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Full Length Research Paper

Integrated culture of shrimp (*Litopenaeus vannamei*), tomato (*Lycopersicon esculentum*) and lettuce (*Lactuca sativa*) using diluted seawater: management, production and water consumption

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The aim of this study was to evaluate the production and water consumption of an integrated culture system using shrimp (*L. vannamei*) as the main culture, and lettuce and two types of tomato as the secondary cultures. Diluted seawater (1.9 g/L) and zero-water exchange tanks were used. The experiment was conducted in the Experimental Module YK located in Mazatlan Sinaloa, Mexico, over a 30-week period. The system employed in the present research consisted of three tanks for shrimp culture and the lettuce crop and four hydroponic beds for the tomato crops. The vegetable production was compared with a hydroponic treatment (control), whereas the shrimp production was contrasted with traditional shrimp monoculture. In the integrated shrimp culture, survival was 90.1 ± 7.1%, the final individual weight was 9.1±0.1 g and the yield was 1.9 ± 0.2 kg/tank (6,131±588 kg/ha). The tomato production per plant, number of tomatoes per plant and yield were significantly (P <0.05) lower than the values obtained for plants irrigated with a nutrient solution (control). While the average individual weight of tomato fruit did not differ significantly (P> 0.05) between the control and integrated culture system, greater lettuce production was obtained using irrigation water from the shrimp tank. The estimated water consumption for the system was 0.68 m^3/kg of biomass produced (for harvested shrimp, tomato and lettuce). The integrated shrimp-tomato-lettuce system is viable, but it is necessary to conduct research to determine the best plant: shrimp ratio to improve production and optimize water use.

Keywords: integrated culture, *Litopenaeus vannamei*, vegetables, yield, water consumption.

INTRODUCTION

Integrated aquaculture-agriculture systems are sustainable production systems of aquatic organisms and plants where wastes from one activity are used in the production of its counterpart. These systems have many advantages including reduced water use by both activities, so that establishment in locations where water resources are limited can be carried out (Prinsloo & Schoonbee, 1993), higher economic return per meter cubic of water due to the simultaneous production of two or more end products (McIntosh & Fitzsimmons, 2003; Silva-Castro *et al*., 2006), minimal fertilizer use in agriculture due to nutrient inputs from aquaculture effluents (Fernando & Halwart, 2000), lower environmental impact through the use of nutrient-rich effluent (Billard & Servin-Reyssac, 1992; Silva-Castro *et al*., 2006) and can be established in highly deprived areas for subsistence or family businesses.

When freshwater is used, the effluents of tilapia (McMurtry *et al*., 1993; Danaher *et al*., 2013), catfish (Endut *et al*., 2010), river prawn (Ronzón-Ortega *et al*., 2012), and perch culture (Graber & Junge, 2009) have been used to irrigate tomato, spinach, basil, and other plants. Shrimp farming using low salinity water or freshwater produces nutrient-rich effluent as a complementary option for irrigation that can be used to increase plant biomass. For example, satisfactory production results have been observed in Thailand in integrated shrimp culture and rice farming (Flaherty *et al*., 2000), and experimentally with olives in the United States (McIntosh & Fitszimmons, 2003), melon farming in Brazil (Miranda *et al*., 2008) and tomato farming in Mexico (Mariscal-Lagarda *et al*., 2012).

One of the great challenges for inland shrimp farming and agriculture is the improved use of water resources for food production. According to SEMARNAT (2013), approximately 50% of the national territory of Mexico is comprised of dry land (arid, semi-arid or dry sub-humid) that is characterized mainly by the limited availability of water. A solution or alternative to convert these regions into productive areas is the development of integrated cultures, where the same amount of water can be used to carry out shrimp farming and agriculture simultaneously. Thus, the hydric resource can be used to obtain two or more products concurrently, which minimizes the use of water and increases food production. The aim of this study was to evaluate the yield and water consumption of the integrated cultures of Pacific white shrimp (main culture) and tomato and lettuce (secondary cultures) using low salinity water (diluted seawater; 1.9 g/L) and zero-exchange water. In the present study, we present and discuss the results of an experiment conducted in Northwestern Mexico (Sinaloa) using a ratio of 75 shrimp:8 tomato plants:1 lettuce plant over a culture cycle of 210 days.

MATERIALS AND METHODS

Description of the experiment

The present study was conducted in the YK Experimental Module located in Mazatlan, Sinaloa, Mexico (23° 12’ 11.9” N and 106° 25’ 41.29” W). The experimental system for the shrimp culture consisted of three tanks, each with a diameter of 2 m (3.14 m^3 capacity per tank). Two beds (0.4 m wide, 7.0 m long and 0.2 m high) for hydroponic tomato crops were integrated at the intersection of the three tanks. These beds were constructed from blocks, covered with plastic and filled with a layer of zeolite at the top (0.1 m) and a layer of gravel at the bottom (0.1 m); one of the beds was used for a round tomato crop, and the other was used for a grape tomato crop (Figure. 1).

The water from the shrimp culture tanks was transferred by gravity to the tomato crop beds. At the end of the tomato crop beds, excess irrigation water was collected in a reservoir and pumped into the shrimp culture tanks using a submersible 1/8-HP pump. Two additional plant beds were constructed parallel to the tomato crops. These beds were irrigated using a nutritive hydroponic solution (Samperio-Ruiz, 2009) and were planted in the same way as those irrigated with the water from the shrimp tank.

A submerged biofilter was introduced into each shrimp culture tank. The function of this filter was to provide a contact surface for nitrifying bacteria. In addition, the biofilm generated on the biofilter served as natural food for the cultivated shrimp. The biofilter consisted of ballast constructed using 4” and 6”-PVC pipe sections and a section of shade cloth cut into strips to provide darkness and direct the airflow (Van Wyk, 1999).

Shrimp culture

Postlarvae (*L. vannamei*) used in this experiment were provided by Proveedora de Larvas S.A. de C.V. (FITMAR) and transported to the experimental module in an ice chest maintained at 23°C with a salinity of 10 g/L. Postlarvae (20 days after the commencement of the postlarval stage, i.e., PL20) were placed in 400-L tanks and were maintained under observation for 24 h. Then, acclimatization was carried out according to the procedure described by Van Wyk (1999) and McGraw & Scarpa (2004) until the required level of electrical conductivity was achieved. During acclimatization, postlarvae were fed FLAKE food (protein, 52%; fat, 9%; fiber, 3%; total ash, 3%; moisture, 10%; Brine Shrimp Co., Providence, Utha, USA) five times

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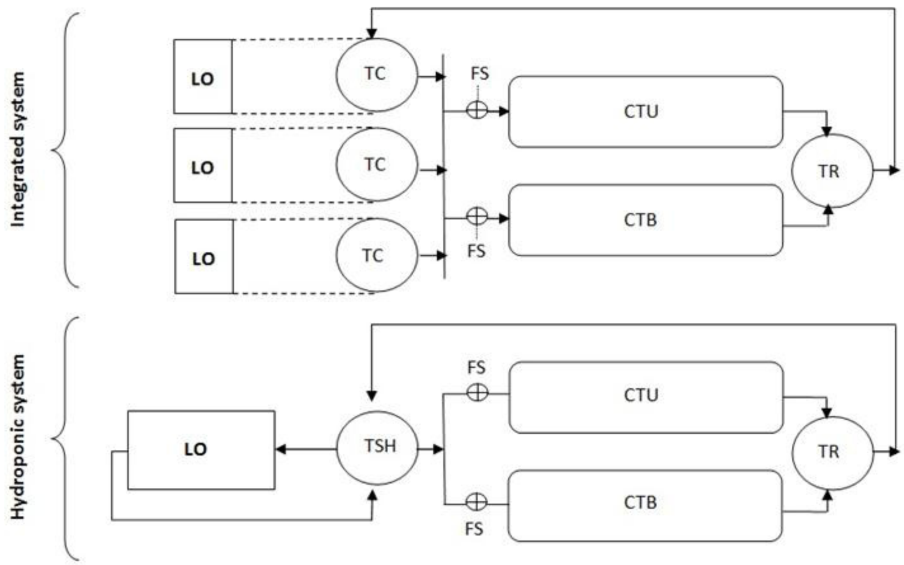

Figure 1. Experimental design of the integrated shrimp-vegetable culture. Arrows: flow of water; TC: shrimp culture tanks; THS: nutritive hydroponic solution tank; FS: suspended solids filter; CTU: grape tomato crop; CTB: tomato crop; TR: water return tank; LO: lettuce crop.

per day (7:00, 10:00, 13:00, 16:00 and 19:00 h). Once the process of acclimatization was completed, post larvae were transferred to the shrimp culture tanks at a density of 75 PL/m^2 in 1.9-g/L diluted seawater (3.0 dS/m).

During the first month, the shrimp received FLAKE food that they were manually fed from the edge of the shrimp culture tanks. From the second month, the shrimp were fed using feeder trays (two trays per shrimp culture tank) containing CAMARONINA food (protein, 35%; fat, 3.5%; fiber, 5%; total ash, 11%; moisture, 12%; Nestlé Purina Pet Care Company, St. Louis, Missouri, EUA). The food was rationed in three portions per day (8:00, 13:00 and 16:00 h) and was adjusted based on the biomass and food remaining in the feeder trays according to Zendejas-Hernandez (1994). The shrimp culture cycle had a 120-day duration; the organisms were harvested, but the water remained in the culture tanks and was then used for the production of hydroponic lettuce.

Vegetable crops

The tomato plants (round tomato and grape tomato) were provided by Agricola El Chaparral S.P.R. de R.L. and were transported to the experimental module in seedling planters containing 240 cavities. The plants were transplanted 30 days after the shrimp culture started. Round tomato and grape tomato plants (36 of each) were coupled with the shrimp culture (3 tanks with 675 shrimp) as a nutritive hydroponic solution treatment. Irrigation was carried out three times per day (8:00, 13:00 and 16:00 h) (Mariscal-Lagarda *et al*., 2012) and after irrigation, excess water was returned to the shrimp culture tanks. The tomatoes were harvested once the fruit started to turn red.

Lettuce seeds were sown in seedbeds with 240 cavities containing a mixture of peat moss, zeolite and perlite (1:1:1) and were irrigated three times per day (8:00, 13:00 and 16:00 h) (Samperio-Ruiz, 2000). The seedlings were transplanted to their respective treatments 30 days after sowing. The lettuce plants were transplanted after the shrimp were harvested (121 days after the shrimp culture was started). The lettuce (9 plants) was floated in the shrimp culture tanks on a polyurethane sheet (1 m x 1 m). At the same time, 9 lettuce plants were floated in a hydroponic bed (DFT system) filled with commercial hydroponic nutritive solution (Samperio-Ruiz, 2000). The lettuce was harvested 50 days after been transplanted.

Sampling and chemical analysis

During the culture cycle, weekly water samples were collected directly from the tanks (25 cm below the surface water) between 12:00 and 13:00 h and were filtered using What man GF/F filter paper. The water samples were stored in clean plastic bottles (120 mL) and transported to the laboratory at a low temperature (4 °C). The temperature and dissolved oxygen were measured using a dissolved oxygen meter (model DO200, YSI, Ohio, USA), the pH and electrical conductivity were measured using a pH meter (model HI 98129, Hanna instruments, Texas, USA); these measurements were conducted twice a day

Table 1. Water quality variables (mean ± standard deviation) of shrimp tanks daily (pH and EC) and weekly (TAN-N, NO_2^--N, NO_3^--N, and PO_4^--P) monitoring in a trial.

Water variables	Mean ± SD
Temperature (°C)	29.0 ± 3.7
O_2 (mg/L)	6.0 ± 0.9
pH*	8.3 ± 0.3
EC (dS/m)	3.1 ± 0.1
TAN-N (mg/L)	0.14 ± 0.25
NO_2^--N (mg/L)	0.06 ± 0.16
NO_3^--N (mg/L)	0.71 ± 0.72
PO_4^--P (mg/L)	0.35 ± 0.39

* In units of pH

(at 6:00 and 18:00) in situ. The water samples were used to determine the nutrient concentrations, which were measured using the procedures outlined by Grasshoff *et al.* (1990). The diluted seawater used in this trial was analyzed in duplicate for major ions using standard techniques (APHA, 1989). With the exception of ammonia, for which the coefficient of variation ranged between 5 and 15%, the precision of determination was <10% for the remaining ions. The estimated detection limits were 0.001 mg/L for N-ammonia, 0.001 mg/L for N-nitrite, 0.001 mg/L for nitrate + nitrite and 0.005 mg/L for phosphate.

Biometry, survival and harvest

During the culture cycle, biometry was performed weekly to record the growth of the shrimp and make necessary adjustments in the feed. Ten shrimp were randomly collected from each tank and weighed using a digital balance (± 0.01 g) to determine the average weight. Then, the shrimp were returned to their respective culture tanks. Shrimp survival, final weight, growth rate and feed conversion ratio (FCR) were determined at harvest. Survival was calculated using the following formula (Esparza-Leal *et al*., 2010): Survival (%) = (final number of shrimp/initial number of shrimp) x 100; growth rate was estimated as follows (Araneda *et al*., 2008): Growth rate (g/week) = (Wf-Wi)/t, where Wf is the final average weight of shrimp at harvest time, Wi is the initial average weight on day 0 of culture and t is the time expressed in weeks. The FCR was calculated using the following equation (Smith *et al*., 2002): FCR = Fi/w, where Fi is the food consumed by the shrimp and w is the weight gain of the shrimp. The shrimp were weighed individually to determine the final average weight at harvest. Tomato fruits were counted and weighed individually, while the lettuce plants were weighed individually but without the roots.

Statistical analysis

The data obtained were subjected to tests of normality and homogeneity of variance. If these assumptions were met, Student's *t* test was used to determine the differences between the treatments. The data that were not normally distributed or that violated the assumption of homogeneity of variance were analyzed using the Mann-Whitney U test using Sigma Stat 3.5 software (Aspire Software International, USA). Both tests were conducted using a confidence interval of 95% (Zar, 1984).

RESULTS

Characterization of water, yield and water consumption

The diluted seawater that was used to fill the shrimp tanks had an electrical conductivity of 3.1±0.10 dS/m, which is equivalent to a salinity of approximately 1.90 ± 0.07 g/L of total dissolved solids (TDS). The water quality variables of the shrimp tanks fluctuated between 21.1 and 35.1°C for temperature; 2.4 and 9.5 mg/L for dissolved oxygen; 7.1 and 9.1 for pH; 0.015 and 0.183 mg/L for ammonium; below detection limits (0.001 mg/L) and 0.699 mg/L for nitrite; 0.273 and 2.495 mg/L for nitrate; and 0.003 and 0.326 mg/L for dissolved phosphates. The mean and standard deviation for the water quality variables are presented in Table 1.

The shrimp were cultured for 120 days, from 16 August to 13 December 2011. The final average shrimp weight was 9.8, 9.1 and 8.9 g for tank 1, 2 and 3, respectively, with survival rates of 97.4, 89.4 and 88.3%, respectively. The FCA was 1.4 for tank 1, 1.6 for tank 2 and 1.7 for tank 3. The estimated growth rates were similar, i.e., 0.54, 0.53 and 0.52 g/week for tanks 1, 2 and 3, respectively. The

Table 2. Production data of white shrimp (*L. vannamei*) obtained during integrated cultured with vegetables.

Production data	Mean ± SD
Stocking density (PL/m^2)	75
Initial weight (mg)	45.0 ± 2.0
Final weight (g)	9.1 ± 0.1
Growthrate (g/week)	0.54 ± 0.01
Specifical growth rate (%/day)	4.41 ± 0.05
Survival (%)	90.1 ± 7.0
FCR	1.6 ± 0.1
Yield (kg/ha)	6131±588

Table 3. Production data of two types of tomato (*L. esculentum*) obtained during integrated culture with white shrimp.

	Tomato		Grape tomato	
	Shrimp effluent	Nutritive solution	Shrimp effluent	Nutritive solution
Fruits per plant	4.21 ± 1.25[a]	6.19 ± 2.26[b]	59.53 ± 18.04[a]	108.20 ± 30.72[b]
Production per plant (g)	320.00 ± 84.94[a]	457.20 ± 191.20[b]	194.80 ± 73.49[a]	406.00 ± 151.10[b]
Fuit mean weight (g)	77.58 ± 12.04[a]	73.58 ± 13.74[a]	3.24 ± 0.44[a]	3.75 ± 0.96[b]
Yield ($t\ ha^{-1}$)	13.40 ± 3.56[a]	19.14 ± 8.00[b]	8.75 ± 3.07[a]	17.00 ± 6.32[b]

Different letters among means are significantly (P<0.05) different.

Table 4. Production data of lettuce (*L. sativa*) obtained during integrated culture with shrimp *L. vannamei*.

Production data	Shrimp effluent	Nutritive solution
Mean individual weigth (g)	280.20 ± 47.23[b]	134.31 ± 29.42[a]
Yield ($kg\ ha^{-1}$)	16,812.00 ± 2829.34[b]	8,056.00 ± 1764.90[a]

Different letters among means are significantly (P<0.05) different.

average shrimp culture data are summarized in Table 2.

The production of round tomato and grape tomato in the integrated shrimp-tomato-lettuce culture containing diluted seawater and in the hydroponic nutritive solution (control) is shown in Table 3. The fruit number, production per plant, and yield were significantly (P<0.05) higher for tomato plants irrigated with the hydroponic nutritive solution; only the average individual fruit weight did not differ significantly (P>0.05) between the plants irrigated using water from the shrimp culture and those irrigated with the hydroponic nutritive solution. The yields obtained for the grape tomato plants irrigated with the nutrient solution were significantly (P<0.05) higher than those irrigated using the water from the shrimp culture; this result is similar to that obtained for the other production variables. The average individual weight and yield of lettuce growing with shrimp effluent were higher (P<0.05) than those obtained in the treatment with the nutrient solution (Table 4).

Table 5. Major chemical components (expressed in mg/L except pH and CE) of the water used in the integrated culture shrimp-vegetables

Variable	Water of shrimp tanks (mean ± SD)	Seawater diluted to 1.9 g/L*
Mg^{+2}	77.7	69.4
K^{+}	21.3	21.5
Ca^{+2}	23.5	22.2
Na^{+}	544.0	582.5
Ratios		
Na:K	25.5	28.7:1
Ca:K	1.1:1	1.1:1
Mg:Ca	3.3:1	3.1:1

*Calculated theoretically from the salinity values (Roy *et al*., 2010)

The water consumption of the integrated shrimp-tomato-lettuce culture was estimated as 3.0 m^3 per kilogram of shrimp harvested, which decreased when tomato and lettuce production were included, i.e., 0.68 m^3 per kilogram of biomass harvested.

DISCUSSION

L. vannamei can survive and grow well at low salinities (Mariscal-Lagarda *et al*., 2012). According to Van Wyk (1999), McGraw *et al*. (2002) and McGraw & Scarpa (2004), this species can be cultivated at salinities as low as 0.5 g/L. The optimum concentrations of major ions and the ratios of Na:K, Ca:K and Mg:Ca in water for shrimp culture using low salinity water can be found in diluted seawater (Boyd & Thunjai, 2003). Therefore, the water used in this trial should theoretically produce the best shrimp growth and the greatest harvest. The major components and ion ratios measured in the water are summarized in Table 5; sodium and magnesium were present in the highest concentrations. Most of the ion concentrations and the ratios of the major ions were theoretically similar to diluted seawater. The average temperature, dissolved oxygen and pH values were within the optimal ranges proposed by Van Wyk & Scarpa (1999) and Boyd (2001); however, certain temperature and dissolved oxygen values fell outside these ranges on some occasions. The ammonia and nitrate concentrations measured in the water used for the culture cycle did not exceed the limits proposed as safe levels: Frías-Espericueta *et al*. (1999) recommended a safe value of 6.5 mg/L for ammonia to avoid toxic effects on juveniles, and Van Wyk & Scarpa (1999) and Kuhn *et al*. (2010) stated that concentrations below 60 and 220 mg/L for nitrate, respectively, had no negative effects on survival or growth. Nitrite concentrations were maintained below 0.45 mg/L, which was proposed by Gross *et al*. (2004) as a safe level.

The shrimp production data obtained using diluted seawater are comparable with those recorded in other studies (Table 6). For example, Esparza-Leal *et al*. (2010) obtained a yield of 3.3 t/ha and a survival rate of 82.5% with a stocking density of 50 PL/m^2 using fresh groundwater with a salinity level below 1.0 g/L. Araneda *et al.* (2008) recorded a yield of 7.8 t/ha and a final average weight of 11.4 g using water with a salinity of 0.6 g/L, which was obtained from a subterranean aquifer (known as cenote) in Yucatán, México. Higher yields and growth rates have been reported for shrimp culture using low salinity water. For example, Samocha *et al*. (1998) reported a yield of 5.2 t/ha with a stocking density of 27 PL/m^2 using diluted seawater with a salinity of 2 g/L. Similarly, Samocha *et al*. (2004) obtained a yield of 11.1 t/ha with a stocking density of 91 PL/m^2 using geothermal (25 °C) deep water with a salinity of 2.2 g/L.

In integrated shrimp culture, Mariscal-Lagarda *et al*. (2012) obtained a yield of 3.9 t/ha with a survival rate of 56.3% and a final average shrimp weight of 13.9 g, in contrast to the present study where salinity and stocking density were lower (0.73 g/L and 50 PL/m^2, respectively). The differences in the shrimp yield and survival can be related to the type of water used; in our case, diluted seawater (1.9 g/L) was used, while Mariscal-Lagarda *et al*. (2012) used groundwater with a salinity of 0.65-0.85 g/L that had been supplemented with salts (K^+ and Mg^{++}). The deficiency of major ions in groundwater has been associated with poor development and growth of shrimp, which is exacerbated by an imbalance between ions (Boyd, 2002). According to Fielder *et al*. (2001) and Roy *et al*. (2010), the ion ratios should be similar to those present in seawater when it is diluted to the same salinity as groundwater to ensure good development of shrimp.

Table 6. Production data of low salinity water and fresh water cultures with shrimp *L. vannamei.*

	Salinity g L^{-1}	Density (PL m^{-2})	Yield (t ha^{-1})	Survival (%)	FCR	Duration (days)	Size (g)	Growth rate (g $week^{-1}$)	Reference
Low salinity water									
	0.5-7.0	60	2.9	68.4	1.4	91	11.2	0.37	Wudtisin y Boyd (2011)
	0.5-7.0	65	2.3	56.9	1.9	72	8.7	0.29	Wudtisin y Boyd (2011)
	4.0	27	5.2	98.8	-	77	19.3	1.70	Samocha *et al*. (1998)
	2.2	91	11.1	66.9	2.8	100	18.5	1.36	Samocha *et al*. (2004)
	2.0	27	5.2	98.8	-	77	19.0	1.67	Samocha *et al*. (1998)
	1.8	13	1.3	61.5	-	77	15.6	1.41	Mariscal –Lagarda *et al.* (2007,2010)
	1.2*	75	3.8	46.8	2.3	120	11.1	0.65	This study
	1.9*	75	6.2	90.0	1.6	120	9.1	0.54	This study
Fresh water									
	0.6*	90	7.8	76.1	-	203	11.4	0.38	Araneda *et al*. (2008)
	0.5	100		77.0	1.6	180	14.1	0.55	Van Wyk *et al.* (1999)
	< 1	50	3.3	82.5	-	84	8.1	0.70	Esparza-Leal *et al.* (2010)
	0.7	39	3.5	47.0	3.0	112	19.3	1.30	Green (2008)
	0.7	23	0.98	82.3	1.9	55	5.5	0.90	Green (2008)
	0.7	28	2.4	99.2	1.2	65	9.0	1.30	Green (2008)
	0.9	50	3.9	56.3	1.6	120	14.0	0.73	Mariscal-Lagarda *et al.*(2012)

*Calculated according to Boyd (2002).

Table 7. Production data, water exchange and use of water in different shrimp cultures.

Specie	Salinity (g L^{-1})	Density (PL m^{-2})	Water exchange (%)	Yield (t ha^{-1})	Duration (days)	m^3 per kg Of shrimp harvested	Reference
L.setiferus	22.9	40	25.0	5.7	140	640	Hopkins *et al.* (1993)
L.setiferus	21.8	40	2.5	6.4	140	9	Hopkins *et al.* (1993)
L.setiferus	18.3	20	0.0	3.2	140	6	Hopkins *et al.* (1993)
L.vannamei	37.5	14	4.0	1.8	130	17-22	Páez-Osuna *et al.* (1997)
P. monodon	20-30	20-30	10-15	3.6	100-120	6.7-9.8	Anh *et al.* (2010)
L.vannamei	36.0	15	15.0	3.1	203	62-71	Casillas Hernández *et al.* (2006)
L.vannamei	42.5	20	12.7	2.0	190	113	Miranda-Baeza *et al.* (2007)
L.vannamei	1.8	13	0.0	1.3	77	64	Mariscal-Lagarda *et al.* (2010)
L.vannamei	0.86	50	1.0	3.9	120	4.7 (2.1)**	Mariscal-Lagarda *et al.* (2012)
L.vannamei	1.9*	75	1.0	6.1	120	3.0 (0.68)***	This study

*Calculated according to Boyd (2002). **Water consumption calculated with shrimp and tomato harvested. *** Water consumption calculated with shrimp, tomato and lettuce harvested.

In Mexico, the average annual yield achieved by commercial tomato monoculture is 57.2 t/ha using seasonal cycles of perennial crops and irrigation methods (SIAP, 2014). This includes open-grown crops, those grown in shade houses and greenhouses, and where fertilizers and pesticides are applied to ensure production. However, Resch (1995) indicated that hydroponic yield may vary from 200 to 700 t/ha in greenhouses under controlled conditions (humidity, light, air exchange, etc.). McMurtry *et al.* (1997) achieved round tomato yields ranging from 93-137 t/ha in cultures with different treatments coupled to hybrid tilapia. Mariscal-Lagarda *et al*. (2012) estimated a yield of 36.1 t/ha for tomato plants irrigated with effluent from shrimp culture; the individual fruit weight was 110.6 g and there were 7.0 tomatoes per plant. These results are higher than those recorded in the present work (yield of 13.4 t/ha, individual fruit weight of 77.6 g and 4.2 tomatoes per plant). There are no available yield records for grape tomato grown in Mexico. Additionally, this plant has not previously been used in integrated cultures. However, Silva-Castro *et al*. (2006) reported a yield of 32 t/ha with an average individual fruit weight of 5.5 g for cherry tomatoes irrigated with tilapia effluent. All the integrated cultures mentioned above used freshwater (<1 g/L) in contrast to the diluted seawater used in the present work. Magán *et al*. (2008) indicated that the threshold value of electrical conductivity at which the production of tomato begins to decrease is 3.5 dS/m. This value was not reached in the present study, but the maximum tolerable concentrations of sodium and chloride in the irrigation solution exceeded the values recommended by Molineux (1996), i.e., 250 and 400 mg/L for sodium and chloride, respectively. Schwarz (1975) indicated that the sodium and chloride concentrations in the irrigation solution should not exceed 400 and 600 mg/L, respectively, while Samperio-Ruiz (2000) mentioned that these ions should be present in very low concentrations. It is likely that the excess of sodium and chloride was the main factor responsible for the low tomato yields in this work; however, it is important to realize that the tomato was a secondary or complementary crop to the shrimp culture.

The average monoculture lettuce yield obtained commercially in Mexico is 20.7 t/ha, while Resch (1990) indicates that hydroponics can reach yields of 23 t/ha and higher. Lennard and Leonard (2006) obtained lettuce yields of 44.7 t/ha with individual weights of 116.9 g in an integrated culture with Murray cod (*Maccullochella peelii peelii*). In addition, Dediu *et al*. (2012) estimated yields of 33.0 to 37.0 t/ha and individual weights of 74.3 to 85.9 g for lettuce grown with effluent from sturgeon culture. In the present work, the mean lettuce yield and individual weight were low (16.8 t/ha and 280.2 g, respectively). This relatively low lettuce yield can be explained by various factors; i.e., the relatively high EC and elevated concentrations of sodium and chloride; and the low stocking density of lettuce per tank (9/m^2). The maximum lettuce EC tolerance is reported as 1.0 to 1.4 dS/m (Maas, 1986) and 1.3 dS/m (Ayers *et al*., 1951), and this plant is classified as moderately sensitive to salinity (Yadav *et al.,* 2011). The results from the present study indicate that an adequate structure system that allows for a high stocking density, such as the conventional DFT (deep flow technique) system beds (Samperio-Ruiz, 2000), is needed.

It is important to emphasize that while relatively low tomato and lettuce yields were obtained in the present study, these can be considered as an addition to the main crop, i.e., shrimp culture. There are two advantages of this integrated culture system: first, the nutrients contained in the effluent water (e.g., nitrogen, phosphorus and other micronutrients) are converted into biomass as the tomato and lettuce plants grow; and second, the discharge of shrimp effluent is avoided, which reduces the impacts on the natural ecosystems (rivers, groundwater, coastal lagoons, estuaries and other wetlands) that would otherwise receive such effluent. The adverse impacts associated with the addition of nutrients, such as the deterioration of water quality (reduction of dissolved oxygen, increase in ammonia, nitrite and suspended solids, etc.) and eutrophication, have serious consequences, and such phenomena are recurrent in the southeastern Gulf of California (NW Mexico) (Páez-Osuna *et al.* 2013).

Although there is no optimal level for the consumption of water per kilogram of shrimp harvested, the lowest water consumption is the most preferable for freshwater and low salinity cultures (Mariscal-Lagarda *et al*., 2012). The use of integrated cultures significantly decreases the water consumption per kilogram of harvested biomass. The water consumed by various traditional shrimp monocultures using different species in several systems is summarized in Table 7. Values as high as 640 m^3 are obtained to produce one kilogram of shrimp at a density of 40 PL m^{-2} with a water exchange of 25% (Hopkins *et al.,* 1993), or as low as 6.7-9.8 m^3 to produce one kilogram of shrimp at a density 20-30 PL m^{-2} with a water exchange of 4% (Ahn *et al.,* 2010). Mariscal-Lagarda *et al*. (2012) estimated a water consumption of 4.7 m^3/kg for shrimp in an integrated culture with a tomato crop; this consumption decreased to 2.1 m^3/kg when tomato production was added. These values are higher than those obtained in this study (i.e., 3.0 and 0.68 m^3/kg for shrimp production and combined shrimp, tomato and lettuce production, respectively) because in our case, a higher shrimp yield was obtained and there were two vegetable crops instead of one, which leads to a better use of water and nutrients. The water consumption of the integrated system described here can be further reduced by improving the ratio of the number of shrimp to the number of plants or by using the total shrimp effluent to irrigate more lettuce crops. Thus, shrimp culture using low salinity water, similar to that used in agriculture, can be carried out with less water, even in arid and semiarid regions where water is a limiting resource.

CONCLUSIONS

Considering the results from the present study (shrimp-tomato-lettuce integrated culture) and the work developed by Mariscal-Lagarda et al. (2012; 2013; 2014) for shrimp-tomato culture seems to present two extreme situations in terms of the yield of the harvested products. When diluted seawater is used, the tendency is that the main crop is shrimp (being the most favored) and plants (less favored) constitute the secondary crop. By contrast, when well-water or surface freshwater (with a composition equal or similar to diluted seawater) is used, it is likely that shrimp farming will be less favored, while the plants produce higher yield. This tendency to favor shrimp or plants is the crux of the shrimp-vegetable culture systems. However, these systems depend on the characteristics of the water source. Clearly, the composition of the available water is a critical point that favors shrimp or vegetable production.

The integrated shrimp-vegetable culture using low salinity water and zero-water exchange presented here shows promising results, but it is necessary to conduct further research to: (i) determine the optimal number of tomato and lettuce plants to develop a more efficient system; (ii) evaluate the composition of the water that will generate the highest shrimp, tomato and lettuce yield; (iii) determine the nitrogen and phosphorus dynamics in these integrated systems; (iv) calculate the economic and financial feasibility of this system; (v) evaluate the environmental value of this system in terms of the reduction and mitigation of impacts on the receiving waters; and (vi) evaluate the quality of the products harvested (tomato, lettuce and shrimp).

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