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GROWTH, SURVIVAL AND PRODUCTION OF *Penaeus monodon* AND OTHER SPECIES IN INTEGRATED MULTITROPHIC AQUACULTURE PONDS

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ABSTRACT

The growth and survival of Penaeus monodon and other commercial species and the production performance of Integrated Multitrophic Aquaculture (IMTA) system were evaluated in a 500 m² experimental grow-out ponds of Mindanao State University at Naawan for 120 days. Three triplicated treatments, monoculture (P. monodon only), polyculture (P. monodon and Chanos chanos) and IMTA (P. monodon, C. chanos, Perna viridis and Gracilaria verrucosa) were evaluated in a semi-intensive pond culture operation. Salinity (24.3 to 34.36‰), temperature (28 to 40.64°C) and pH (7.5 to 9.49) exceeded the maximum ideal limit for the cultured organisms in all treatments. Dissolved oxygen levels (2.76-5.43) were within the optimal range of some cultured organisms. Growth of shrimp (5.33±0.02 %SGR P <0.05) and milkfish (4.49±0.03 %SGR P <0.05) were significantly better in IMTA than in polyculture. Shrimp's survival was also significantly higher in IMTA (24.13%±3.95, P <0.05) than in the other treatments. Shrimp-milkfish biomass was highest in IMTA (89.67 kg), followed by polyculture (57.72 kg) and lowest in monoculture (11.33 kg). The higher biomass and survival of shrimp and milkfish in IMTA ponds could be attributed to the cultured organisms' synergistic interaction, such as shading and nutrient remediation by G. verrucosa and bioremediation by P. viridis. Revenue and profit followed a similar trend, with IMTA revealing profitability over the polyculture and monoculture. Hence, the results demonstrate the efficiency of the IMTA systems over monoculture and polyculture in the growth and survival of the high-valued jumbo tiger shrimp, P. monodon and the overall production and profitability.

KEYWORDS: IMTA; monoculture; *Penaeus monodon*; pond, polyculture

INTRODUCTION

Aquaculture contributes nearly half of global fisheries production, reaching 82 million tons out of 179 million tons in 2018 (FAO, 2020), providing vital sustenance for the growing global population (Palanca-Tan *et al.,* 2018). In the Philippines, aquaculture is one of the significant contributors to world fisheries, with 2,304,365.31 fisheries production in 2018 (Tahiluddin & Terzi, 2021). The major cultured species include shrimps/prawns like *Penaeus monodon*, milkfish, tilapia and seaweeds. The *P. monodon,* highly valued in commercial trade, ranks among the top shrimp species globally, producing 750 thousand tons in 2018 (FAO, 2020). However, intensified farming practices in the Philippines led to industry collapse in the mid-1990s, attributed to issues like feed quality, water conditions, and diseases (Anka *et al.,* 2013). In response, many shrimp farmers have reverted to extensive stocking densities as a solution.

Milkfish, the Philippines' most widely cultured finfish, remains the cornerstone of the nation's aquaculture, valued at PHP 44.19 million, accounting for 9.6% of the total fisheries production of 4,403,709.08 metric tons in 2017 (PSA, 2017). Its abundance in seedstock, compatibility with culture technology, and market demand make it a prime candidate species for cultivation in the country. On the other hand, seaweeds can significantly reduce nutrient concentrations, control eutrophication, stabilize marine ecosystems, and promote sustainable aquaculture (Huo *et al.,* 2010). In this study, *G. verrucosa,* a common red seaweed in Northern Mindanao, was used to remediate inorganic nutrients in an Integrated Multitrophic Aquaculture (IMTA) pond system.

The green mussel *P. viridis* has been well documented for its cleaning effects in coastal areas due

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to their filtration of particulates in the water column, reducing the organic matter from fish farming (Liutkus *et al.,* 2012) and shrimp waste (Van Khoi & Fotedar, 2012). Researchers have become interested in green mussels because of their ability to withstand fluctuating environmental conditions.

Waste accumulation and water degradation due to excess nitrogen and phosphorus (Haque *et al.,* 2016) are the major challenges in profitable *P. monodon* farming. Research on technologies that ensure environmental sustainability and economic profitability is crucial for adoptable aquaculture success. Integrated Multitrophic Aquaculture (IMTA), which combines species from different trophic levels, offers a promising solution to efficiently manage nutrients and increase profitability (Fang, 2018).

IMTA application originated in open sea culture systems and efforts to develop IMTA systems are taking place in Canada, Chile, China, Israel, South Africa, the USA, and in several European countries (Chopin, 2003) with commercial existence in China (Hossain *et al.,* 2022). In the Philippines, the first documented IMTA study was the work with Largo (2016) using three seaweed species and abalone in an open water system that encountered problems brought by the impact of sea waves. While IMTA has demonstrated waste remediation efficiency and high growth in open sea aquaculture, there is a lack of information available for pond systems. Moreover, only few studies (Balasubramanian *et al*., 2018; Biswas *et al*., 2019, Arriesgado *et al.,* 2022) have been conducted on IMTA with shrimps. Hence, this study evaluates *P. monodon* and other commercial species' performance in three aquaculture systems, highlighting the potential of IMTA in pond production. It used the best pre-identified species combination (*P. monodon, C. chanos, G. verrucosa, P. viridis*) for IMTA to compare its performance with shrimp monoculture and the traditional shrimp-milkfish polyculture. The study's results provide valuable information to support the culture and revival of *P. monodon* in Northern Mindanao.

MATERIALS AND METHODS

Study Area

The study was conducted on January 2023 to June 2023 in the ponds of Mindanao State University at Naawan located in Naawan, Misamis Oriental, Northern Mindanao (N8.42610, E124.29046) and 160 meters away from Pan-Philippine Highway (AH 26) (Fig. 1). The ponds generally have an upper-brackish (30 ppt) to marine (32 ppt) water salinity levels and draw water from Iligan Bay through Simanok Creek.

Figure 1. Philippine map showing the location of Naawan, Misamis Oriental and the experimental ponds at MSU at Naawan.

Cultured Species

Four species, namely, *P. monodon* (main species), *C. chanos* (co-culture species), *G. verrucosa* (nutrient extractor) and *P. viridis* (bioremediator species), were used for culture. The species were selected based on their suitability for an IMTA pond system culture (Arriesgado *et al.,* 2022) and owing to their better production, profitability performance, reported remediation properties, availability in Northern Mindanao, and ability to survive within the salinity requirement optimal for the growth of *P. monodon*, which is 20-30 ppt.

Healthy seedstocks of *P. monodon* and *C. chanos* were secured from nearby private hatcheries with known good track records. Healthy thalli of seaweeds were collected from Lala, Lanao Del Norte, while mussels were collected from Binuni, Camiguin Province. Standard acclimation was applied to the seedstocks prior to stocking them in ponds for one week.

Experimental Design and Set-up

Nine units of 500 m^2 earthen ponds were utilized for the grow-out culture experiments following a complete randomized design to represent three trip-

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licate culture system treatments under semi-intensive culture conditions. Standard pond preparation including draining, pest control, teaseed application, drying, liming, flushing and water filling was carried out prior to experiment, but no fertilizer was applied. A two-horsepower water pump with pipings and a water outlet to each pond was on standby to be switched on as a flow-through system in case of any dissolved oxygen (DO) related problem. While there were times that the DO levels were below the ideal, no DO-related problem was encountered. The description of the three treatments and the stocking densities was adopted and modified from the previous study by Arriesgado *et al.* (2022) are shown in Table 1.

Table 1. The three treatments represented by three cultured systems, the cultured organism for each treatment, the sizes of the organisms and their respective stocking density (m^{-2})

Treatments	Description & cultured organism	Stocking density (m^{-2})
T1	Shrimp monoculture (*P. monodon* only), acts as the control	*P. monodon* 15-postlarvae (PL 20) of 0.015-0.025g average body weight (ABW)
T2	Polyculture (*P. monodon* and *C. chanos)*	*C. chanos* 0.4-fingerling of 3.18 g ABW
T3	IMTA (*P. monodon, C. chanos, G. verrucosa, P. viridis)*	*P. viridis* 50 juveniles of 2.5 cm shell length *G. verrucosa* 500g for the macroalga

Shrimps, mussels, and macroalgae were stocked three days after the ponds were filled to a depth of one meter. Seedstocks stocking was carried out in the early morning (5-9 a.m.) and late afternoon to evening (5-9 p.m.) on the same day.

The principles, methods and processes of managing an IMTA system according to Chopin (2006) served as a guide for the implementation of an IMTA system in this study. The grow-out experiment was conducted for 120 days.

Feeding and Water Management

Commercial feed containing 30-35% crude protein was given at 5% daily feeding rate of the total body weights of *P. monodon* and *C. chanos* and reduced by 1% every month until harvest. Shrimps were given sinker feeds four times a day between 5:00 a.m. and 7:00 p.m., while milkfish were fed floater feed three times daily and ahead of shrimps between 7:00 a.m. and 4:00 p.m. Two feeding trays for shrimps were installed in each pond to monitor feed consumption. They were covered with polyethylene mesh nets in polyculture and IMTA ponds to avoid the entry of milkfish. The feeding ratio was adjusted every 15 days based on the average body weight of shrimp and fish and the expected survival rate.

Water was managed in each pond by adding water every spring tide from Simanok Creek. This was done to compensate for water loss through evaporation and seepages and to maintain the ponds at a depth of one meter.

Growth, Survival, Biomass and Production of tiger shrimp and milkfish

Thirty (30) samples of shrimp, milkfish and mussels were measured using a digital weighing scale for each species' body weight. The same samples were also measured for length (TL) using a ruler for shrimp, a tape measure for milkfish and a vernier caliper for mussels. For the seaweed, only weight gain was monitored by measuring 10% of its total stocks. Shrimps and milkfish samples were collected from ponds using a cast net, while mussels and seaweeds were collected from their tray confinements. Survival of shrimps, milkfish, and mussels was monitored by counting the number of organisms that survived during the final sampling. The growth and survival rate of shrimps, milkfish and mussels were determined using the formula (Zaikov *et al.,* 2008; Bautista-Teruel *et al.,* 2003; Hafiz *et al.,* 2012):

$$DGR = (Wf \text{ or } Lf - Wi \text{ or } Li)/t$$

Where:

DGR is the average daily growth (weight or length)

Wf or LF and Wi or Li are the final and the initial body weight or length,

t – is the duration of the experimental period

$$\text{Specific growth rate (\% SGR)} = \frac{\ln \text{final BW (g)} - \ln \text{initial BW (g)}}{\text{cultured period (days)}} x\ 100$$

where BW= body weight;

$$\text{Survival rate (\%)} = \frac{\text{final numbers of stocks (shrimp/milkfish/mussel)}}{\text{Initial number of stocks}} x\ 100$$

The growth determination of *G. verrucosa* was in terms of a specific growth rate based on the formula (Penniman *et al.*,1986):

$$\text{Specific growth rate (\% SGR)} = \frac{\left(\frac{Gt}{Go}\right)1}{t-1} x\ 100$$

Where: SGR = specific growth rate (% in wet weight per day); Gt = weight (g) after t days; Go = initial weight (g); t = time in days

Production and Economics

Production performance was evaluated in terms of cost of production, gross revenue or income, net income, return on investment and benefit-cost ratio specific to *P. monodon* and *C. chanos*. Production parameters were obtained using the following formula:

$$\text{Net income} = \text{Gross income} - \text{Total costs}$$

$$\text{Return of Investment (ROI \%)} = \text{Net profit / Investment x 100}$$

$$\text{Benefit} - \text{cost ratio} = \frac{\text{discounted value of incremental benefits}}{\text{discounted value of incremental costs}}$$

Statistical Analysis

Statistical analyses were performed using SPSS 2010 to evaluate the growth and biomass of shrimp, milkfish and seaweed and the survival of shrimp, milkfish and mussels. All measured numerical data were encoded in Excel 2010, and log data transformation was applied. Analysis of variance (ANOVA) was performed to evaluate the significance (0.05 P value) of the mentioned parameters. Tukey's test was applied in evaluating the significant differences in three treatments at a 5% level of significance, while T-test analysis was used in comparing two treatments, e.g. milkfish's growth and survival at a 5% level of significance.

RESULTS AND DISCUSSION

Growth and Survival of Cultured Organisms

IMTA and monoculture had the same results for average daily growth (g^{d-1}) of the shrimps (0.09±0.00) and were significantly higher compared to polyculture (0.05±0.01) (Table 2). The specific growth rate of shrimp in weight in three treatments was highest in IMTA (5.33±0.02 %SGR), followed by monoculture (5.29±0.02 %SGR), and lowest in polyculture (4.85±0.10 %SGR). For the *C. chanos*, IMTA had significantly higher growth day^{-1} and %SGR in weight (3.36±0.10 g d^{-1}, 4.49±0.03 %SGR) (ANOVA, $P < 0.05$) compared to polyculture.

Table 2. Growth in weight of cultured organisms in different aquaculture systems. Values with different superscripts on specific parameter are significantly different from each other ($P<0.05$).

Treatments	DOC*	Initial weight (g)	Final ABW** (g)	Weight gain (g)	Growth (g^{d-1})	SGR (%)
P. monodon						
Monoculture	120	0.018	10.30 ± 0.19 [a]	10.28 ± 0.19[a]	0.09 ± 0.00[a]	5.29 ± 0.02[a]
Polyculture	120	0.018	6.10 ± 0.78 [b]	6.08 ± 0.78[b]	0.05 ± 0.01[b]	4.85 ± 0.10[b]
IMTA	120	0.018	10.83 ± 0.27 [a]	10.82 ± 0.27[a]	0.09 ± 0.00[a]	5.33 ± 0.02[a]
C. chanos						
Polyculture	105	3.18	297.91 ± 8.70 [b]	294.73 ± 8.70[b]	2.81 ± 0.08[b]	4.32 ± 0.03[b]
IMTA	105	3.18	356.28 ± 10.13 [a]	353.10 ± 10.13[a]	3.36 ± 0.10[a]	4.49 ± 0.03[a]
P. viridis (IMTA)	105	2.50	17.32 ± 0.63	14.82 ± 0.63	0.14 ± 0.01	1.84 ± 0.03
G. verrucosa (IMTA)	95	150.00	207.13 ± 13.09	57.13 ± 13.09	0.63 ± 0.15	1.55 ± 0.06

*Days of Culture, **Average Body Weight

Likewise, IMTA and monoculture also had the same results of the growth day^{-1} of the shrimp's length (0.09±0.001) (Table 3). They were significantly higher compared to polyculture (0.07±0.003) (ANOVA, $P < 0.05$). Furthermore, the shrimp's specific growth rate in terms of length was similar in IMTA and monoculture (2.00 %SGR). It was significantly different from polyculture (1.81% SGR). For the *C. chanos*, IMTA had significantly higher growth day^{-1} and %SGR in length (0.24 ± 0.005 g d^{-1}, 1.27 ± 0.01 %SGR) (ANOVA, $P < 0.05$).

The survival rate of shrimp was significantly higher in IMTA (24.13 ± 3.95%) than in monoculture (14.67 ± 1.30%) and polyculture (13.3 ± 1.54%) (ANOVA, $P < 0.05$) (Table 3). However, no significant difference was observed in the survival rate between monoculture and polyculture. For *C. chanos,* there was no significant difference in their survival rate between IMTA (98.33 ± 2.89%) and polyculture (86.67 ± 11.55%). *P. viridis'* survival was 67.14 ± 8.7%. However, mass mortality in mussels was encountered in ponds after episodes of heavy rain downpours that prompted the removal of all mussels and milkfish in ponds to avoid further adverse effects on the cultured shrimp. Hence, the growth and survival of mussels and milkfish were monitored until 105 days of culture only. Simultaneous mass mortalities happened with seaweeds and the final viable monitored growth was on Day 95.

Table 3. Growth in length and survival rate (%) of cultured organisms in different aquaculture systems. Values with different superscripts on specific parameter are significantly different from each other ($P < 0.05$).

Treatments	DOC*	Initial length (cm)	Final ABL** (cm)	Length gain (cm)	Average daily growth (cm^{d-1})	SGR (%)	Survival rate (%)
P. monodon							
Monoculture	120	1.10	12.07 ± 0.08^{a}	10.97 ± 0.08^{a}	0.09 ± 0.001^{a}	2.00 ± 0.01^{a}	14.67 ± 1.30^{b}
Polyculture	120	1.10	9.70 ± 0.39^{b}	8.60 ± 0.39^{b}	0.07 ± 0.003^{b}	1.81 ± 0.03^{b}	13.30 ± 1.54^{b}
IMTA	120	1.10	12.11 ± 0.02^{a}	11.01 ± 0.02^{a}	0.09 ± 0.000^{a}	2.00 ± 0.00^{a}	24.13 ± 3.95^{a}
C. chanos							
Polyculture	105	9.00	32.37 ± 0.23^{b}	23.37 ± 0.23^{b}	0.22 ± 0.002^{b}	1.22 ± 0.01^{b}	86.67 ± 11.55
IMTA	105	9.00	34.10 ± 0.53^{a}	25.10 ± 0.53^{a}	0.24 ± 0.005^{a}	1.27 ± 0.01^{a}	98.33 ± 2.89
P. viridis (IMTA)	105	3.10	6.32 ± 0.07	3.22 ± 0.07	0.03 ± 0.001	0.68 ± 0.01	67.14 ± 8.70

*Days of Culture, **Average Body Length

The growth and survival of *P. monodon* and *C. chanos* were highest in IMTA compared to polyculture and monoculture, which could be due to mussels and seaweed acting as bioremediators. The synergistic interaction of the cultured organisms, including a shading and nutrient remediation by *G. verrucosa* and the bioremediation by the green mussel, provided a healthier culture environment in the system, which conforms to the study of Troell *et al.* (2003) Neori *et al.* (2004) and Chopin *et al.* (2008). A study on *P. monodon* co-cultured with finfishes obtained the highest growth in treatment added with an organic extractor (*Crassostrea cuttackensis*) compared to traditional polyculture (Biswas *et al.,* 2020). Irisarri *et al.* (2015) elaborated that introducing filter-feeding animals efficiently utilized organic and particulate wastes. On the other hand, the use of seaweeds in IMTA has been proposed as an alternative for environment-sustainable expansion of aquaculture for water remediation due to their high capability to remove inorganic nutrients from wastewater (Fleurence *et al.,* 2012). Despite a higher survival of milkfish reared in IMTA than in polyculture, no significant difference was observed between the treatments. Nevertheless, the combined growth, survival and biomass performance of milkfish and shrimps provide an edge in favor of the IMTA system. Although significantly different, a lower biomass and survival of the shrimps in both IMTA and polyculture were observed in this study. These were possibly affected by the high stocking density of the co-cultured milkfish. Simão *et al.* (2013) emphasized that increasing the finfish's density decreases the shrimp's final weight and survival rate. The growth of *P. monodon* (0.05 ± 0.006 to 0.09 ± 0.002 g^{d-1}) obtained in this study is lower compared to a growth range of 0.22-0.34 g^{d-1} or 1.55 to 2.4 g^{week} (Janakiram *et al.,* 2011), and 0.27–0.28 g^{day} (Arriesgado *et al.,* 2022) for a semi-intensive *P. monodon* IMTA pond. The extreme salinity and temperature brought by the summer season and the El Niño phenomenon adversely resulted in the slow growth of shrimps. The occurrence of high salinity (>25‰) had a substantial impact, where less energy was budgeted for shrimp's growth and metabolism in favor of more energy spent on osmotic regulation (Ye *et al.,* 2009). However, the growth and survival of shrimps in this study could have yielded different and better results under normal climatic conditions. This notion is supported by Bertrand *et al.* (2020), reporting that El Niño events reduced aquaculture production. Hence, climatic factors like El Niño and sudden weather changes become a limiting factor for an IMTA grow-out pond system.

In this study, *G. verrucosa* had a lower growth rate compared to the reported optimum (>3% day^{-1}) by Annas *et al.* (2019). However, the result conforms to the study of Widowati *et al.* (2021) obtaining a lowest growth rate of 1.6% d^{-1} for *G. verrucosa* stocked at higher density (200g/m^2) but a highest growth of 2.6% day^{-1} at lower density (50g/m^2). Seaweeds had shown promising growth and survival in IMTA systems with shrimps (Anh *et al.,* 2019), however, the extreme temperature and salinity and probably a high stocking density (500 g/m^2) may have hindered the growth of *G. verrucosa*. The mass mortality of the mussels was due to the heavy rain. The rain exacerbated plankton die-off due to water parameter changes (Tan & Ransangan, 2019), which resulted in the unavailability of food for the mussels and the sudden changes in the water parameters (Chatterjiet *et al.,* 1984; Alexander *et al.,* 1994; Tan and Ransangan, 2019) that could be detrimental to the cultured organisms. Like any grow-out outdoor culture, the abrupt weather changes that were encountered during this study became a challenge that needs careful water management consideration for all the cultured organisms. Further research to address mortalities complemented with a careful management consideration is required to maintain an ideal water quality for the cultured organisms. Moreover, the water parameters in ponds, including salinity (24.3 to 34.36‰), temperature (28 to 40.64°C) and pH (7.5 to 9.49) exceeded the maximum ideal limit in all three treatments required by all culture organisms. Temperature showed the widest and highest ranges beyond the optimal value for all three treatments. Dissolved oxygen levels (2.76-5.43) were within the optimal range of some cultured organisms.

Table 4. Cost-benefit analysis on monoculture, polyculture and IMTA pond systems.

Treatments	Monoculture	Polyculture	IMTA
Variables			
A. Production			
Production of shrimp (kg)	11.33	6.08	19.60
Production of milkfish (kg)		51.64	70.07
Total Production shrimps & fish (kg)	11.33	57.72	89.67
B. Operating costs			
Seeds			
P. monodon @ PhP 0.25/PL for 7500 pcs	1,875.00	1,875.00	1,875.00
C. chanos @ Php 4/fingerling for 200 pcs		800.00	800.00
P. viridis @ PhP 7/kg for 15 kgs			87.50
Gracilaria sp.@ PhP 1/kg for 260 kgs			260.00
Feeds			
P. monodon	1,532.82	1,140.82	1,860.65
C. chanos		3,573.71	3,832.62
Caretaker @PhP5000/ha/month/	250.00	250.00	250.00
Labor-harvest @PhP2500/ha	125.00	125.00	125.00
Electricity @ PhP3000/ha/month	450.00	450.00	450.00
Repair & maintenance @ PhP10000/ha	500.00	500.00	500.00
Transport @ PhP5500/ha	275.00	275.00	275.00
Lime @ 2000kg/ha;@PhP5/kg	500.00	500.00	500.00
Teaseed @100kg/ha;@PhP95/kg	475.00	475.00	475.00
Ice, plastic bags	300.00	300.00	300.00
Miscellaneous @5000/ha/month	750.00	750.00	750.00
Total operating costs	7,032.82	11,014.54	12,340.77
C. Revenue*			
Shrimp @ Php 250/kg	2,833.14	1,521.19	4,899.90
Milkfish @ PhP 120/kg		6,196.77	8,407.92
Total revenue of shrimp & fish estimates (PhP)	2,833.14	7,717.95	13,307.82
Net revenue estimates (PhP)	- 4,199.68	- 3,296.58	967.05
D. FCR	2.38	2.22	1.62
E. ROI	- 59.72	- 29.93	7.84
F. BCR	- 0.60	- 0.30	0.08
G. Annual production estimates per hectare			
Shrimp (tons)	0.57	0.30	0.98
Milkfish (tons)		2.58	3.50
Total for shrimp and fish (tons)	0.57	2.89	4.48

*- based on prevailing market price in Naawan, Misamis Oriental, Philippines (USD 1 = PHP 55.00)

Economics of Production

Total shrimp-milkfish production was highest in IMTA (89.67 kg per 500 m^2 per cycle), followed by polyculture (57.72 kg) and lowest in monoculture (11.33 kg) (Table 4). Total operating cost was also highest in the IMTA system (PhP12,340.77), followed by polyculture (PhP11,014.54) and lowest in monoculture (PhP7,032.82). The effect of biomass was reflected in the revenues of the three treatments, with the highest revenue obtained in IMTA (PhP13,307.82), followed by polyculture (PhP7,717.95) and lowest in monoculture (PhP 2,833.14). IMTA system showed the highest profit at PhP967.05, while negative profits were observed in polyculture (PhP-3,296.58) and monoculture (PhP-4,199.68). The highest ROI (7.84 %) was obtained in IMTA, while negative ROIs were observed in polyculture (-29.93%) and monoculture (-59.72%).

The total annual production of a one-hectare pond with 2.5 production cycles for *P. monodon* and *C. chanos* is estimated at 4.48 tons for an IMTA system, 2.89 T for polyculture and 0.57 tons for monoculture. Milkfish provides the highest annual production estimates of 3.50 tons for IMTA and 2.58 tons for polyculture. Annual shrimp production estimate is highest in IMTA (0.98 t), followed by monoculture (0.57 t) and lowest in polyculture (0.30 t).

Cost-benefit analysis showed that IMTA performs better than polyculture and monoculture. Adding milkfish in polyculture and IMTA ponds resulted in higher production and revenues than monoculture. The result conformed with the studies in the IMTA pond, citing that adding more commercial species improves revenue, (Biswas *et al.,* 2020), higher productivity with better benefit-cost ratio in IMTA shrimp-fishes compared to shrimp monoculture (Balasubramanian *et al.,* 2018). Moreover, in an abalone-seaweed IMTA operation where increased profits is reported by 1.4–5% over abalone monoculture (Nobre *et al.*, 2010). Shrimp production for a semi-intensive farm varied from 0.5 to 5 T/ha/year (Janakiram *et al.,* 2011), with an average of 2.4 tons (Sabbir *et al.,* 2018). Only the IMTA ponds showed profitability among the three treatments, while polyculture and monoculture showed negative profits, which conforms to the study of Shi *et al.* (2013) showing significantly higher economic and environmental sustainability for IMTA than for two major monoculture models. IMTA models in brackish water ponds cultured with shrimps were better performers in terms of production and economic return than the polyculture system (Biswas *et al.,* 2020).

The cost-benefit analysis did not include initial investment and capital outlay, considering that the experiment had only used existing ponds. Moreover, on the intention that IMTA technology will be applied to existing unutilized ponds.

CONCLUSION

Penaeus monodon and *Chanos chanos* thrived better in IMTA compared to polyculture and monoculture due to organisms' synergistic interactions in the system, such as nutrient remediation by *G. verrucosa*, and bioremediation by the green mussel, which provide a healthier culture environment. The stocking density of milkfish may have influenced the shrimps' growth and survival, and further studies are needed to determine the ideal density of milkfish in an IMTA system. Adverse effects of climatic changes such as El Niño in the form of extreme temperature and salinity possibly resulted in shrimps' slow growth and low survival performance for the three culture systems. Abrupt weather changes like sudden rains resulted in the mortalities of mussels and seaweeds, thus requiring further research to address such mortalities and achieve a maximum bioremediation efficiency. Among the three culture systems, only IMTA showed profitability due to better growth, survival and biomass of *P. monodon* and *C. chanos.* However, the production performance of the three systems would have been better under normal climatic conditions.

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