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RESEARCH PAPER

Development of a Sustainable Polyculture Technique Using Asian Watergrass as Fish Feed in the Southern Coastal Region of Bangladesh

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Abstract

Globally, the quality and high cost of fish feed are vital issues for the development of sustainable aquaculture and food security. Present study was investigated in 4 treatments to find out the compatible species combination for polyculture using Asian watergrass as natural feed for fish in the tidally flooded coastal wetlands for a period of 6 months. Grass carp, common carp, tilapia, mrigal and silver barb were stocked in different species combination with an identical density of 12500 fish ha^{-1}. In all treatments, grass carp and common carp were commonly stocked but other 3 species were disparate to stock among the treatments. Important water quality parameters were monitored those were suitable and acceptable range for aquaculture. The survival of fishes varied from 66.7±8.3 to 91.2±2.9% irrespective of fish species. The total fish production was found significantly higher ($p<0.05$), 5579.04±238.74 kg ha^{-1} in T_3 followed by 4582.21±200.01 kg ha^{-1} in T_2, 4571.52±189.78 kg ha^{-1} in T_4 and 4448.37±247.26 kg ha^{-1} in T_1 respectively. The results demonstrate that the combination of grass carp, common carp, tilapia, and silver barb in T_3 was ideal compatible species for polyculture in coastal wetlands. This technique should be applied in *haor, baor, beel, canals*, and other water-logged areas pervaded by climate changes.

Introduction

Aquaculture has grown faster in comparison with some other important food industries in the world, and its expansion has been planned to meet the increased global fish demand conserving the stocks of natural fishes (FAO, 2018). Inland open water fish production in Bangladesh has gradually been decreased, and at the same time, aquaculture production sectors have been diversified, expanded, and increased utilizing advanced technology. According to Belton et al. (2011), natural open water fish production in Bangladesh has been decreased due to a diversity of causes such as environmental degradation, habitat loss, urbanization, pollution, and overexploitation. DoF (2020) estimates that Bangladesh produced 4.4 million metric tons of fish overall, of which 56.76% came from aquaculture. Indian major carps, exotic carps (mainly grass carp and common carp), silver barb, tilapia and pangas are the main polyculture species in Bangladesh. With a hidden aim to fulfill the demand, the production of farmed fish has gradually been increased to about 2.95 times from 2000 onwards and the average annual growth rate of fish production during three years prior to 2018 is 5.10% (DoF, 2018).

Currently, the price of fish feed is being increased due to the increase of the fishmeal price all over the world. FAO (2020) mentioned about the increase of

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price of fish meal and fish oil throughout the world due to the decline of world capture fisheries. On the other hand, the reduction of the environmental impact from aquaculture is a prime issue to produce quantity and quality fish through improving culture systems (Robinson et al., 2018). Accordingly, using substitute plant protein components for fish meal is crucial for the sustainable growth of aquaculture (Olukayode & Emmanuel, 2012; Daniel, 2018). Moreover, aquatic plants are a crucial source of fish food, and they also help to enhance water quality and treat aquaculture waste (Sipauba-Tavares et al., 2002; Henry-Silva & Camargo, 2006; Ferdoushi et al., 2008; Carlozzi & Padovani, 2016).

The Asian watergrass (*Hygroryza aristata*) is an important aquatic plant that naturally grows in all the freshwater bodies and vigorously grows in the tidally flooded coastal wetlands of Bangladesh Hossain et al., 2020a). Bangladesh's coastline region covers 47201 sq km of land, or around 32% of the nation's overall area (Islam, 2004). The Coastal Zone Policy (CZPo, 2005) of the Government of Bangladesh states that 19 of the country's 64 districts—covering a total of 147 upazilas (sub districts)—are in the coastal zone. The coastal wetlands become flooded twice daily during high tide throughout the year. Fish polyculture can be practiced in the tidally flooded low-lying coastal wetlands where Asian watergrass thrives year-round (Hossain et al., 2020a). The important encouraging aspect in the coastal wetlands of Bangladesh is the regular exchange of water by the tidal action that helps in maintaining the water quality for good farming practices. In addition to actively promoting and maintaining food webs and ecosystem services in freshwater habitats, aquatic plants have the capacity to enhance water quality by absorbing nutrients through their efficient root systems (Lesiv et al., 2020). In addition, *H. aristata* contains requisite amount of protein, lipid and carbohydrate and whole body of the grass is very soft and preferred food of grass carp that has been used as natural feed for fishes in polyculture (Hossain et al., 2020b). Hossain et al. (2021) reported that the leaf of Asian watergrass contains 17.49±0.21% crude protein, 2.15±0.02% lipid and 50.96±0.65% carbohydrate. Pipalova (2006) reported that the grass carp favors filamentous algae, duckweeds, and soft-tissue aquatic plants and eats all sections of these plants. Once more, common carp is an omnivorous bottom-dwelling fish that relies heavily on grass carp's decomposing floral matter and benthic animals to thrive. Mrigal is also a bottom dweller fish and prefers feed on detritus and benthic fauna. Since, the silver barb mostly consumes aquatic plants, grasses, and algae, it can tolerate a variety of environmental conditions and grows well on low-protein diets (Srisuwantach, 1981; Bentsen et al., 1996). Tilapia can be a good species for polyculture with grass carp employing Asian watergrass as natural feed for fish, according to our past study findings and published studies. Therefore, grass carp, common carp, mrigal, silver barb and tilapia may be a compatible species combination for polyculture using Asian watergrass as feed.

Polyculture is one of the most important culture techniques among different technologies of fish culture. The importance of polyculture for increasing the fish production is well documented (Azim & Wahab, 2003; Asadujjaman & Hossain, 2016). A compatible combination of species with diversified feeding habit should be included column feeders to benthic feeders as well as omnivorous to macro-vegetation feeding fish species. Selection of suitable fish species in polyculture is therefore very important. In this system fast growing well-matched species of diverse feeding behavior are stocked in different proportions in the same water body (Rohmana et al., 2015) allowing farmers to get higher profits (Li & Dong, 2000). The system has been practiced with different species in the water body occupying different niches with their harmonizing feeding habits, utilizing all the natural food available in that water body for increasing the fish production (Wahab et al., 2001; Alam et al., 2001). In a practical polyculture system, the species combination increases synergistic effects, decreases antagonistic fish-fish and fish-environment association, and improves growth and production results (Haque et al., 2015). According to Barcellos et al. (2012), in polyculture systems a proper combination of ecologically different species at adequate densities will utilize the available resources efficiently, maximize the synergistic fish-fish and fish-environment relationships and minimize the antagonistic ones. Additionally, it is one of the most crucial culture techniques in the aquaculture industry to generate the highest output using readily accessible feeds at the lowest possible cost. Polyculture may be more cost effective if we can maximize the utilization of available natural foods. Therefore, the aim of this study is to find out the compatible species combination to develop a sustainable polyculture technique using Asian watergrass as natural feed of fishes in the southern coastal area of Bangladesh.

Materials and Methods

Study Area

The research was carried out in the natural condition of coastal wetlands in Bisharkandi union of Banaripara upazila (sub district) under Barishal District (latitude 22°47´ to 22°53´ north and longitude 90°00´ to 90°05´ east) for a period of 6 months from May to October (Figure 1). The tidally flooded low-lying wetlands in this area are ideal for growing Asian watergrass.

Preparation of the Experimental Plots

For conducting this research, four treatments each with three replications were set up in the tidally flooded coastal wetlands (Figure 2). In the experimental area, the two lateral sides were previously closed by 1.5 m high dykes (locally called kandi). Because of this, the selected area was around 0.4-0.5 m deeper than the nearby wetlands. At the beginning of the work, the dykes' heights were raised. The excavated bottom soil of the experimental area was utilized to raise the dykes. The other two sides were kept open in such a way that allowed natural tidal flow of water into the experimental site, but not the fish. In doing this, the open two sides of all six selected areas were closed using mats made of bamboo splits and small mesh sized knotless net (mesh size: 0.5 cm) (Figure 2). Tidal water could pass through the mats regularly exchanging water with the experimental area, but not the fish. Subsequently, the selected areas were divided into 2 equal sized experimental plots (each plot: 10 m × 6 m, 60 m^2) to make12 plots (Figure 2) that were randomly selected for experiments. Asian watergrass was planted on the bottom soil in each experimental plot in the middle of January and grown as fish feed before three and a half months of fish stocking. The homogeneity of the growth and production of Asian watergrass was confirmed in each plot of all treatments before stocking of fish.

Asian Watergrass Plantation

At the beginning of the work, the unnecessary weeds were removed from the experimental area. Then, on the bottom soil of each treatment, Asian watergrass was planted, covering roughly 80% of the area following Hossain et al. (2020b).

Fish Stocking

On 01 May, after three and a half months of the Asian watergrass plantation, healthy fingerlings of grass carp (*Ctenopharyngodon idella*), common carp (*Cyprinus carpio*), mrigal (*Cirrhinus cirrhosus*), silver barb (*Barbonymus gonionotus*) and tilapia (*Oreochromis niloticus*) were stocked in different species combination. Commonly grass carp and common carp were stocked in all treatments, but other species (tilapia, mrigal and silver barb) were disparate to stock among the

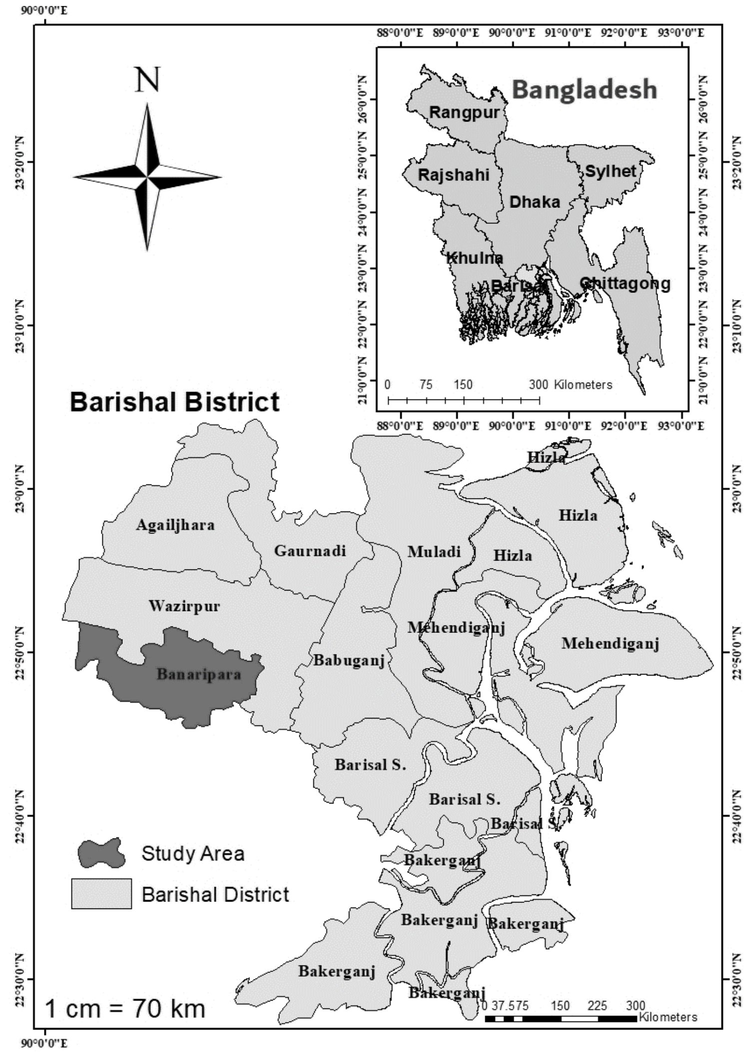

Figure 1. Map of Bangladesh showing the study area. The paste color indicates the Asian watergrass growing zone and red color indicate the experimental site in the coastal region of Bangladesh

treatments. The stocking densities were similar in all treatments (75 fish per 60 m^2; 12500 fish ha^{-1}), but the species combinations were different (in treatment one, T_1: grass carp 53, common carp 7, tilapia 8, mrigal 7; in treatment two, T_2: grass carp 53, common carp 7, silver barb 8, mrigal 7; in treatment three, T_3: grass carp 53, common carp 7, tilapia 8, silver barb 7; and in treatment four, T_4: grass carp 53, common carp 5, tilapia 7, mrigal 5 and silver barb 5). Before stocking of fish, the initial weight of 20% of grass carp and 50% of other species in each treatment weighed using a digital weighing balance (model: M-ACS015G/C).

Monitoring of Water Quality Parameters

The water quality parameters such as water temperature (ºC), transparency (cm), dissolved oxygen (mg L^{-1}), pH and salinity (‰) were measured at monthly interval by using a thermometer, a Secchi disk, a portable DO meter (DO-5509, AF.11581, Taiwan), a portable pH meter (pHep, HANNA Instruments, Romania) and a portable digital refractometer (Brix HI 96801), respectively. Water samples were collected from each treatment in plastic bottles to determine the total alkalinity (mg L^{-1}), ammonia (mg L^{-1}), nitrate-nitrogen (mg L^{-1}), nitrite-nitrogen (mg L^{-1}) and phosphate-phosphorus (mg L^{-1}). By employing a titrimetric technique with a 0.02N H_2SO_4 titrant and methyl orange indicator, the total alkalinity was determined. The ammonia, nitrate-nitrogen, nitrite-nitrogen, and phosphate-phosphorus were measured using a spectrophotometer (DR 1900, HACH, USA). Mineral stabilizer, polyvinyl alcohol dispersing agent and nessler reagent were employed to measure ammonia. NitraVer®6 nitrate reagent, NitriVer@3 nitrite reagent and PhosVer@3 phosphate reagent were used for the determination of nitrate-nitrogen, nitrite-nitrogen, and phosphate-phosphorus, respectively.

Harvesting of Fish

At the end of the experiment in October, all the stocked fishes were harvested. The harvested fishes of each species were counted and weighed separately for each treatment. Thereafter, the growth performance (final weight, weight gain, specific growth rate), survival and the total production were calculated by using the following formulae:

(a) Weight gain = Final weight (g) – Initial weight (g)

(b) Specific growth rate (% body weight day^{-1}) = [{ln (final weight) – ln (initial weight)} /culture period (days)] × 100 (Brown 1957)

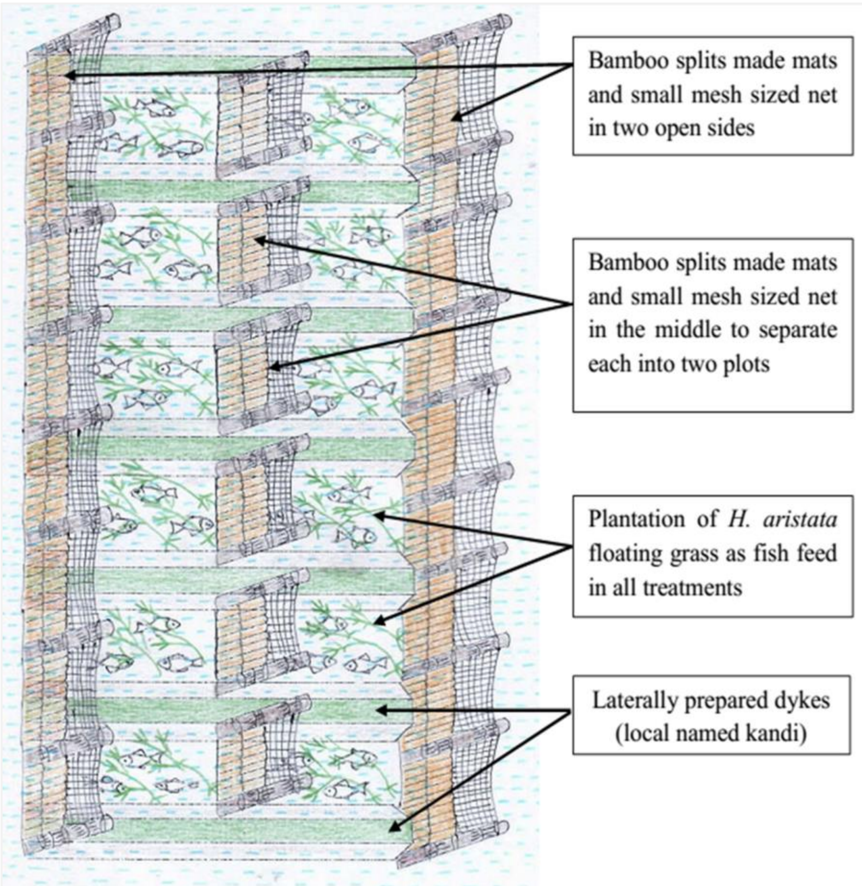

Figure 2. Sketch diagram showing the experimental plots and different parts of the system. The experiment was randomly selected under four treatments each with three replications. The Asian watergrass was planted before three and a half months of fish stocking and grown on the bottom soil as fish feed in all treatments.

(c) Survival (%) = [No. of harvested fishes/Initial no. of stocked fish] ×100

(d) Production (kg ha^{-1}) = [{No. of total harvested fishes × average individual weight of fish (g) / cultured area} × 10000] /1000.

Data Analysis

Values of all the measured variables have been revealed as mean±SD. The data of growth performance and water quality parameters were analyzed following a one-way analysis of variance (ANOVA). Following Duncan's Multiple Range Test (DMRT), the paired comparison was made. All data groups underwent normality and homogeneity of variance testing prior to statistical analysis. Significance was assigned at the 5% level ($P<0.05$). Statistical analyses were performed using PASW statistics 20.0 software (IBM SPSS Statistics, IBM, Chicago, USA).

Results

Water Quality Parameters

The measured water quality parameters did not show any significant variation among the treatment (Table 1). During the study period the water temperature ranged from 29.0-32.9°C, dissolved oxygen from 5.1-5.8 mg L^{-1} and pH from 7.0-7.9. The salinity of water was 1.0 ‰ throughout the study period. The total alkalinity was found reasonably high (104-188 mg L^{-1}) in all treatments. Low levels of nitrate-nitrogen (0.03-0.09 mg L^{-1}), nitrite-nitrogen (0.003-0.014 mg L^{-1}), phosphate-phosphorus (0.12-0.67 mg L^{-1}) and ammonia (0.01-0.13 mg L^{-1}) were observed (Table 1) throughout the study period.

Growth Performance

The growth performance, survival, and total production of the cultured fishes in four different treatments are displayed in Table 2, 3 and Figure 3-8. The growth performance (final weight, weight gain and SGR) of grass carp, common carp, silver barb and tilapia were found to be significantly higher ($P<0.05$) in T_3 followed by T_2 (no tilapia), T_4, and T_1 (no silver barb), respectively. The mrigal showed higher growth performance in T_1 followed by T_2 and T_4 (Table 3). The survival rates were varied from 66.7±8.3 to 91.2±2.9% irrespective of fish species. The highest survival was found in grass carp (91.2±2.9%) followed by tilapia (83.3±7.2%), common carp (81.0±8.3%), silver barb (81.0±8.3%) and mrigal (80.0±20.0%) in different treatments (Table 3). The productions of grass carp, common carp, tilapia, and silver barb were found to be significantly higher ($P<0.05$) in T_3 in comparison with other 3 treatments (Table 3, Figure 4, 5, 7, 8). But, the production of mrigal was found to be higher in T_2 followed by T_1 and T_4 (Table 3; Figure 6). The total production of all species was found significantly higher ($P<0.05$) in T_3 followed by T_2, T_4 and T_1 respectively, but in T_1, T_2 and T_4 did not show any significant difference among themselves (Figure 3).

Discussion

In contrast to other fish species that rely on them, grass carp were introduced to consume the grass directly for nutrients and to develop like cattle, fertilizing the system by discharging excrement and enhancing other natural feeds like plankton and benthic invertebrates. Accordingly, the common carp and mrigal were stocked to feed the defecated materials of grass carp, detritus and the benthic food organisms of the

Table 1. Water quality parameters (mean±SD, n= 18) in four different treatments.

Parameters	Treatments			
	T_1	T_2	T_3	T_4
Water temperature (°C)	31.0±1.0 (29.3-32.5)	30.9±1.2 (29.0-32.9)	31.0±1.2 (29.0-32.8)	31.0±1.1 (29.3-32.9)
Transparency (cm)	44.1±5.7 (31.0-53.0)	44.2±6.5 (30.0-53.0)	43.3±5.3 (31.0-51.0)	43.6±5.6 (32.0-52.0)
Dissolved oxygen (mg L^{-1})	5.5±0.16 (5.2-5.8)	5.6±0.19 (5.1-5.8)	5.6±0.30 (5.2-5.7)	5.5±0.17 (5.2-5.8)
pH	7.4±0.24 (7.1-7.8)	7.4±0.22 (7.1-7.8)	7.4±0.26 (7.0-7.9)	7.4±0.21 (7.1-7.8)
Salinity (‰)	1.0±0.0	1.0±0.0	1.0±0.0	1.0±0.0
Total alkalinity (mg L^{-1})	129.5±20.0 (108.0-178.0)	128.1±22.4 (108.0-188.0)	126.1±18.1 (108.0-178.0)	126.9±20.4 (104.0-182.0)
Ammonia (mg L^{-1})	0.07±0.03 (0.03-0.13)	0.08±0.03 (0.01-0.13)	0.08±0.03 (0.04-0.13)	0.08±0.03 (0.04-0.13)
Nitrate-nitrogen (mg L^{-1})	0.06±0.01 (0.04-0.08)	0.06±0.02 (0.03-0.09)	0.05±0.01 (0.04-0.08)	0.05±0.02 (0.03-0.09)
Nitrite-nitrogen (mg L^{-1})	0.007±0.003 (0.004-0.014)	0.008±0.003 (0.004-0.014)	0.007±0.002 (0.004-0.013)	0.007±0.002 (0.003-0.011)
Phosphate-phosphorous (mg L^{-1})	0.24±0.07 (0.16-0.41)	0.24±0.07 (0.17-0.41)	0.24±0.11 (0.16-0.55)	0.24±0.13 (0.12-0.67)

SD: Standard deviation, n: Number, C: Celsius, cm: Centimeter, ‰: Parts per thousand, mg: Milligram, L: Liter, and T: Treatment. Values within the parenthesis indicate the range.

bottom mud. The silver barb was stocked to grow eating available plankton and root of the grass. Additionally, omnivorous tilapia were supplied for growth, fed on grass, different kinds of plankton, and other naturally occurring items.

In this study, all the observed water quality parameters were found suitable and within the suitable range for fish culture (Kirkagac & Demir, 2004; Jena et al., 2007; Rahman et al., 2012; Mamun & Mahamud, 2014; Haque et al., 2015; Hossain et al., 2020b). The monthly deviations were found in all observed water quality parameters except salinity due to the seasonal changes. Throughout the study period 1.0 ‰ salinity was found in all treatments that supported by Hossain et al. (2020a,b). Throughout the research period, the water temperature was observed reasonably higher (29.0-32.9ºC) which might be suitable for the higher growth of both the grass and the fish. Sun & Chen (2014), reported that fish growth, food consumption and energy utilization increased with increasing water temperature at 27.0-33.0°C. Comparatively low levels of nitrate-nitrogen, nitrite-nitrogen, phosphate-phosphorus, and ammonia were recorded in all treatments those might be due to the exchange of water daily by tidal action into the experimental site (Hossain et al. 2020a,b). Additionally, the present study found that the polyculture was appropriate for all of the measured water quality parameters, which is validated by several other authors (Kirkagac & Demir, 2004; Haque et al., 2015; Chowdhury & Hasan, 2015; Hossain et al., 2020a).

The growth performance, survival and total production of grass carp were found highest in T_3 followed by T_2, T_4 and T_1, respectively which indicate that species combination in T_3 with grass carp were compatible compared to other three treatments. Although, the growth and production performance of grass carp of all treatments were satisfactory and encouraging considering the feed. The feed of grass carp was Asian watergrass that contains requisite amount of protein 17.49±0.21% in leaves and 12.17±0.65% in roots and higher carbohydrate 50.96±0.65% in leaves and 56.97±0.97% in roots (Hossain et al., 2021), and the entire body of the grass is very soft and ideal food of this fish. According to Pipalova (2006), the grass carp favors filamentous algae, duckweed, and soft tissue of aquatic

Table 2. Total biomass production (kg ha^{-1}) in each treatment in four different treatments.

Treatments	Plots	Species wise production (kg ha^{-1} 6 months^{-1})	Total production (kg ha^{-1} 6 months^{-1})	Average production (kg ha^{-1} 6 months^{-1})
Treatment one (T_1)	T1R1	(Grass carp:3426.38; Common carp: 309.17; Tilapia:380; Mrigal:166)	4281.55	
	T1R2	(Grass carp:3885.60; Common carp: 358.67; Tilapia:329; Mrigal:159.17)	4732.44	4448.36±247.26
	T1R3	(Grass carp:3520; Common carp: 294.17; Tilapia:359.72; Mrigal:157.22)	4331.11	
Treatment one (T_2)	T2R1	(Grass carp:3690; Common carp: 321.39; Silver barb:282.78; Mrigal:196)	4490.17	
	T2R2	(Grass carp:4012.28; Common carp: 368; Silver barb:272.22; Mrigal:159.17)	4811.67	4582.21±200.01
	T2R3	(Grass carp:3619.73; Common carp: 319.72; Silver barb:339.33; Mrigal:166)	4444.78	
Treatment one (T_3)	T3R1	(Grass carp:4711.67; Common carp: 432; Silver barb:296.39; Tilapia:413.78)	5853.84	
	T3R2	(Grass carp: 4251.93; Common carp: 391.33; Silver barb:356.67; Tilapia:422.72)	5422.65	5579.04±38.74
	T3R3	(Grass carp:4403.20; Common carp: 326.11; Silver barb:365; Tilapia:366.33)	5460.64	
Treatment one (T_4)	T4R1	(Grass carp:3518.90; Common carp: 185.33; Silver barb:223.78; Tilapia:301.39; Mrigal:123.56)	4352.96	
	T4R2	(Grass carp:3885.60; Common carp: 240.67; Silver barb:237.78; Tilapia:237.56; Mrigal:93)	4694.61	4571.51±189.78
	T4R3	(Grass carp:3793.47; Common carp: 246.44; Silver barb:170.67; Tilapia:305.83; Mrigal:150.56)	4666.97	

Kg: Kilogram, T: Treatment, R: Replication, and ha: hectare

Table 3. Growth and production performance of the cultured fish species (mean±SD) in different treatments.

Species	Treatment	Initial weight (g)	Final weight (g)	Weight gain (g)	SGR (% day^{-1})	Survival (%)	Production (kg ha^{-1} 6 month^{-1})
Grass carp	T_1	52.7±6.7	481.3±58.7^b	428.5±59.5^b	1.45±.12^b	84.9±5.0	3610.7±242.7^b
	T_2	52.7±6.0	492.3±44.0^b	439.6±44.1^b	1.46±0.10^b	86.8±5.0	3774.0±209.3^b
	T_3	53.2±7.2	552.9±79.7^a	499.7±79.7^a	1.53±0.13^a	91.2±2.9	4455.6±234.3^a
	T_4	53.1±8.4	494.4±50.9^b	441.3±51.1^b	1.46±0.12^b	85.5±5.8	3732.7±190.8^b
Common carp	T_1	34.1±7.4	360.9±24.6^b	326.8±28.0^b	1.55±.14	76.2±8.3	320.7±33.8^a
	T_2	32.3±8.5	379.1±14.8^{ab}	346.8±17.3^{ab}	1.63±0.16	76.2±8.3	336.4±27.4^a
	T_3	31.7±5.6	404.9±46.2^a	373.2±46.9^a	1.67±0.15	81.0±8.3	383.2±53.4^a
	T_4	29.1±4.7	367.1±29.5^b	338.0±32.7^b	1.66±0.15	73.3±11.6	224.2±33.7^b
Mrigal	T_1	20.8±2.8	188.0±14.3	167.2±14.5	1.44±0.10	76.2±8.3	160.8±4.6^a
	T_2	21.6±3.7	184.3±24.6	162.8±25.6	1.40±0.15	70.8±7.2	173.7±19.6^a
	T_3	-	-	-	-	-	-
	T_4	22.4±3.7	184.0±20.0	161.6±22.8	1.38±0.17	80.0±20.0	122.4±28.8^b
Silver barb	T_1	-	-	-	-	-	-
	T_2	10.9±1.6	335.1±21.3	324.2±21.4	2.25±0.11	76.2±8.3	298.1±36.1^a
	T_3	11.3±1.9	359.1±43.8	347.8±45.5	2.26±0.19	81.0±8.3	339.4±37.4^a
	T_4	11.0±1.8	344.6±49.5	333.6±49.6	2.25±0.15	73.3±11.6	210.8±35.4^b
Tilapia	T_1	31.6±3.7	324.0±38.6^b	292.4±38.6^b	1.52±0.10	83.3±7.2^a	356.2±25.7^a
	T_2	-	-	-	-	-	-
	T_3	34.9±7.4	361.1±30.7^a	326.2±27.6^{ab}	1.54±0.13	79.2±7.2^a	400.9±30.3^a
	T_4	32.6±6.8	361.7±49.8^a	329.1±39.8^a	1.58±0.16	66.7±8.3^b	281.6±38.2^b

SD: Standard deviation, SGR: Specific growth rate, g: Gram, kg: Kilogram, %: Percentage, ha: Hectare. Figures in the same column of a particular fish species having the different superscripts in different treatments are significantly different (P<0.05)

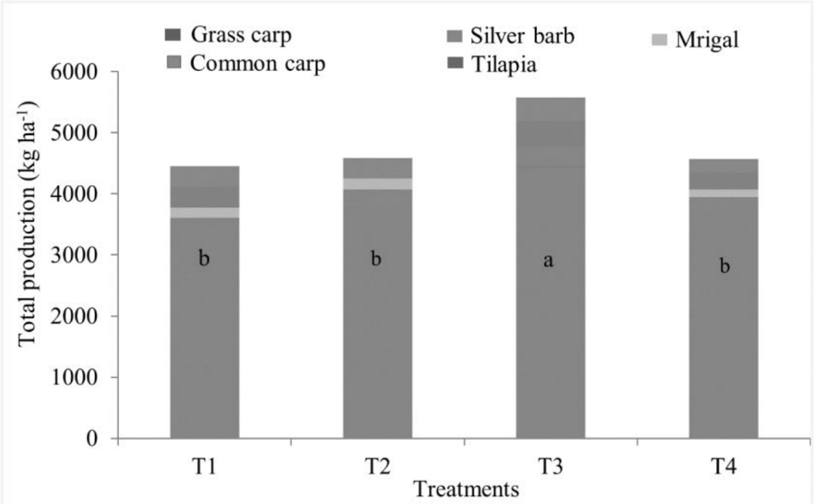

Figure 3. Total production performance (kg ha^{-1} 6 months^{-1}) in four different treatments. Values accompanied by different letters are significantly different (P<0.05) among the treatments.

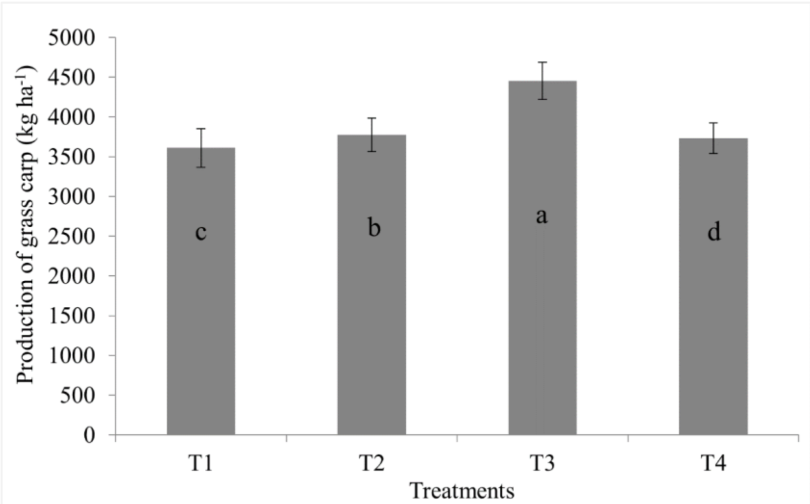

Figure 4. Production performance of grass carp (kg ha^{-1} 6 months^{-1}) in four different treatments. Values accompanied by different letters are significantly different (P<0.05) among the treatments.

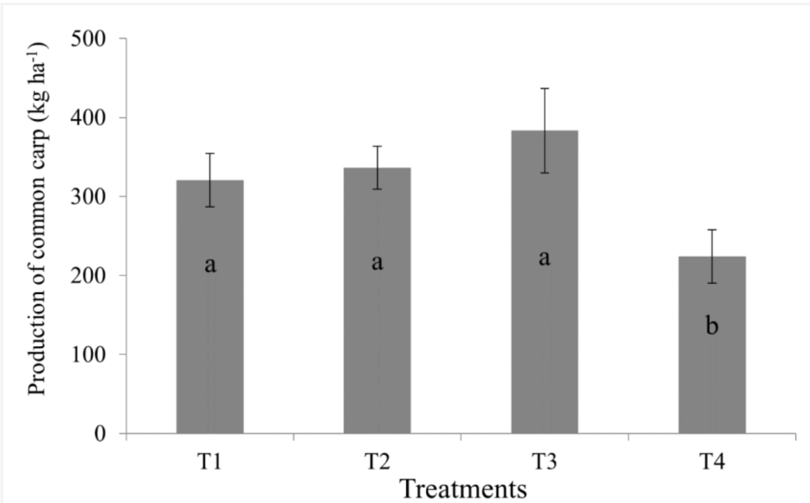

Figure 5. Production performance of common carp (kg ha^{-1} 6 months^{-1}) in four different treatments. Values accompanied by different letters are significantly different (P<0.05) among the treatments.

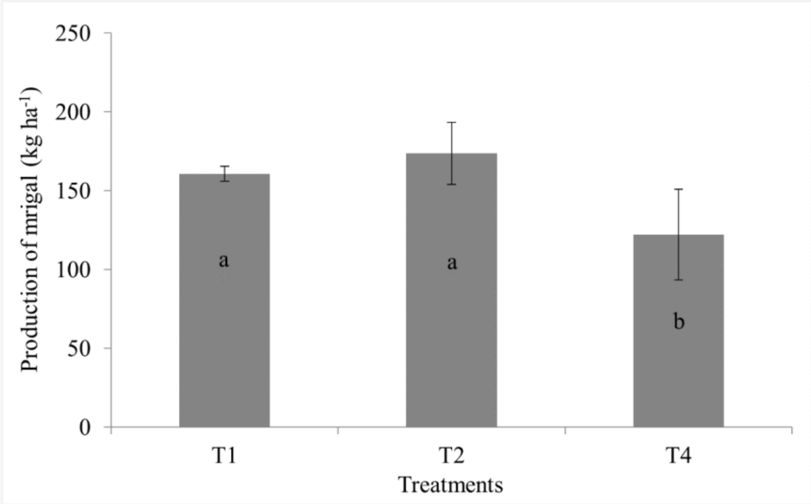

Figure 6. Production performance of mrigal (kg ha^{-1} 6 months^{-1}) in three different treatments. Values accompanied by different letters are significantly different (P<0.05) among the treatments.

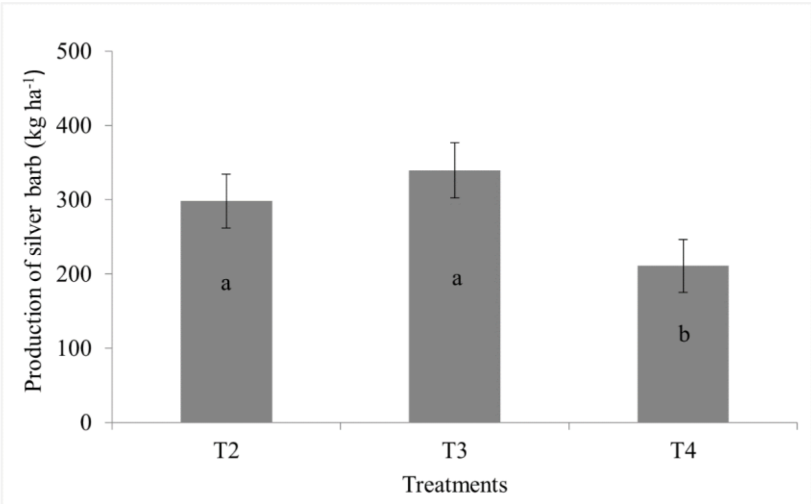

Figure 7. Production performance of silver barb (kg ha^{-1} 6 months^{-1}) in three different treatments. Values accompanied by different letters are significantly different (P<0.05) among the treatments.

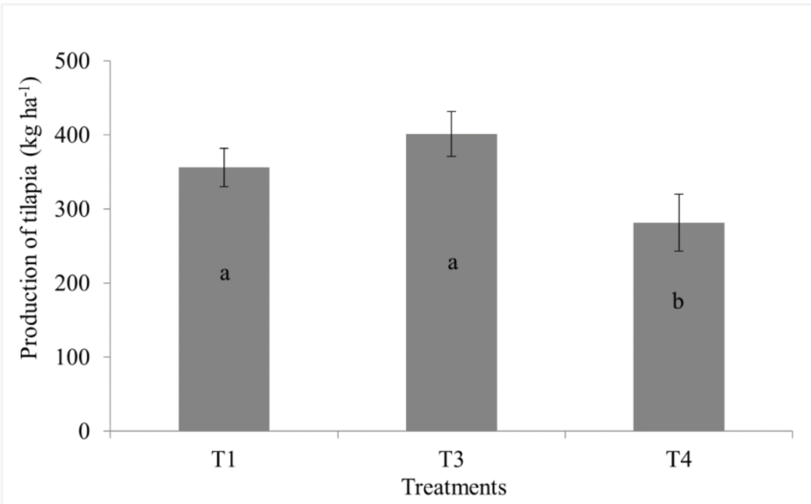

Figure 8. Production performance of tilapia (kg ha^{-1} 6 months^{-1}) in three different treatments. Values accompanied by different letters are significantly different (P<0.05) among the treatments.

plants, and eats all portions of these plants. High-carbohydrate feedstuffs can ideally be utilized to trigger the protein-sparing effect, making the feed more affordable (Hidalgo et al., 1993). Grass carp have herbivorous appetites and consume large quantities of higher aquatic plants and it can be cultured by providing fish edible leaves and whole soft plants either aquatic or terrestrial in the water body without costly artificial feeds (Halver & Hardy, 2002; Pillay, 2004). Fish may be fed on edible aquatic plants that naturally grow in bodies of water by converting them into feed (Edwards et al., 1992; Gavina, 1994). Dibble & Kovalenko (2009) reported that the submerged aquatic plants, algae, and pond weeds (*Potamogeton spp.*) are the regular food items eaten by grass carp. In China, the floating aquatic plant *Hydrocharis dubia* is harvested and grown as a rich source of nutrition for grass carp fingerlings (Hasan & Rina, 2009). Many authors reported the grass carp as a good species for aquaculture considering its fast growth and herbivorous feeding habit (Pipalova, 2006; Dibble & Kovalenko, 2009; Hossain et al., 2020a) that strongly supported our findings.

The bottom-dwelling omnivorous common carp mostly consumes benthic organisms and decomposing plant materials. Its growth is often influenced by the availability of benthic macro-invertebrates, the quality and quantity of additional feed that is provided, as well as the density of its own stock. Mrigal is also a bottom dweller fish and prefers to feed on detritus and benthic fauna. In the present study, the common carp and mrigal were stocked to feed the defecated materials of grass carp, detritus and the benthic food organisms of the bottom mud. The growth, survival and production performance of common carp were found more or less similar and satisfactory in all treatments except in T_4 considering the fish feed. The survival and production of common carp in T_4 were found comparatively low in comparison with other three treatments that might be due to that the species combination were not compatible in T_4. On the other hand, the growth and production performance of mrigal were not satisfactory in comparison with the common carp among the treatments that might be due to the higher competition with common carp, and available detritus, defecated materials of grass carp and benthic food organisms those present were more preferred by common carp in comparison with mrigal. Besides, common carp fed the byproduct materials of grass carp provided from the system where Asian watergrass was used as natural feed, and those materials become detritus through microbial decomposition and settled down on the bottom mud (Hossain et al., 2020b). Most probably the by production and defecated materials of grass carp in this system were not preferred food by the mrigal, and for this reason the growth and production of mrigal were comparatively low in comparison with the common carp. Parameswaran et al. (1971) mentioned higher growth performance of common carp in comparison to Indian major carps having similar feeding habits. Common carp exposes exceptional growth rate, omnivorous feeding habit and easy adaptation to diversified feeds. The common carp was found as a suitable species in the polyculture system with grass carp using Asian watergrass as feed (Hossain et al., 2020b). Many studies reported that common carp cultured alone or in combination with other fish species provided high growth, production performance and economic benefit (Ibrahim, 2011; Noman et al., 2011; Abbas et al., 2014; Khan et al., 2016) that strongly supported our findings. Comparatively higher growth and production performance of common carp were found in T_3 in comparison with other three treatments indicated that the species combination was compatible in T_3 for polyculture using Asian watergrass as fish feed.

Silver barb introduction into native carp polyculture enhanced overall fish yield (Kohinoor et al., 1994; Wahab et al., 1995), and it is a suitable candidate for polyculture with carps and obtained suitable growth and production (Halim et al., 2018). Significantly higher ($P<0.05$) production of silver barb was found in T_3 in comparison with T_2 and T_4 indicated that the species combination was compatible in T_3 for polyculture using Asian watergrass as feed in comparison with T_2 and T_4. Silver barb is an herbivorous species and grows well on low protein diets, feeding mainly on aquatic plants, grasses, and algae, and can tolerate a wide range of environmental parameters (Srisuwantach, 1981; Bentsen et al., 1996). Due to its quick development, strong market demand, bright silvery appearance, delicious taste, year-round reproduction, and adaptation to a variety of cultural circumstances, silver barb has become a common species in popular culture (Hussain et al., 1989; Haque et al., 1998; Mollah et al., 2011; Halim et al. 2018). Gupta & Rab (1994) reported that the silver barb can survive and grow in brackish water having salinity as more as 7.0 ‰ and become to table size within three to four months. Many authors reported silver barb as an environmentally compassionate species and has no adverse effect on native and exotic species and it may be an excellent candidate for polyculture (Haque et al., 1998; Rahman et al., 2006; Mollah et al., 2011; Halim et al., 2018). Silver barb is considered to be a suitable species for inclusion in the widely practiced Indian major carp-based polyculture system without compromising the total production (Haque et al., 1998; Jena et al., 2007; Mollah et al., 2011), which encouraged us to select this species in polyculture using Asian watergrass as feed directly in the coastal wetlands of Bangladesh.

Tilapia has gained popularity as a commercial aquaculture species among different cultured fishes in Bangladesh and in many other tropical and sub-tropical countries in the world. It is the second important cultured fish in the world (FAO, 2018). Some characteristics of tilapia such as rapid growth, omnivorous feeding habit, excellent meat quality, resistance to diseases and the ability to feed on the lowest trophic level make it widely popular in the world

(Pullin, 1988; Grassi et al., 2016). Since tilapia is extensively cultured in tropical and subtropical regions, it is expected that in a few decades, tilapia may become the main species of aquaculture in the world (Tacon et al., 2011). In the present study, the growth and production performance of tilapia were found higher in T_3 followed by T_1 and T_4 indicated that the species combination was ideal and suitable in T_3. The growth and production performance of tilapia in all treatments were reasonably good considering the feed. Hossain et al. (2020b) reported that tilapia can be a good species for polyculture with grass carp utilizing Asian watergrass as feed. Compared to many other fish species raised in captivity, tilapia can tolerate greater nutritional fiber and carbohydrate concentrations (El-Sayed & Teshima, 1992; Ogello et al., 2014). In natural condition tilapia consume large quantity of plant materials dominated by detritus, algae and the associated bacteria (Moriarty, 1973; Getachew, 1987; Diana et al., 1991 and Temesgen et al., 2022). In the present study, the utilization of Asian watergrass in natural condition as fish feed in polyculture is coherent with the findings of Santiago et al. (1988), Mbagwu & Adeniji (1988), Wahab et al. (2001), Uddin et al. (2007), Chowdhury et al. (2008) and Agbo et al. (2011), who used fresh duckweed as feed for tilapia and silver barb. Tilapia farmers may consider the alternative dietary sources because replacement of fishmeal in the supplemental diet of tilapia is experimentally proved and would be economic (Ogello et al., 2014), and our findings may provide valuable information for using aquatic plant directly as fish as well as in formulated feed.

Generally, in the aquaculture system, huge amount of feeds and fertilizers are used all over the world including Bangladesh and uneaten portion of applying feeds and biomass metabolic wastes release nutrients in water and sediments through microbial decomposition which create water body hyper-nutrified (Hossain et al., 2005). These excess nutrients in the water body create phytoplankton blooms and mass mortality occurred of cultured fish in some tropical countries. Asian watergrass is very interesting source of fish feed and it has capacity to improve the water quality by absorbing excess nutrients, with their effective root system. At the same time, they actively contribute to the promotion and maintenance of food webs and service in freshwater ecosystems (Scheffer & Jeppesen, 2007; Smith, 2011). Aquatic plants are very interesting source of fish feed and have positive effects for improvement of water quality and remediation of aquaculture effluents (Sipa uba-Tavares et al., 2002; Henry-Silva & Camargo, 2006; Carlozzi & Padovani, 2016). These two eco-services are beneficial for increasing the sustainability of small-scale fish farming all over the world. In the present study, the total fish production accumulating all species in each treatment was found significantly higher ($P<0.05$) 5579.04±238.74 kg ha^{-1} in T_3 followed by 4582.21±200.01 kg ha^{-1} in T_2, 4571.52±189.78 kg ha^{-1} in T_4 and 4448.37±247.26 kg ha^{-1} in T_1 respectively that very encouraging using solely Asian watergrass as fish feed with the maintenance of water quality.

Conclusion

Polyculture is very important in contrast of developing countries like Bangladesh to increase the fish production of the rural poor levels that contribute the blue economy of the country. Moreover, compatible fish species in polyculture is very important, which assemble the farmers more beneficial from their efforts and enhance their livelihood. Considering the fish feed cost, Asian watergrass utilization in the polyculture system is more practical to produce quality fish with the maintenance of friendly environment. The present findings indicate that the grass carp, common carp, silver barb and tilapia are the best combination in T_3 for obtaining maximum growth and production using Asian watergrass as natural feed for fishes. To improve the productivity, this technique should be developed in *beels*, canals, coastal ponds, baors, and other water-logged areas affected by climate changes. More research on the use of this grass as fish feed ingredients to formulate commercial feed for other animals may enrich the feed industry.

Ethical Statement

Not applicable.

Author Contribution

Md. Moazzem Hossain: conceived, designed, performed the experiments, analyzed data, and wrote the manuscript.

Md. Shahjahan: assisted in the experimental design, edited the manuscript.

Md. Hafizur Rahman: assisted in data analysis and drafting the manuscript.

Saleha Khan: edited the manuscript.

Newton Saha: analyzed and interpreted the data; wrote the paper. All authors reviewed and approved the final manuscript.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional or non-professional conflict that would have appeared to influence the work reported in this paper.

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