm d^{-1} and increased yield. The estimated low seepage loss ranged between 0.46 and 0.56 m^3 water kg^{-1} shrimp production was probably due to high clay content (48.8%) in the soil. Water use in various other shrimp production systems such as semi-intensive shrimp culture (50–100 $m^3\ kg^{-1}$) and intensive shrimp culture (20–40 $m^3\ kg^{-1}$) has already been reported by Boyd et al. (2007). Treatment-wise estimated CWUI ranged between 1.9 and 2.2 $m^3\ kg^{-1}$ biomass produced. This improvement in CWUI was probably due to demand driven regulated water exchange and increased yield. Significantly higher ($p < 0.05$) TWU, CWU and CWUI in T_3 were probably due to increased water exchange (1.3 × 10^4, m^3). Water use in ponds (Table 6) usually varies with the intensity of production, frequency and water exchange rate. Lower the water exchange rate, lower is the TWU as in case of T_1. Shrimp production typically requires TWU between 20 and 40 $m^3\ kg^{-1}$ biomass produced, where daily water exchange is a regular practice (Boyd, 2005). In this study, TWU ranged between 3.32 and 3.43 $m^3\ kg^{-1}$ biomass produced mainly due to the increased biomass, water quality monitoring using WQSI and reduced frequency of water exchange. In general, total water use varies greatly in aquaculture depending mainly upon the culture method used. After harvesting, the nutrient rich non-consumptive left-over water (NWU) from the shrimp ponds (1.39–1.43 × 10^4, m^3) can be recycled using the bio-pond system (Mohanty et al., 2014a), that consists of chemical, biological and mechanical treatment units.

4.4. Growth and production performance

Water exchange has no influence on the overall crop performance (Good et al., 2009) and is not necessary in most types of pond aquaculture (Boyd and Tucker, 1998). However, controlled water exchange helps in reducing organic and nutrient load, toxic metabolites, reduces turbidity, induces molting and promotes growth in shrimp culture (Mohanty et al., 2014b). Further, in terms of water quality, the low water exchange protocol creates the most stable and suitable water quality that reduced stress and mortality rate in shrimp (Duy et al., 2012). In this experiment, moderate/reasonable rates of water exchange (T_2) showed significantly ($p < 0.05$) improved water use efficiency (3.32 $m^3\ kg^{-1}$ biomass) and overall crop performance (Table 7) over the low water exchange at low density (T_1) and high water exchange at higher density (T_3). Production of shrimp in limited water exchange systems can provide more biosecurity while addressing sustainability. Further, shrimp can effectively be raised at high stocking densities with limited water exchange without compromising productivity and with better feed utilization and reduced negative environmental impacts (Patnaik and Samocha, 2009). Significantly higher ($p < 0.05$) SGR, SR%, PI, PSI, FE and yield in T_2 was probably due to the minimal required water exchange (0.8×10^4, m^3) and the prevailing optimal salinity (18.6 ± 1.8 ppt), DO (5.1 ± 1.0 ppm), water pH (7.43 ± 0.14) and TSS (238 ± 12 ppm). The optimal range of salinity (15–25 ppt), DO (> 5.0 ppm), water pH (> 7.0) and TSS (< 500 ppm) plays a key role in growth, survival and yield of *L. vannamei* (Cheng et al., 2003; Zhang et al., 2006; Bett and Vinatea, 2009; Gaona et al., 2011). Significantly lower ($p < 0.05$) growth rate (24.1 ± 0.14 g), SR% (78.7 ± 2.28), PI (16.00 ± 0.52) and FE (54.6 ± 1.42%) in T_3 was probably due density-dependent growth performance at higher population densities (Mohanty et al., 2014b) and water quality (Fig. 1).

4.5. Water productivity and economic efficiency

Water productivity is an index of the economic value of water used (Boyd, 2005), a useful indicator of efficient water management (Mohanty et al., 2016) and is used to define the relationship between crop produced and the amount of water involved in crop production. In this experiment, density-dependent moderate water use (T_2) performed well ($p < 0.05$) in terms of higher GTWP, NTWP and NCWP against high density-dependent water use (T_3) and low density-dependent water use (T_1). Significantly higher ($p < 0.05$) water productivity, lower total water footprint (1426 $m^3\ t^{-1}$ biomass) and higher OV-CC ratio (1.99 ± 0.05) in T_2, is not only an indicative of efficient water use, also minimizes the operational cost (Table 8, Fig. 3). This also infers that density-dependent moderate water use has a distinct edge over the lower and higher water use due to density-dependent input requirement. In aquaculture the total water use is important where water is pumped out and in to ponds, for there is an energy cost for doing so, as in the present case. The demand driven water use not only helps in improving water quality, water use efficiency, total water footprint and water productivity but also important in lessening pumping cost ($8.1 per 1000 m^3). Aquaculture has been criticized widely by environmentalists for wasteful use of water resources and for causing negative environmental impacts (Naylor et al., 2000; Boyd et al., 2007). Even with the implementation of water saving approach, shrimp farming is a water-intensive endeavor which consumes more water per unit of area than irrigated agriculture. It is reported that 1 m^3 water produces 400 g of rice (Bouman, 2009). However, in this study the best treatment (T_2) result infers that, 1 m^3 of water can produce 518 g of shrimp biomass which is much richer in protein/nutrient content vs that of rice biomass. This confirms the fact that, though shrimp farming is a water consuming practice, the value of aquacultural production per unit of water used greatly exceeds that of irrigated agriculture (Boyd and Gross, 2000).

5. Conclusions

The future development of shrimp farming requires responsible practices to improve operational efficiency and help prevent wasteful use of water and deterioration of pond water quality. Water budgeting, density-dependent water use and monitoring of water quality using WQSI are three major requirements in improving aquaculture performance. In *L. vannamei* culture, minimization of total water use (3.42×10^4, m^3) and water exchange (0.80×10^4, m^3) at optimum stocking density of 50 post-larvae m^{-2}, is perceived as a way to improve productivity (10.31 $t\ ha^{-1}$ 120 d^{-1}), CWUI (1.93), total water footprint (1426 $m^3\ t^{-1}$ biomass), NCWP (USD 1.13 m^{-3}) and OV-CC ratio (1.99). Further, farming systems with low to moderate water exchange, serves to keep the water quality suitable for the shrimp growth, improves water use efficiency and helps in minimizing the quantity of sediment load and effluent outputs (0.8×10^4, m^3). In this study, the use of WQSI was helpful for fast and easy data interpretation, and its application helped in deciding the water exchange requirement and maintenance of overall water quality. The knowledge derived from this study could provide the basis to optimize pond rearing efforts in shrimp culture and the water management strategies can be tailored to minimize production costs.

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