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Research Article

Efficacy of the environmentally oriented system design of wastewater fish culture and ecological services in the Mudialy Fish Farm, Kolkata, West Bengal, India

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Abstract

The environment based operational aspects of the Mudialy Fish Farm operated by the Mudialy Fisherman's Cooperative Society (MFCS) has been investigated in terms of wastewater reclamation potential, fish production efficiency and other ecological services of the primarily industrial wastewater fed culture ponds. The system design of this farm is unique as, besides fish production, it renders a number of ecological services. Water and sediment qualities were analyzed from different locations of the sequential wastewater reclamation process in the fish farm at monthly intervals for a period of ten months. The results showed that average reduction in Biochemical oxygen demand (BOD) and Chemical oxygen demand (COD) in the anaerobic pond and culture pond was 71.17% and 50.75%, and, 45.46% and 57.33%, respectively. Removal of nitrate-N from sewage water was 44.08 - 39.29%, whereas ortho-P removal was 56.95% - 48.25% from the inlet raw sewage water. Both phytoplankton and zooplankton abundance increased (P< 0.001) in the anaerobic pond and in the culture pond, respectively by 89.84% and 1384.81%, and, 611.62% and 4448.83%. High degree of diversification in species composition was recorded with 14 numbers of purposively stocked species and 22 numbers of native wild species in the culture system. Annual average fish production from the sewage-fed culture ponds was estimated as 8.225 tonne/hectare.

Key words: Ecological services, Fish yield, Mudialy Fish Farm, Reclamation potential, Wastewater aquaculture

Highlights

- Macrophyte based industrial wastewater reclamation strategy was studied.
- Significant reduction of BOD, COD and nutrients was recorded in the anaerobic and culture ponds.
- pH and dissolved oxygen profile of the treated sewage improved significantly.
- Highly diversified species composition was adopted.
- Annual yield was estimated as 8.225 tonne/ha.

INTRODUCTION

Sewage-fed aquaculture practice is a traditional low-input technology for producing aquaculture crops long originated in south and south-east Asian countries. This unique technology is environmentally sound and ecologically oriented towards bio-circularity of resource management, amalgamating low-cost methods of wastewater treatment and different trophic levels of energy flow from waste to wealth. It reduces environmental pollution through bioremediation of wastewater into valuable fish protein that has otherwise been directly discharged into surface waters in many cases (Edwards, 2000), particularly in economically poorer nations with a limited capacity for wastewater management. Aquaculture has steadily grown and emerged as an industry with a 4% annual growth rate; from the global perspective; Asian aquaculture continued to dominate with 91.6% contribution (FAO, 2022). However, Das (2022) reported

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that intensification in aquaculture often occurs at the expense of the environment; thereby, sustainable aquaculture development becomes vulnerable to be critical towards supplying the increasing demand for aqua-crops.

Urban and peri-urban domestic wastewater is loaded with invaluable nutritional resources as waste. The eco-sanitation approach of waste disposal practice is based on the ecological ethics of 'solution to pollution is dilution'. The principal objectives of bio-circulation in wastewater reuse in aquaculture is to harvest the organic and toxic forms of nitrogen, phosphorus, carbon and others through sequential biological processing at successive trophic levels leading to generation of fish biomass (Das and Mandal, 2018). Transformation and transfer of nutrients occurs through abiotic and biotic components of the aquatic ecosystem where bacteria, fungi, actinomycetes, plankton and heterotrophs at different trophic levels. Also, the macrophyte-based wastewater processing system has been proved to have significantly reduced faecal coliforms and other pathogens (Das and Jana, 2002). Therefore, such environmentally sound bio-transformation approach of resource recovery and reuse has become more pertinent in the changed and challenged environmental perspectives. However, wastewater-fed aquaculture in general, is either gradually declining or being phased out because of intense pressure on urban land use and increasing health concerns of the practitioners (Das, 2022). The major constraints of wastewater aquaculture are rapid urbanization consequent with declining availability of peri-urban land, increasing contamination of city sewage with industrial toxicants and upscaling of living standards of city dwellers who prefer higher value fish (Howgate *et al.*, 2002; Edwards 2005; Little and Bunting 2005).

Low-cost wastewater recycling system that evolved in Kolkata has long been considered as unique in the world in transforming waste into consumable agriculture and aquaculture produces. Mudialy Fish Farm is one of the scientifically managed sewage-fed fisheries in and around Kolkata (Ganguly *et al.*, 2015) that has bagged National Productivity Award for five times. Mudialy Fisherman's Cooperative Society (MFCS) has developed a unique system for recycling industrial and municipal waste and wastewater, along with an integrated production center for horticulture, floriculture, animal husbandry, farm forestry and eco-park. The annual fish sale amounted to Rs.1.16 crores in the year 2018-19. The average daily loading of sewage water is approximately 23 million liters, of which about 70% is from industries and the rest from domestic sewage. During the past, the marshy wetlands of Mudialy are used to be flooded with polluted wastewater from the city and the adjoining industrial complex. In subsequent times, these wetlands have radically been transformed into sewage-fed fish farms and a water-front recreational eco-park. The present work focuses on the environment based operational aspects of the farm based on the system efficiency in terms of wastewater reclamation, fish production and other ecological services of the primarily dominated industrial wastewater fed culture ponds of Mudialy Fish Farm (Fig. 1).

MATERIALS AND METHODS

Description of the study area: The Mudialy Fisherman's Cooperative Society (MFCS) is located 10 km southwest from the heart of the metropolis of Kolkata. The operational area of the farm is around 80 ha wetland leased from the Kolkata Port Trust (KPT).

System design of MFCS fish farm: The average daily loading of sewage water in the farm is estimated as 23 million liters of which about 70% is sourced from adjoining industries and the rest from the domestic sewage (Sengupta *et al.*, 2012). This wastewater enters into the fishery where the nature-based treatment of such wastewater is located. The flowchart is presented in Fig. 2.

Sampling and analysis of water samples and sediment: As the wastewater is processed and

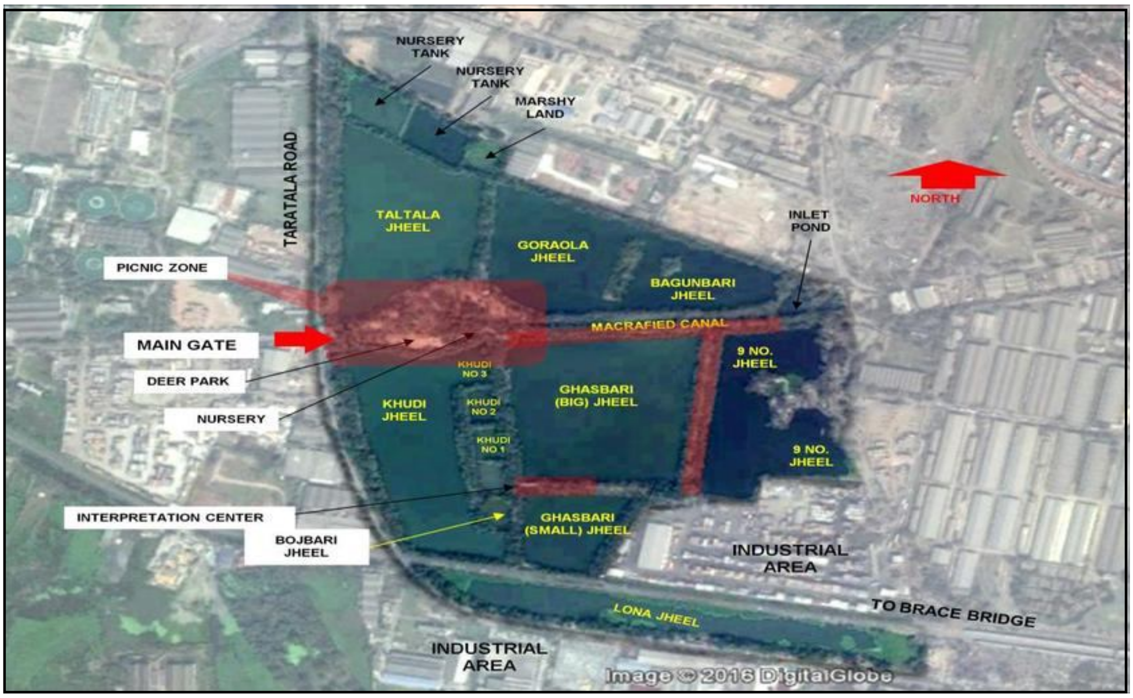

Fig. 1. Satellite view of the Mudialy Fish Farm

The wastewater passes through a series of anaerobic tanks, where the water is limed and other biochemical agents

Water hyacinths are kept in the anaerobic tanks for absorption of oil, grease and heavy metals from the waste water.

Water flows from one tank to another through a narrow channel, which is used as breeding ground for hardy fish viz. *Tilapia nilotica, Heteropneustes fossilis*), *Clarias batrachus* and *Anasbas testudineus*.

The water then flows into a series of ponds and through a saprophytic canal; the water quality improves and become congenial for fish culture. Finally, the water is let into the Manikhal canal that ends into the Hooghly River.

Fig. 2. Flow chart of the system design of Mudialy Fish Farm

treated as it passes through specially designated three categories of ponds and tanks, water and sediment samples were collected from all three categories of water bodies. Three ponds each from purification tanks and fish culture units viz. Gorala, Ghasbari and Taltala; and three inlet ponds were selected as sampling sites. Following all the standard procedures, water and sediment samples were collected at monthly intervals from each of the ponds at a fixed hour of the day (10,00 -10.30 A.M.) for physico-chemical analyses. Plankton samples were also collected at monthly intervals with the help of a conical plankton net made up of bolting silk cloth (No. 21 with 77 meshes per square cm). About 20 liters of water from each pond was collected from randomly selected locations with the help of 1000 mL beaker and pooled together for filtering, 20 mL filtrate was preserved in 4% formalin solution and stored in labelled vials for subsequent quantitative and qualitative analyses. Abundance of macrophytes were also recorded and variability in heterogeneity was tested. Fish heterogeneity were recorded on the date of harvesting in every month, and monthly fish yield data from the culture units were collected from the MFCS authority.

The data of water and sediment analyses were expressed as mean ± SE (Standard error). All the data were subjected to a one-way analysis of variance (ANOVA) using MS-EXCEL 2016 followed by DMRT (SPSS) and the level of acceptance at confidence level of 95% ($P<0.05$).

RESULTS

Water quality: The pH of water ranged from 6.4-7.2, 7.1-7.96 and 7.1- 8.25 in the raw sewage, anaerobic pond and culture pond, respectively. Dissolved free carbon di-oxide differed significantly and the mean value was highest (46.77 mg L^{-1}) in raw sewage, 30.14 mg L^{-1} in the anaerobic pond and lowest (12.70 mg L^{-1}) in the culture pond. Total alkalinity of water did not differ between the raw sewage and anaerobic pond (98.29-112.11 mg L^{-1}), but was significantly higher in the culture pond (155.05 mg L^{-1}). However, hardness of water was reduced significantly by 19.31% and 38.50% from the inlet raw sewage in the aerobic pond and culture pond, respectively (Table 1).

Among the primary water quality parameters concerning to wastewater reclamation, dissolved oxygen concentration of water was highest in the culture ponds (7.17 - 9.5 mg L^{-1}) followed by anaerobic ponds (3.45 - 5.28 mg L^{-1}) and lowest in inlet water (2.42 - 4.42 mg L^{-1}) (Fig. 3A). The average change in concentration from the raw sewage water in the inlet was 23.80 and 96.22% in anaerobic and culture ponds,

Table 1. Range of pH and Mean (± SE) values of water and sediment quality parameters in different sub-systems

Parameter	Raw sewage		Anaerobic pond		Culture pond	
	Range	Mean± SE	Range	Mean± SE	Range	Mean± SE
Water						
pH	6.4-7.2	-	7.1-7.96	-	7.1-8.25	-
Free CO_2 (mg L^{-1})	34.20-66.05	46.77±1.06^{a}	18.40-38.25	30.14±0.74^{b}	10.20-16.50	12.70±0.44^{c}
Alkalinity (mg L^{-1})	73.6-109.40	98.29±3.57^{a}	98.0-129.50	112.11±3.40^{a}	125.30-169.60	155.05±5.04^{b}
Hardness (mg L^{-1})	152.5-235.3	194.97±2.54^{a}	145.3-169.2	157.31±1.06^{b}	95.40-138	119.91±1.19^{c}
Total phytoplankton (nos. L^{-1})	50-126	79±13.86^{a}	530-1100	778±118.87^{b}	920-1400	1173±146.97^{c}
Total zooplankton (nos. L^{-1})	10-38	21.5±9.73^{a}	130-168	153±21.01^{b}	470-1330	978±92.17^{c}
Sediment						
pH	6.27-6.55	-	6.75-7.25	-	7.04-8.16	-
Organic C (%)	2.45-18.32	11.91±1.44^{a}	3.22-7.33	6.31±0.53^{b}	3.17-5.58	4.09±0.75^{c}
Available-P (mg kg^{-1})	18.21-21.52	19.15±0.27^{a}	9.03-12.85	10.57±0.24^{b}	9.35-11.37	10.46±0.06^{b}
Available-N (mg kg^{-1})	421.15-527.26	469.78±13.59^{a}	208.36-396.37	340.13±27.55^{b}	184.29-340.36	252.04±19.02^{c}

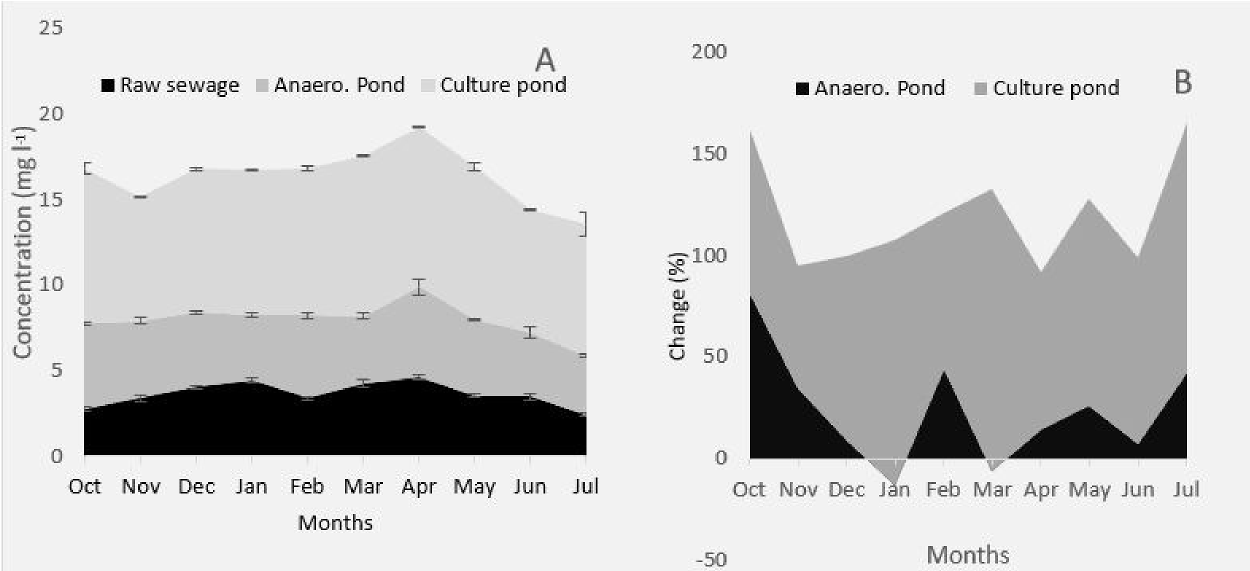

Fig. 3. Temporal changes of dissolved oxygen (A) and change (%) of dissolved oxygen in anaerobic ponds and culture ponds

respectively (Fig. 3B). BOD_5 values of water were maximal in inlet water (103.62 mg L^{-1}) and minimal in the culture pond (14.67 mg L^{-1}) (Fig. 4A). The successive average reduction in BOD_5 values in the anaerobic pond and culture pond was 71.17% and 50.75%, respectively in comparison to the raw sewage water (Fig. 4B). COD values of water responded identically to that of BOD_5 with maximal and minimal values in inlet water (217.01 mg L^{-1}) and culture ponds (48.91 mg L^{-1}), respectively (Fig. 5A). The average reduction of COD values from the raw sewage in the inlet was 45.46% and 57.33% in anaerobic ponds and culture ponds, respectively (Fig. 5B). Average concentration of nitrate-N in general, declined gradually in the anaerobic ponds and culture ponds (Fig. 6A), and the successive average reduction of nitrate-N of water from the raw sewage was 44.08 and 39.29581% in the former and later pond, respectively (Fig. 6B). Ortho-P concentration of water in the inlet water was significantly higher in raw sewage (0.77 mg L^{-1}) compared to the anaerobic ponds (0.32 mg L^{-1}) and culture ponds (0.167 mg L^{-1}) (Fig. 7A). The sequential reduction in anaerobic pond and culture pond was 56.95% and 48.25% from the inlet water (Fig. 7B). Both phytoplankton and zooplankton density increased highly significantly (P, 0.001) in the anaerobic and culture ponds, respectively by 89.84% and 1384.81%; and, 611.62% and 4448.83% compared to the raw sewage water at the inlet (Table 1).

Sediment quality: The sediment pH was highest in the culture ponds (7.04-8.16) followed by anaerobic ponds (6.75-7.25) and raw sewage (6.27-6.55). Organic-C was significantly higher in the raw sewage (11.91±1.44%) and lowest (4.09±0.75) in the culture ponds. Both available-N and P significantly decreased successively in the anaerobic ponds and culture ponds by 44.80% and 45.37%; and, 27.59% and 46.35% compared to the inlet water (Table 1).

Catch composition and abundance of fish: The catch composition of fish in the culture ponds showed that there were 14 intended species of culture and 22 wild native species. As per the frequency of occurrence in the catch in different months, Among the Indian major carps, *Catla catla* and *Labeo rohita* were of most common occurrence and among the exotics, *Hypothalmicthys molithrix* and tilapias viz.

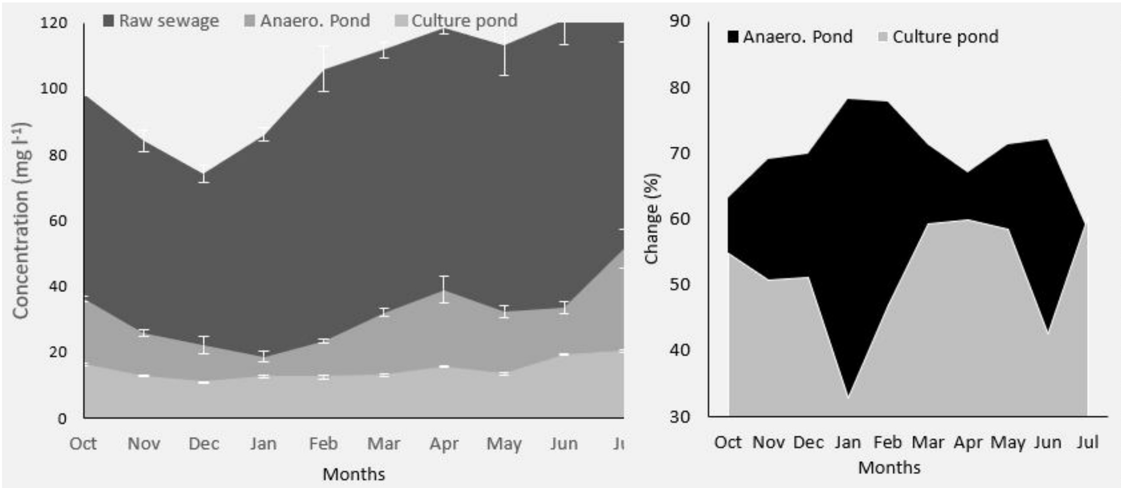

Fig. 4. Temporal changes of dissolved BOD_5 (A) and change (%) of BOD_5 in anaerobic ponds and culture ponds

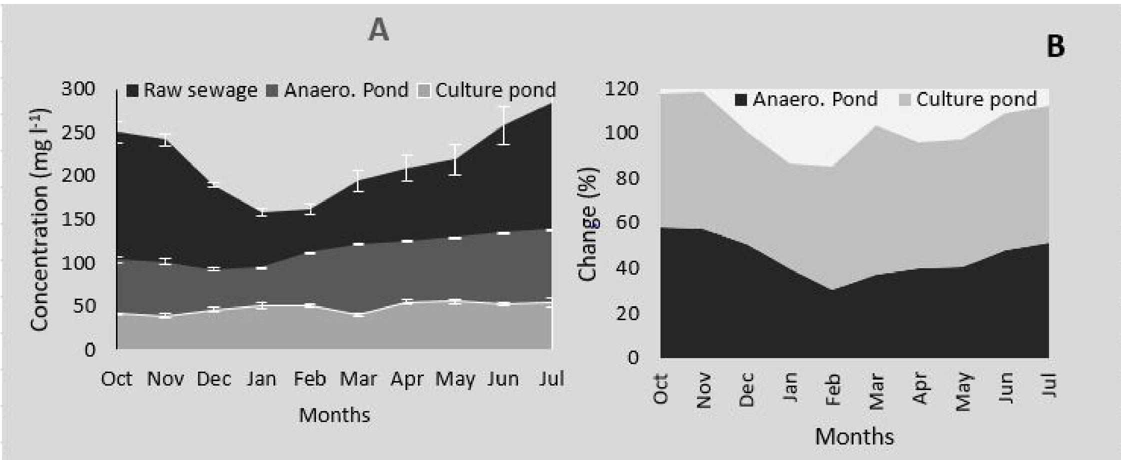

Fig. 5. Temporal changes of dissolved COD (A) and change (%) of COD in anaerobic ponds and culture ponds

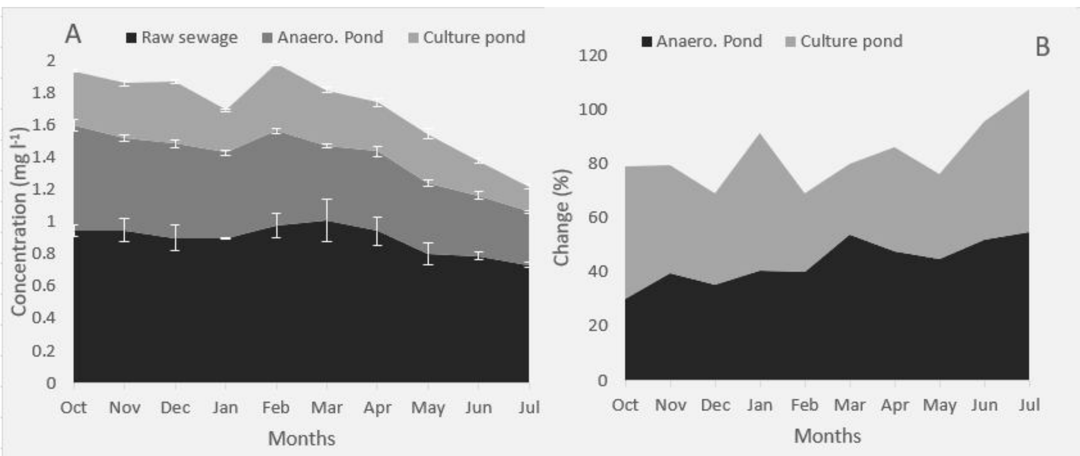

Fig. 6. Temporal changes of nitrate-N (A) and change (%) of nitrate-N in anaerobic ponds and culture ponds

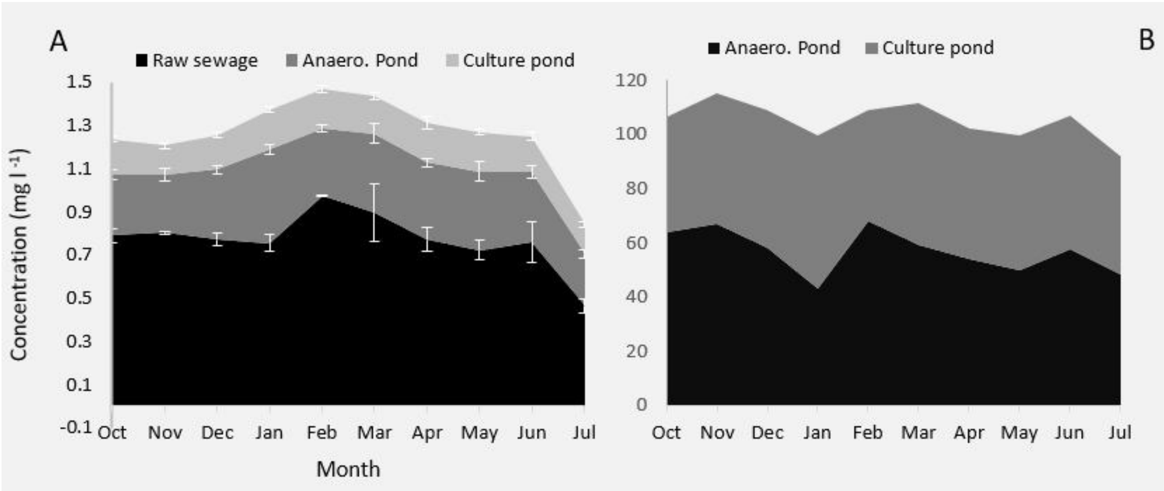

Fig. 7. Temporal changes of orthophosphate (A) and change (%) of orthophosphate in anaerobic ponds and culture ponds

Oreochromis mossambicas and *O. niloticus* were maximally frequented in the catch composition. Among the native wild fishes, *Mystus vittatus*, *Macrognathus armatus*, *Anabas testudineus* were most common (Table 2).

Fish yield: The maximal and minimal average catch of fish from the culture ponds was recorded in February and July respectively. Monthly fish catch from the culture ponds ranged from 0.16-1.255 tonne/ha (Fig. 8) and the estimated yield during the investigation period of ten months was 6.854 tonne/ha that corresponded to 8.225 tonne/ha/yr.

Table 2. Heterogeneity and relative abundance of fish in the catch composition

Sl. No	Scientific name	Common name	Abundance
A	Cultured Fish		
1	*Catla catla*	Catla	+++
2	*Labeo rohita*	Rui	+++
3	*Cirrhinus mrigala*	Mrigal	++
4	*Labeo bata*	Bata	+++
5	*Labeo calbasu*	Kalbaus	++
6	*Hypothalmicthys molithrix*	Silver Carp	+++
7	*Ctenopharyngodon idella*	Grass Carp	++
8	*Cyprinus carpio*	Common Carp	+
9	*Aristichthysnobillis nobilis*	American Rui	+
10	*Hypophthalmichthys nobilis*	Bighead Carp	+
11	*Oreochromis mossambicas*	Tilapia	+++
12	*Oreochromis nilotica*	Nilontica	+++
13	*Lates calcarifer*	Bhetki	++
14	*Liza parsia*	Perse	+

Table 2., Cont. ...

Cont. Table 2.

Sl. No	Scientific name	Common name	Abundance
B	Wild Fish		
1	*Puntius chola*	Puti	+
2	*Puntius guganio*	Puti	+
3	*Amblypharyngodon mola*	Mourala	+
4	*Glossogobius giuris*	Bele	+
5	*Salmostoma bacaila*	Chala	+
6	*Aploeheilus panchax*	Techoka	++
7	*Mystus vittatus*	Tangra	+++
8	*Mystus gulio*	Tangra	++
9	*Channa striatius*	Sol	+
10	*Channa punctatus*	Lata	++
11	*Channa gachua*	Chang	+
12	*Heteroneustes fossilis*	Singi	+
13	*Macrognathus pancalus*	Pankal	++
14	*Macrognathus armatus*	Ban	+++
15	*Pisodonophis boro*	Kucho	++
16	*Ophisternon bengalense*	Bero	+
17	*Chanda nama*	Chanda	+
18	*Chanda ranga*	Rangachanda	+
19	*Notopterus notopterus*	Falui	++
20	*Anabas testudineus*	Koi	+++
21	*Badis badis*	Bhada	+
22	*Clarias batrachus*	Magur	++

Common: +++; Sporadic: ++; Rare: +

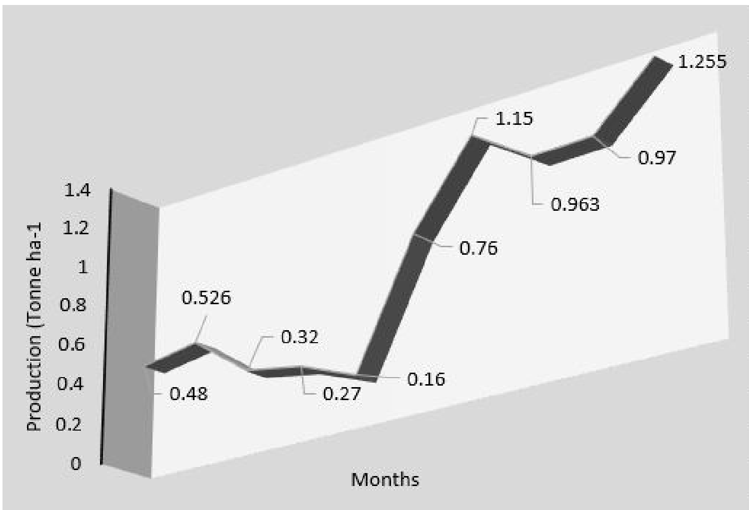

Fig. 8. Temporal changes of fish production in the culture ponds

DISCUSSION

The results of the study strongly established the efficacy of the low-cost environmentally sound approach of wastewater reclamation, reuse and resource recovery with clearly discernible positive ecological footprints. This model of sewage-based fish culture system largely differs from the East Kolkata Wetlands, where the principal source of wastewater is from the domestic urban sewage against primarily dominated industrial wastewater in the present model of study. In spite of that, all the parameters of prime concern in reclamation of wastewater viz. reduction of nutrient loads, BOD, COD; attaining congenial pH and dissolved oxygen in water for fish culture; reduction of nutrient (N, P and C) loads from the sediments of wastewater ponds exhibited significant response in the reclamation pathway. This has been established strongly in Fig. 9, where except dissolved oxygen of water, BOD_5, COD, nitrate-N and orthophosphate decreased sequentially from the inlet point of sewage water entry into the system to anaerobic ponds and finally to the fish culture ponds ($R^2 \geq 0.93$). In contrast, dissolved oxygen increased exponentially ($y=2.1891e^{0.423x}$; $R^2 = 0.93$) from inlet water to culture ponds which was the prime necessity for fish culture. Therefore, the efficacy of the macrophyte bed and the anaerobic ponds in the subsequent stages in the reclamation process was sound and highly effective. Though several studies documented the efficiencies of different aquatic macrophytes in the nutrient removal process (Das and Jana, 2002; Das and Mandal, 2018), these were based on urban sewage-based models. The present study quantified the nutrient removal capacity of the large bodied aquatic macrophyte, *Eichhornia crassipes* from primarily dominated industrial wastewater. The multifaced ecological services of the aquatic macrophyte in the reclamation process was manifested as the hazardous BOD and COD load has also significantly reduced with concomitant increase in dissolved oxygen by 96.22% compared to the raw sewage. The environmental benefit of macrophyte based nutrient removal process is ecologically sound as such hydrophytes are more effective in carbon sequestration also (Kochi *et al.*, 2020). All other physico-chemical water quality parameters, viz. pH, dissolved free carbon di-oxide, alkalinity, and hardness also significantly changed favourably towards fish culture. The increased abundance both of phytoplankton and zooplankton in the culture ponds further established the strong efficacy of the system design being followed in the present study area.

Though the sediment quality also improved a lot with regards to pH, N and P content; organic-C content in the culture pond sediment still remained in the higher range (4.09%) that was beyond the best suitable level (1-3%) for fish culture ponds as reported by Boyd (2002). High concentration of sediment organic matter negatively affects the overlying water quality of the pond (Boyd, 2003).

The results of the present study clearly indicated high degree of diversification in species composition in the culture ponds where 14 nos. of species were stocked purposively, and another 22 nos. of valuable native wild species remained in the culture system as co-habitant. This is unique in that the wastewater culture system serves not only for table fish production but also acts as a repository of a wide variety of indigenous small and medium category fishes. Species diversification has been stated to be an effective strategy for production enhancement and sustainability of the culture system (Das, 2022). The fitted relationship exhibited that the monthly production of fish tended to increase from February onwards (Fig. 10). This was because fish being poikilothermic animal depend upon its ambient temperature for their enhanced metabolic activity and growth. Therefore, with increasing water temperature from the onset of spring onwards, the growth rate increased and reflected in the production. The average estimated yield of 8.225 tonne ha^{-1} $yr.^{-1}$ in the culture pond was commendable against the national productivity of 3.22 tonnes ha^{-1} $yr.^{-1}$.

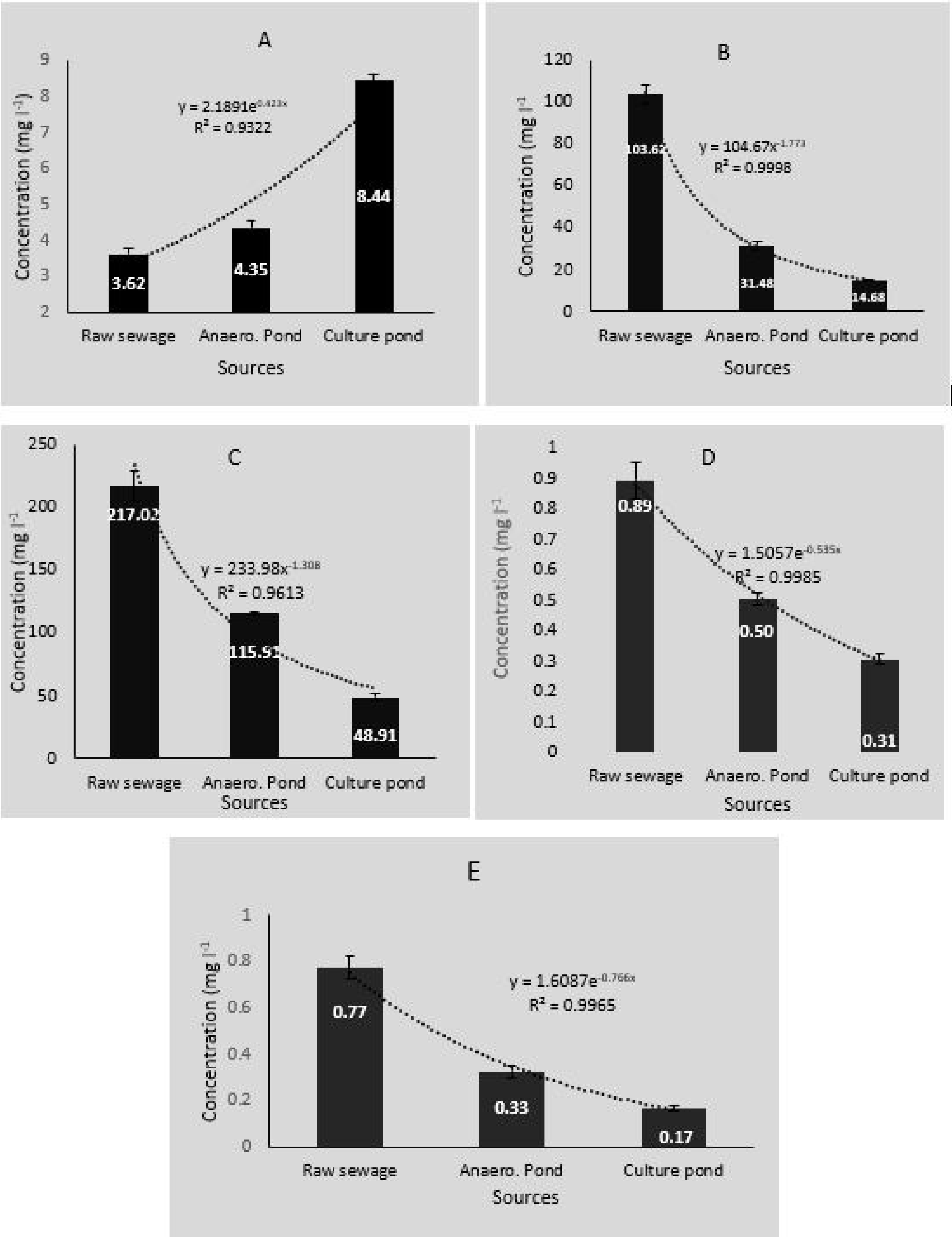

Fig. 9. Fitted changes of dissolved oxygen (A), BOD_5 (B), COD (C), nitrate-N (D) and orthophosphate (E) in different sources of water

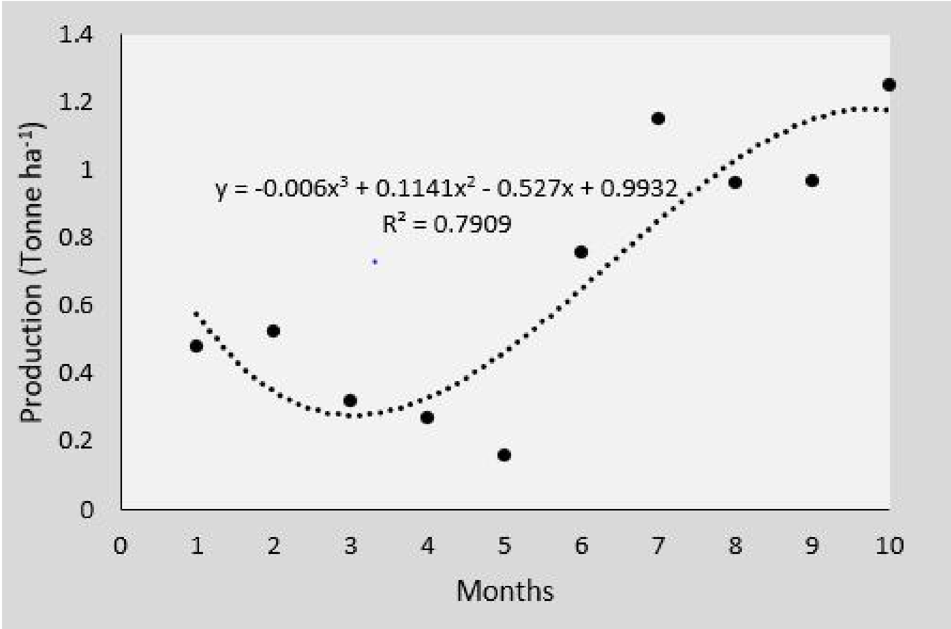

Fig. 10. Fitted temporal trend of fish production in the culture ponds

The present study conclusively established the sound environmentally oriented wastewater reclamation strategy subsequently amalgamated with fish culture in the MFCS in Mudialy Fish Farm. Besides wastewater recycling, this strategy was found to be strongly effective in converting waste to wealth taking environmental service and returning back a number of ecological services with strong footprints. Such strategy might be adopted in other areas where sufficient land is available to achieve bio-circularity in resource use with zero disposal to safeguard our mother nature.

Conflict of interest: Authors have no conflict of interest in this study.

Author's contribution: MB: Executed sample collection and analyses; SKD: Designed the work and finalized the graphics and write-ups.

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