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Sustainable coastal mariculture through integrated multi-trophic aquaculture of green mussel (*Perna viridis*) and silver pompano (*Trachinotus blochii*)

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ABSTRACT

The present study assesses the performance of an Integrated Multi-Trophic Aquaculture (IMTA) system combining *Trachinotus blochii* (silver pompano) and *Perna viridis* (green mussel) across estuarine areas in Udupi district, Karnataka, India. The IMTA system consisted of two fish cages integrated with two mussel rafts. In contrast, the control system, located approximately 1 km away from the IMTA unit, comprised two fish cages and two mussel rafts maintained separately, with a distance of about 500 m between the fish cages and mussel rafts to prevent interaction effects. This experimental arrangement was replicated across four locations. Over a 180-day culture period, key indicators including water quality, growth metrics, survival rates, and economic performance were monitored. Fish reared under the IMTA system exhibited superior growth; with an average weight of 412 ± 7.20 g compared to 338.8 ± 0.72 g at the control site wherein mussels and fishes are reared in isolation. Mussels cultured within the IMTA system achieved higher shell lengths (75.9 ± 1.15 mm) opposed to those in the control (68.2 ± 0.54 mm). Fish survival was notably higher in the IMTA system (84.9 ± 0.9%) relative to the control (78.3 ± 0.5%). Similarly, mussel survival was improved in IMTA (90.54 ± 2.8%), contrast to the control (77.62 ± 9.6%), indicating more favourable rearing conditions. Economically, IMTA demonstrated a better benefit-cost ratio (1.75) over the control (1.34), reflecting improved cost-efficiency and profitability. The findings highlight IMTA's advantages in terms of enhanced nutrient utilization, growth performance, and economic returns. Additionally, a survey of farmer's perception on IMTA indicated strong support for IMTA as a community-based, sustainable aquaculture approach, underlining its potential for wider regional implementation.

1. Introduction

Aquaculture has emerged as the world's fastest-growing food production sector, playing a crucial role in meeting the rising global demand for protein-rich aquatic foods. From 1990–2020, global aquaculture production increased more than sixfold, growing at an average rate of about 6–7% per year (FAO, 2024). Its rapid growth highlights its increasing role in supplying affordable, nutritious fish protein while generally exerting lower environmental pressure compared to many other animal-based food production systems (Bjørndal et al., 2024; Yeşilsu et al., 2025).

In the last decade, India has made significant strides in aquaculture production, primarily led by shrimp and carp culture, positioning the country among the top aquaculture producers worldwide (FAO, 2024). The expansion of aquaculture in to the coastal and estuarine areas through cage farming, mussel and oyster farming in India has not only supported food security but also created substantial livelihood opportunities, especially in coastal and rural regions.

Karnataka, a maritime state on India's western coast, is endowed with extensive aquatic resources, particularly estuarine systems. These estuarine ecosystems have supported the rise of diverse aquaculture practices, including cage farming, mussel farming, and other coastal aquaculture initiatives. These systems have played a vital role in enhancing the income and nutritional security of local fishing

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communities. However, the rapid intensification of aquaculture, while beneficial economically, has also brought about several environmental challenges including nutrient loading, eutrophication, and habitat degradation (Naylor et al., 2000; Biswas et al., 2019).

To address these concerns, the concept of Integrated Multi-Trophic Aquaculture (IMTA) has gained prominence as a sustainable alternative. IMTA involves the co-culture of species from different trophic levels, where the waste (both organic and inorganic) generated by one species serves as input (food or nutrients) for another (Grosso et al., 2023; Batır et al., 2025). This ecological approach creates a balanced system that mimics natural ecosystem processes (Knowler et al., 2020). In a typical IMTA system, fed species like finfish or shrimp are cultured alongside organic extractive species such as shellfish (e.g., mussels, oysters) and inorganic extractive species like seaweeds that absorb dissolved nutrients. The interconnectedness of these species, facilitated through the movement of nutrients and energy via water, contributes to environmental remediation, resource efficiency, and product diversification (Chopin, 2013).

Unlike traditional polyculture systems, where a range of species may be raised in a common space with minimal nutrient recycling, IMTA is structured and functionally integrated to maximize ecological efficiency. Traditional low-input polyculture continues to be prevalent in tropical Asian countries, but attention is increasingly shifting toward IMTA due to its multiple benefits (Shyu and Liao, 2004; Barrington et al., 2009). Moreover, while land-based aquaculture systems have received significant research attention, IMTA in marine and open-water environments—despite their species richness and potential—remains comparatively underexplored (Shyu and Liao, 2004; Barrington et al., 2009).

Marine aquaculture, particularly of finfish, has intensified over the past 15 years due to advancements in feed formulation, site selection, and farming technology (Read and Fernandes, 2003). However, this growth has been accompanied by increased nutrient discharge, primarily nitrogen and phosphorus, stemming from uneaten feed and fish excretion (Tovar et al., 2000; Herath and Satoh, 2015). Studies report that up to 55% of nitrogen and 40% of phosphorus from feed remain unused by cultured fish, accumulating in the sediment (Barbosa et al., 2024). Shellfish and seaweeds, when integrated in IMTA systems, can effectively uptake these nutrients, converting waste into biomass and thereby mitigating environmental impacts (Troell et al., 2003; Abreu et al., 2009; Biswas et al., 2019).

With the rapid expansion of mariculture and increasing competition for coastal space, stakeholders—ranging from producers to regulators and consumers—are progressively advocating for more sustainable and integrated farming approaches (De Silva and Soto, 2009). The present study was conducted to evaluate the technical performance, environmental sustainability, and economic viability of a fish–mussel Integrated Multi-Trophic Aquaculture (IMTA) system along the Karnataka coast, India. Using silver pompano (*Trachinotus blochii*) and green mussel (*Perna viridis*) as candidate species, the study compared integrated culture with conventional standalone fish cage and mussel raft systems across four estuarine locations. The investigation assessed growth, survival, production performance, water quality dynamics, and economic returns to determine whether trophic integration enhances resource use efficiency and reduces environmental impacts. The findings are intended to provide scientific evidence supporting the adoption of IMTA as a sustainable mariculture strategy in the coastal ecosystem.

2. Materials and methods

2.1. Study area and culture species

The study was conducted in the estuarine regions of Udupi district, located along the west coast of Karnataka, India. This region is characterized by a network of interconnected estuaries, creeks, and backwaters that support a rich diversity of aquatic life and have traditionally been utilized for small-scale fishing and aquaculture practices. Four distinct estuarine sites within the similar geographical locations were selected for the implementation of the study, based on their suitability for fish cage farming and bivalve cultivation (Fig. 1). The selection of sites also considered factors such as water quality, tidal influence, depth, salinity, and accessibility for regular monitoring and maintenance.

Local fish farmers from each of the selected sites were identified and chosen as participants in the study, primarily based on their prior experience, interest, and skill in aquaculture-related activities. These stakeholders were then actively engaged in the project through capacity-building initiatives. A series of structured training programs were organized to equip them with the necessary technical knowledge and practical skills required for Integrated Multi-Trophic Aquaculture (IMTA) practices. The training sessions covered key aspects of IMTA, including the principles and benefits of integrated farming, cage design and fabrication, site preparation, mussel seeding and roping techniques, species compatibility, feeding protocols, and daily management.

In this study, silver pompano (*T. blochii*) was utilized as the fed aquaculture species, while green mussel served as the extractive species in the integrated aquaculture system. Silver pompano distributed along Indo-Pacific region, fast-growing, high-value species well suited for brackishwater ponds and marine cage farming. Due to its excellent meat quality and strong market demand, it is widely cultured in several Asian countries, including India (Sukumaran et al., 2025). Recent advances in hatchery and farming technologies have boosted its production; it reaches 0.4–0.5 kg within 5–6 months under culture conditions.

The Asian green mussel (*P. viridis*) is a large, fast-growing estuarine and intertidal bivalve distributed widely across the tropical and subtropical Indo-Pacific region. Its rapid growth, high market demand, and adaptability to coastal conditions make it highly suitable for commercial-scale farming, particularly along the Indian coast where it has shown strong aquaculture potential as it reaches marketable size in 5–6 months period (Kripa and Mohamed, 2008).

2.2. Experimental design

The IMTA system consisted of two fish cages integrated with two mussel rafts. In contrast, the control system, located approximately 1 km away from the IMTA unit, comprised two fish cages and two mussel rafts maintained separately, with a distance of about 500 m between the fish cages and mussel rafts to prevent interaction effects (Fig. 2). This experimental arrangement was replicated across four locations.

2.2.1. Design and fabrication of the cage

The cage frames were constructed using 32 mm galvanized iron (GI) pipes, with each cage measuring 6 × 3 × 2 m (length x width x depth) and a water holding capacity of approximately 36 tonnes (Fig. 3). To enhance structural integrity, the frames were reinforced with crossbars of appropriate dimensions. The upper section of each frame extended outward to support flotation devices and also served as a working platform, facilitating routine maintenance and operational activities. The cage corners were securely welded to increase stability and overall structural strength, making the units robust and capable of withstanding estuarine conditions. To prolong durability and minimize biofouling and corrosion, the frames were coated with anti-corrosive and anti-fouling marine-grade paint. Each cage was enclosed with a double layer of nylon (polyamide) netting with a mesh size of 40 mm, providing protection while allowing optimal water exchange. For flotation, six high-density polyethylene (HDPE) drums (200 liters capacity each) were attached to each cage.

Mooring systems were installed using appropriately sized anchors, designed in accordance with the site-specific parameters such as depth, bottom type, and the direction and velocity of water currents. Mooring lines consisted of 18–20 mm diameter nylon or polyethylene ropes, ensuring secure anchorage and stability of the cages under dynamic tidal conditions.

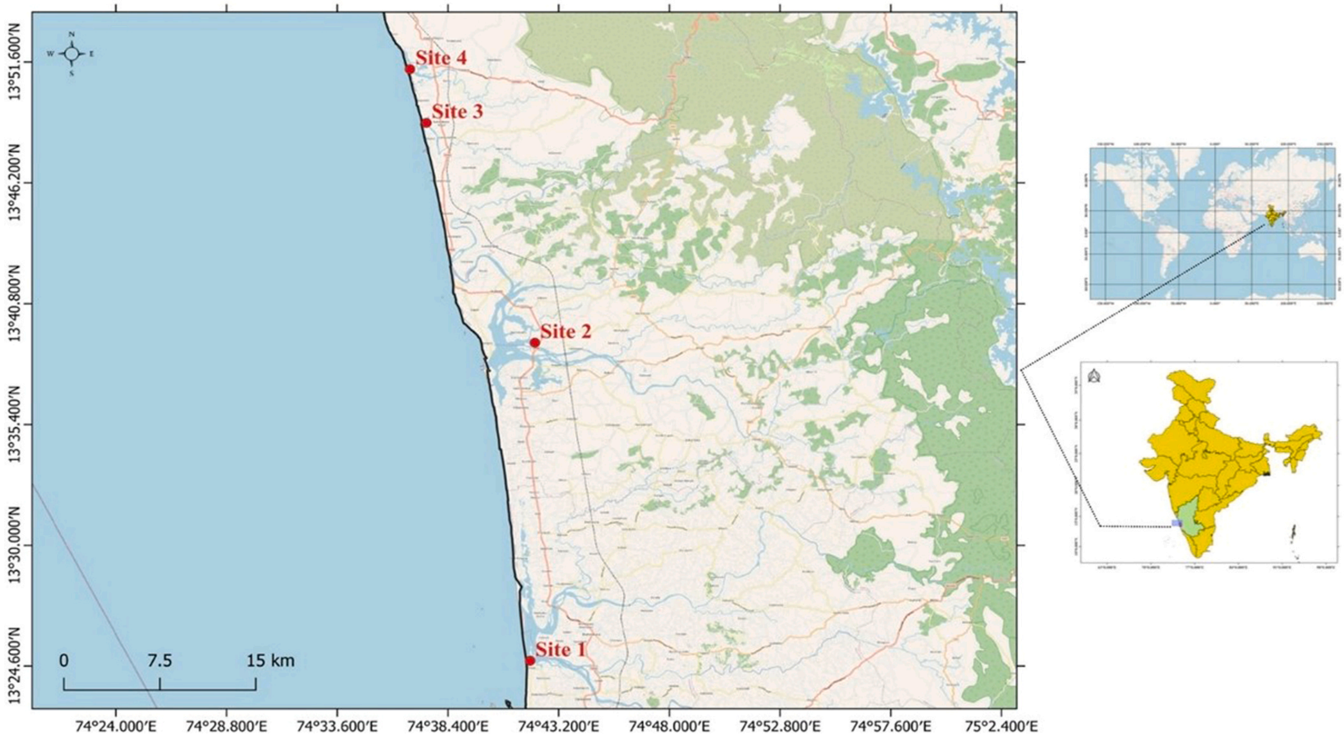

Fig. 1. Map showing the locations of integrated (IMTA) and isolated (monoculture) farming sites of silver pompano (*Trachinotus blochii*) in cages and green mussel (*Perna viridis*) in rafts at Udupi district, Karnataka, India.

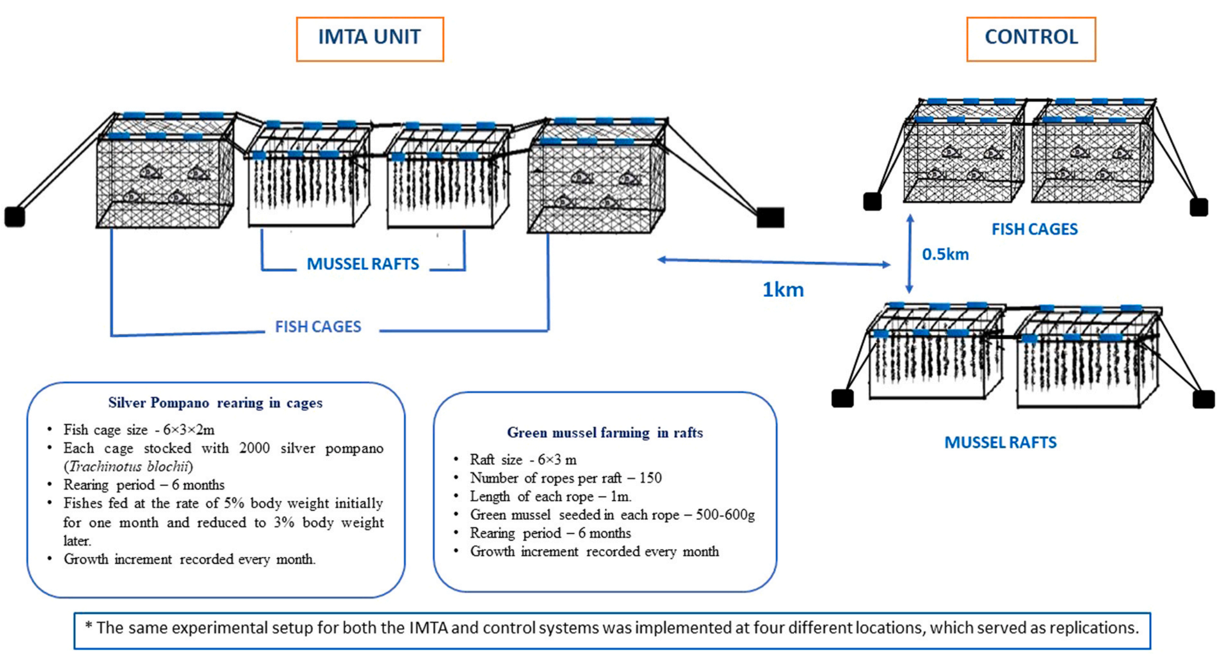

Fig. 2. Schematic diagram of cage (6 m×3 m×2 m: length x width x depth) and mussel raft (6 ×3 m; length×width) installations under Integrated Multi-Trophic Aquaculture (IMTA) and isolated (control) systems.

2.2.2. Design and fabrication of hapa

A hapa (miniature of cage) measuring 3.5 × 2.5 × 1.5 m (length × width × depth) was installed within each cage and tied securely to temporarily hold juvenile fish during the initial rearing phase (Fig. 4). The hapa was fabricated using nylon netting with a mesh size of 18 mm, providing adequate containment while allowing for sufficient water exchange. The juvenile fish were maintained in the hapa for approximately four weeks to ensure acclimatization and initial growth under protected conditions. Once the fish reached an average size of 8–10 g, they were carefully transferred to the main cage for further grow-out.

2.2.3. Fabrication of feeding trays

Given the dynamic nature of estuarine waters, which experience regular tidal fluctuations and bidirectional flow from both marine and riverine sources, feed loss from the cages is a common issue. The movement of water often displaces feed particles, resulting in reduced

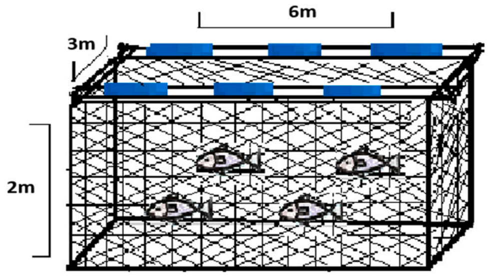

Fig. 3. An illustration of cage unit having a dimension of 6 m× 3 m× 2 m (Length, Width and Height) used for the study for rearing silver pompano (*Trachinotus blochii)*. Each cage is stocked with 2000 fish fingerlings (55 m^{-3}).

feed availability for the cultured fish and increased wastage. To mitigate this problem, a feeding tray measuring 2.0 × 1.5 m was initially fabricated for use within the hapa. The tray frame was constructed using 2-inch diameter PVC pipes, over which a high-density polyethylene (HDPE) monofilament mesh fabric with a 0.5 mm mesh size was securely tied using plastic rope. This design helped retain the feed within the tray, allowing juvenile fish better access to feed while minimizing losses due to water current.

After the juvenile rearing phase (approximately four weeks), a larger feeding tray measuring 2.5 × 2.5 m was fabricated using the same materials and construction principles. This larger tray was installed in the main cage to accommodate the increased feeding space requirements of the growing fish. The use of these feeding trays ensured more efficient feed utilization and contributed to maintaining water quality by reducing excess feed dispersal in the environment.

2.2.4. Design of the raft for mussel culture

A floating raft system was constructed for mussel farming, consisting of a rectangular frame fabricated from galvanized iron (GI) pipes, with dimensions of 6 × 3 m. The frame corners were securely joined by welding to ensure structural stability. For buoyancy, the frame was mounted on four high-density polyethylene (HDPE) drums, each with a capacity of 200 litres. To support mussel cultivation, 18 mm diameter nylon ropes were tied both vertically and horizontally across the frame at equal intervals. These ropes served as the suspension lines for the seeded mussel ropes. After fabrication, the raft was installed in the estuarine site and moored in alignment with the fish cages, using a combination of concrete blocks and suitable anchors to ensure stability under tidal and current conditions. Each raft was equipped with 150 seeded ropes, on which mussel spat were attached. Two mussel rafts were installed in each location along with two cages in integration in IMTA locations and two mussel rafts with two cages in isolation in control site.

2.2.5. Fish seed stocking

A total of 2000 seeds of silver pompano at a stocking density of 55 m^{-3}**,** with an average initial weight of 0.8 ± 0.1 g, were stocked in the hapa installed within each cage at all four study locations. The juvenile fish were reared in the hapa for approximately four weeks, during which they were closely monitored and managed to ensure optimal growth and survival. Once the fish reached an average weight of 8–10 g, they were carefully transferred to the main cages for grow-out and further rearing under standard IMTA conditions.

2.2.6. Feed and feeding

The fish were fed a commercial floating pellet feed (Skretting, India) containing 40% crude protein**.** Feeding was initially carried out at 5% of the fish biomass**,** and subsequently reduced to 3% after one month.

2.2.7. Preparation of mussel seeded ropes

Mussel seeds, collected from natural mussel beds, were acclimatized in estuarine water for 12–18 h prior to transplantation. Approximately 500–600 g of mussel seeds, measuring 20–30 mm in shell length, were used for each 1-meter-long nylon rope. The seeds were evenly spread along the rope, which was placed on a strip of mosquito curtain cloth of appropriate width. The cloth was then carefully stitched around the rope to enclose the seeds, forming a uniform seed layer. These prepared ropes were subsequently suspended from the floating raft. Within 48 h, the mussel seeds firmly attached themselves to the rope, and the enclosing mosquito net naturally disintegrated within 10 days, leaving the mussels securely attached to the substrate for further growth.

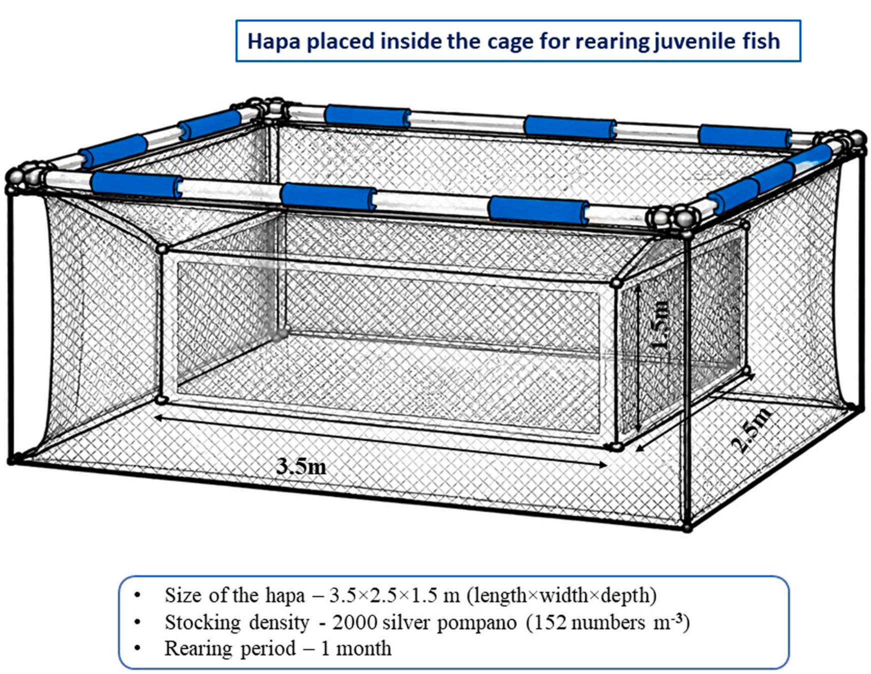

Fig. 4. An illustration of hapa having a dimension of (3.5 m×2.5 m×1.5 m: Length, Width and Height) placed inside the cage unit for rearing small sized silver pompano (*Trachinotus blochii) measuring* 0.8±0.1 g, to 8–10 g.

2.3. Monitoring of water quality

Monthly water quality monitoring was conducted at all culture sites from IMTA and control to assess key physical and chemical parameters. Parameters such as water temperature, dissolved oxygen (DO), pH, total dissolved solids (TDS), and salinity were measured in situ using a Horiba U-50 Multi-parameter Water Quality Checker (HORIBA Advanced Techno Co., Ltd., Japan). In addition, concentrations of ammonia, nitrate, nitrite, phosphate, and total suspended solids (TSS), were determined using standard analytical methods as prescribed by the American Public Health Association (APHA, 2023).

2.4. Growth performance evaluation metrics

Monthly sampling of fish was conducted at all study sites to evaluate growth performance. During each sampling, the total length (mm) and total weight (g) of the fish were recorded. These data were used to calculate key growth and production metrics, including Weight Gain (WG), Specific Growth Rate (SGR), Feed Conversion Ratio (FCR), Average Daily Gain (ADG), Thermal Growth Coefficient (TGC), and Survival Rate (SR). The following standard formulae as per Lugert et al. (2014) were used for the calculations.

$$Weight\ gain\ (g) = Average\ final\ weight - Average\ initial\ weight$$

$$SGR(\%) = \frac{\log(Final\ weight) - \log(Initial\ weight)}{Number\ of\ days} \times 100$$

$$FCR = \frac{Total\ feed\ given}{Total\ weight\ gain}$$

$$Average\ daily\ gain\ (g/day) = \frac{(Average\ final\ weight - Average\ initial\ weight)}{Number\ of\ days}$$

$$Thermal\ growth\ coefficient = \frac{\sqrt[3]{Final\ body\ weight} - \sqrt[3]{Initial\ body\ weight}}{Mean\ water\ temperature\ (^\circ C) \times Number\ of\ days} \times 1000$$

$$Survival\ rate\ (\%) = \frac{Number\ of\ fish\ survived}{Number\ of\ fish\ stocked} \times 100$$

$$Total\ yield\ (Kg) = Average\ final\ weight \times Number\ of\ fish\ harvested$$

The growth performance of green mussels was assessed through monthly sampling at all study sites. Using vernier calipers, the shell length of individual mussels was measured. These measurements were used to calculate the Specific Length Growth Rate (SGR L) as an indicator of growth over the culture period. The following formula was used to calculate the SGR L;

$$SGR\ L(\%) = \frac{\log(Final\ length) - \log(Initial\ length)}{Number\ of\ days} \times 100$$

2.5. Economics of IMTA culture

The indicative economic performance of the IMTA and control systems was estimated by averaging the economic parameters obtained from the four experimental locations, following the methodology described by Aswathy et al. (2020).

The major operational cost components, including the cost of fingerlings, feed, labour, and other miscellaneous expenses, were estimated. All economic values were standardized and expressed in USD (1 USD = INR 85.6, exchange rate as of 1 July 2025). Economic performance indicators, including net profit and benefit–cost ratio (BCR), for both IMTA and control systems were computed using standard formulae as follows:

$$Net\ profit = Total\ revenue - Total\ cost$$

$$Benefit - Cost\ Ratio = \frac{Total\ revenue}{Total\ cost}$$

$$Operating\ ratio = \frac{Total\ operating\ cost}{Total\ revenue}$$

2.6. Assessment of farmer perception on IMTA

The perception of farmers regarding Integrated Multi-Trophic Aquaculture (IMTA) was evaluated both before and after the study. Participants were asked to rate various criteria on a Likert scale ranging from 0 to 5 (Chang and Zepeda, 2005; Ail et al., 2019). A structured questionnaire was administered to gather opinions on several key attributes, including: knowledge about IMTA, its impact on survival and growth rates, disease management, environmental sustainability, profitability, and the potential for fostering community-based aquaculture initiatives. A total of 25 farmers, each with over a decade of experience in cage and mussel farming, were selected for the study. The scores recorded before and after the IMTA study were statistically analysed using a paired t-test to determine significant changes in perception.

2.7. Statistical analysis

The data were tested for normality by Kolmogorov-Smirnoff test and homogeneity of variance by Levene's test before analysis wherever applicable. Growth parameters and water quality parameters were analysed using Linear Mixed-Effects Models (LMM) in R (R Core Team) with the packages lme4 and lmerTest. Models were fitted using Restricted Maximum Likelihood (REML). In each model, treatment was included as a fixed effect, while site was incorporated as a random intercept to account for potential variability among sites and to accommodate the hierarchical structure of the experimental design.

The general form of the model was:

$$Y_{ij} = \beta_0 + \beta_1(Treatment_{ij}) + b_j + \epsilon_{ij}$$

where Y_{ij}represents the observed growth parameter, $\beta_0$is the overall intercept, $\beta_1$denotes the fixed effect of treatment, $b_j$is the random effect associated with site, and $\epsilon_{ij}$is the residual error term. The significance of fixed effects was assessed using Satterthwaite's approximation for degrees of freedom. Statistical significance was considered at $p < 0.05$.

3. Results

The study was designed to understand the potential of integrated multi-trophic aquaculture by integrating the silver pompano fish reared in cages and green mussels in raft in the estuarine waters. The following section reveals the various outcomes of the study with respect to water quality, growth, and economic characteristics of the culture technology. All values of the results are expressed as mean ± standard error mean (SEM).

3.1. Physical and chemical characteristics

The results indicated that most of the measured physical and chemical parameters exhibited significant differences ($p < 0.05$) between the IMTA sites and the control sites except the temperature and salinity. (Tables 1 and 2). Compared to the control site, the IMTA site exhibited significantly lower levels of total dissolved solids, ammonia, and nitrite-nitrogen and nitrate-nitrogen. In contrast, the IMTA site recorded significantly higher concentrations of dissolved oxygen and silicate-silicon (Tables 1 and 2).

Table 1
Physical and chemical characteristics of the water collected from the control and Integrated multitrophic aquaculture (IMTA) sites.

Parameters	Control site		IMTA site
	Fish cage site	Mussel site	
Temperature (°C)	32.9 ± 0.19	32.5 ± 0.12	32.1 ± 0.27
pH	8.2 ± 0.52	8.1 ± 0.52	7.88 ± 0.09
Salinity (ppt)	30.5 ± 0.35	30.6 ± 0.35	31.2 ± 0.51
Dissolved Oxygen (mg/L)	4.3 ± 0.40	4.8 ± 0.30	4.9 ± 0.14
Total Dissolved Solids (mg/L)	32.2 ± 1.01	29.4 ± 0.95	28.3 ± 0.65
Ammonia (mg/L)	0.28 ± 0.89	0.15 ± 0.23	0.12 ± 0.01
Nitrite-Nitrogen (μg/L)	54.42 ± 0.56	50.38 ± 1.26	49.07 ± 6.73
Nitrate-Nitrogen (μg/L)	87.71 ± 1.58	60.57 ± 1.58	56.87 ± 3.13
Phosphate-Phosphorous (mg/L)	0.06 ± 0.01	0.04 ± 0.01	0.04 ± 0.01

*Values are expressed as mean ± SEM

Table 2
Results of the linear mixed-effects model (LMM) assessing the effects of culture system (IMTA vs. control) on water quality parameters.

Fixed effects	Estimate	SE	*t*-value	*P*-value
Temperature (°C)	-0.68	0.57	-1.19	0.320
pH	-0.36	0.12	-3.01	0.017
Salinity (ppt)	1.01	1.04	0.97	0.406
Dissolved Oxygen (mg/L)	0.50	0.12	4.16	0.025
Total Dissolved Solids (mg/L)	3.56	0.90	3.96	0.004
Ammonia (mg/L)	-0.14	0.03	-4.31	0.023
Nitrite-Nitrogen (μg/L)	4.92	0.70	-7.03	0.006
Phosphate-Phosphorous (mg/L)	-0.02	0.01	-4.03	0.004

3.2. Growth analysis

A comprehensive assessment of fish growth performance in cage culture was conducted using several key metrics, including Weight Gain, Specific Growth Rate (SGR), Feed Conversion Ratio (FCR), Average Daily Gain (ADG), Thermal Growth Coefficient (TGC), and Survival Rate (Table 3). The results indicated that fish and mussel reared at the IMTA site demonstrated significantly better growth performance compared to those at the control (Table 4).

Table 3
Growth characteristics of the fishes and mussels sampled from control and Integrated multitrophic aquaculture (IMTA) sites.

Parameters	Silver pompano		Green mussel	
	control	IMTA	control	IMTA
Initial length (mm)	34.7 ± 0.42	33.8 ± 0.29	36.8 ± 0.17	36.3 ± 0.76
Final length (mm)	241.2 ± 1.94	275.4 ± 7.64	68.2 ± 0.54	75.9 ± 1.15
Initial weight (g)	0.52 ± 0.01	0.56 ± 0.01	1.38 ± 0.05	1.45 ± 0.10
Final weight (g)	338.7 ± 0.72	412 ± 7.20	25.2 ± 0.36	34.6 ± 0.88
weight gain (g)	337.9 ± 0.51	411.5 ± 7.20	23.85 ± 0.03	33.15 ± 0.06
Specific Growth Rate (SGRW)	1.40 ± 0.09	1.60 ± 0.01	-	-
Specific Growth Rate SGR L	-	-	0.13 ± 0.01	0.17 ± 0.01
Yield (kg)	530.63 ± 2.35	699.65 ± 9.82	380 ± 15.28	435 ± 15.55
Feed Conversion Ratio (FCR)	1.80 ± 0.18	1.60 ± 0.03	-	-
Average Daily Gain (ADG)	2.05 ± 0.11	2.29 ± 0.04	0.13 ± 0.01	0.18 ± 0.01
Thermal Growth Co-efficient (TGC)	1.14 ± 0.75	1.40 ± 0.01	0.37 ± 0.01	0.44 ± 0.01
Survival (%)	78.3 ± 0.5	84.9 ± 0.9	77.62 ± 9.6	90.54 ± 2.8

*Values are presented as mean ± SEM

At the IMTA site, pompano achieved a notably higher average final length and weight (Fig. 5. and Fig. 6.), with the final weight reaching 412 ± 7.20 g, as opposed to 338.7 ± 0.72 g recorded at the control. This enhanced growth is further supported by the higher SGR observed at the IMTA site (1.60 ± 0.01), compared to (1.40 ± 0.09) the control, indicating a more efficient biomass accumulation over time under IMTA conditions. Similarly, the Average Daily Gain (ADG) of fish at the IMTA site was significantly greater, averaging 2.29 ± 0.04 g/day, while fish at the control gained only 2.05 ± 0.11 g/day (Tables 3 and 4). Although the Feed Conversion Ratio (FCR) was slightly lower at the IMTA site (1.60 ± 0.03) compared to the control (1.80 ± 0.18), it still suggests a more efficient feed utilization in IMTA due to the better growth output.

In terms of the Thermal Growth Coefficient (TGC), which integrates the effect of temperature on growth, the IMTA-reared fish again showed superior performance (1.40 ± 0.01) compared to their counterparts at the control (1.14 ± 0.75), reflecting a better temperature-adjusted growth rate.

Furthermore, the Survival was considerably higher at the IMTA site, with 84.9 ± 0.9% of fish surviving through the culture period, compared to 78.3 ± 0.5% at the control. This higher survival percentage highlights the favourable rearing environment under IMTA practices.

The mussels were cultured alongside of the cages stocked with fish and growth was monitored throughout the study period. Comparatively, the mussels in the integrated system grew better (Fig. 7). There was a significant difference ($p < 0.05$) in the length specific growth rate between the control and the IMTA (Table 4). The mussels at the IMTA location grew more, averaging 75.9 ± 1.15 mm in length at the end, as opposed to 68.2 ± 0.54 mm at the control. Higher ultimate weights were also encouraged by the IMTA system; mussels attained 34.6 ± 0.88 g as opposed to 25.2 ± 0.36 g at the control site. The IMTA site had a significantly greater specific growth rate based on length (0.17 ± 0.01) than the control site (0.13 ± 0.01).

The Thermal Growth Coefficient (TGC) was notably higher in mussels reared under IMTA conditions (0.44 ± 0.01) than at the control (0.37 ± 0.01), indicating improved temperature-adjusted growth. Additionally, survival rate was also better at the IMTA site, with 90.54 ± 2.8%, compared to 77.62 ± 9.6% at the control, underscoring the more favorable rearing conditions provided by IMTA.

3.3. Economic analysis

An analysis was conducted on the economic performance of IMTA and control farming focusing on their revenue, cost, profitability, and efficiency metrics. The total fixed cost of the IMTA unit was lower than

Table 4
Results of the linear mixed-effects model (LMM) assessing the effects of culture system (IMTA vs. control) on growth performance of silver pompano (*Trachinotus blochii*) and green mussel (*Perna viridis*).

Fixed effects	Estimate	SE	*t*-value	*P*-value
Growth parameters of silver pompano				
Final length	39.89	5.49	7.27	< 0.001
Final weight	61.69	16.72	3.69	0.006
Weight gain	61.75	16.72	3.69	0.006
Average daily weight gain (ADG)	0.28	0.08	3.53	0.008
Specific growth rate (SGR)	0.12	0.04	2.82	0.022
Thermal growth coefficient (TGC)	0.18	0.03	6.32	< 0.001
Survival	6.15	0.51	11.96	< 0.001
Growth parameters of green mussel				
Final length	8.27	2.86	2.89	0.020
Final weight	10.10	1.17	8.63	< 0.001
Weight gain	10.03	1.17	8.57	< 0.001
Average daily weight gain (ADG)	0.06	0.01	8.57	< 0.001
Specific growth rate (SGR Length)	0.03	0.01	9.37	< 0.001
Thermal growth coefficient (TGC)	0.07	0.01	9.12	< 0.001
Survival	12.73	0.56	22.87	< 0.001

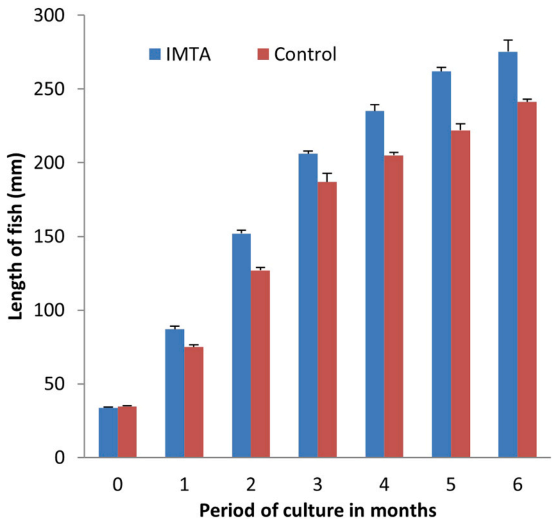

Fig. 5. Progress in the length of silver pompano (*Trachinotus blochii*) reared in integration with green mussel (*Perna viridis*) under the integratedted multi-trophic aquaculture (IMTA) concept and control during the culture period of 180 days.

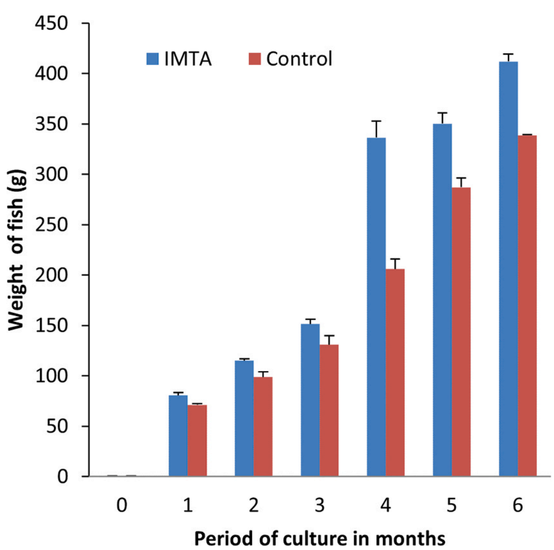

Fig. 6. Progress in the weight(g) of silver pompano (*Trachinotus blochii*) reared in integration with green mussel (*Perna viridis*) under the integratedted multi-trophic aquaculture (IMTA) concept and control during the culture period of 180 days.

that of the control system, primarily because the control required two separate mooring and anchoring arrangements, as the cages and mussel rafts were maintained independently at a distance of 0.5 km from each other. The results shown that the IMTA exhibited the highest total revenue of USD 4038 compared to control (USD 3106), indicating its capacity to optimize production value using integrated methodologies. The highest benefit-cost ratio (B:C ratio) was recorded in IMTA farming (1.75), signifying its exceptional cost-effectiveness and profitability per unit investment. Mussel and fishes when reared in isolation (control) resulted in the lowest B:C ratio (1.34) indicating comparatively reduced cost efficiency (Table 5).

3.4. Farmers perception on IMTA

The results of the paired *t*-test comparing the scores before and after the study for each evaluation criterion are presented in Table 6. The t-

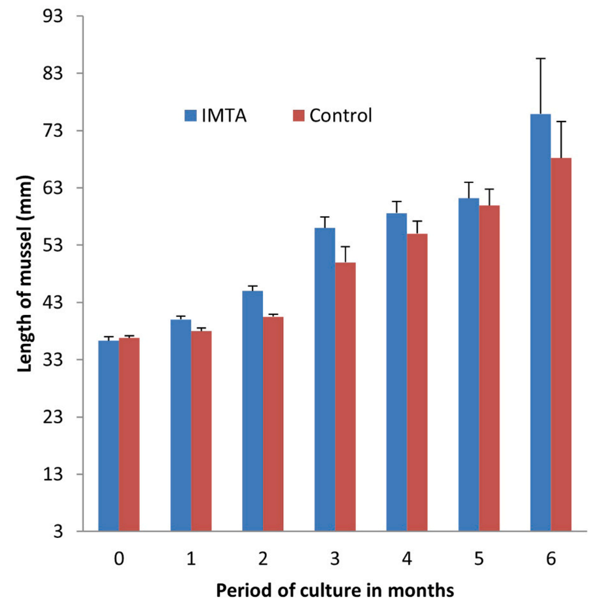

Fig. 7. Progress in length of green mussel (*Perna viridis*) reared in integration with silver pompano (*Trachinotus blochii*) under the integratedted multitrophic aquaculture (IMTA) concept and control during the culture period of 180 days.

statistics for all the criteria related to IMTA farming were statistically significant ($p \leq 0.05$), indicating a marked improvement in farmers' perceptions following the study. The post-study scores were significantly higher than the pre-demonstration scores across all evaluated parameters.

The mean total perception score increased significantly from 6.16 before the demonstration to 24.4 after the demonstration (Fig. 8), indicating a substantial improvement in farmers' understanding and acceptance of the IMTA concept. The radar chart (Fig. 9), which illustrates farmers' perceptions across individual evaluation criteria, highlights that the majority of respondents placed particular emphasis on the role of community-based aquaculture as a key strategy for achieving sustainable and profitable aquaculture practices.

4. Discussion

4.1. Impact of integrated aquaculture

Integrated Multi-Trophic Aquaculture (IMTA) is an ecosystem-based aquaculture approach that integrates species from different trophic levels within the same farming system (Neori et al., 2004). In such systems, wastes generated by fed species like fish are utilized by extractive species such as seaweeds and filter feeders, thereby enhancing nutrient recycling and system efficiency (Troell et al., 2009; Chopin, 2013).

The findings of the present study support the ecological and functional benefits of IMTA, particularly in improving feed utilization, growth performance, and water quality. By reducing nutrient loading and mitigating eutrophication risks, IMTA contributes to minimizing the environmental footprint of aquaculture. Additionally, the co-production of secondary crops enhances economic returns and promotes sustainable aquaculture development (Chopin, 2011).

4.2. Water quality

The water quality parameters observed in this study underscore the ecological benefits of the Integrated Multi-Trophic Aquaculture (IMTA) system compared to control where mussel and fishes are reared in isolation. The dissolved oxygen levels were consistently higher in the

Table 5
Economic characteristics of Integrated multitrophic aquaculture (IMTA) and control when silver pompano (*Trachinotus blochii*) and green mussel (*Perna viridis*) reared in integration and isolation.

Particulars	IMTA			Control		
	Cage unit	Mussel unit	Total	Cage unit	Mussel unit	Control
Total fixed cost per cage/raft including installation in USD (A)	445.8	277.9	723.6	463.3	307.1	770.4
Seed cost in USD (B) (USD 14 for 100 pompano fish seed and USD 1.04 for 1 kg mussel seed)	327.6	128.7	456.3	327.6	128.7	456.3
Feed quantity required (kg) (C)	1120.0	-	1120.0	1120.0	-	1120.0
Cost of feed in USD (D) (USD 1.29 for 1 kg feed)	1441.4	-	1441.4	1441.4	-	1441.4
Labour cost in USD (E)	114.7	23.4	138.1	114.7	23.4	138.1
Total Operating cost in USD (F = B+D+E)	1883.7	152.1	2035.8	1883.7	152.1	2035.8
Depreciation cost in UDS (G = 20% of A)	89.2	55.6	144.7	92.7	61.4	154.1
Maintenance cost in USD (H = 5% of A)	22.3	13.9	36.2	23.2	15.4	38.6
Interest on total fixed cost in USD (I = 12% of A)	53.5	33.3	86.8	55.6	36.9	92.5
Total cost in USD (*J* = F+G+H+I)	2048.6	254.9	2303.5	2055.1	265.7	2320.9
Total Production in kg (K)	699.7	435.0	1134.7	530.6	380.0	910.6
Price per kg of fish/mussel in USD (L)	4.7	1.8	-	4.7	1.6	-
Total Revenue in USD (M = K×L)	3274.4	763.4	4037.8	2483.3	622.4	3105.8
Gross profit in USD (N = M -F)	1390.7	611.3	2001.9	599.6	470.3	1069.9
Net profit in USD (O = M -J)	1225.7	508.5	1734.2	428.2	356.7	784.9
B:C Ratio (P = M/J)	1.60	2.99	1.75	1.21	2.34	1.34
Operating Ratio (Q = F/M)	0.58	0.20	0.50	0.76	0.24	0.66

* One US Dollar = 85.6 Indian Rupee as on 1 July 2025.

Table 6
Results of the paired *t*-test comparing farmers' perception scores on Integrated Multi-Trophic Aquaculture (IMTA) before and after the study, wherein silver pompano (*Trachinotus blochii*) and green mussel (*Perna viridis*) were reared in an integrated system.

Criteria	t-statistic ($p \leq 0.05$)
Knowledge on IMTA	-33.95
Increased Growth and Survival	-21.69
Management of Diseases	-23.24
Environmental Safety	-18.44
Profitability	-23.11
Community-based Aquaculture	-20.82

IMTA unit and mussel farming component of control compared to the cage culture component of control unit. Similarly, the IMTA sites and the mussel farming component of control site had significantly lower total dissolved solids compared to the cage farming unit of control sites. This could be attributed to the efficient waste management inherent in the IMTA and mussel component of control system, where mussels play a vital role by filtering and consuming suspended organic particles, particularly uneaten feed and fecal matter in IMTA and the dissolved organic particulate in mussel farming site of control. This biofiltration process reduces nutrient accumulation in the water, minimizes microbial decomposition that typically depletes oxygen, and thereby contributes to maintaining higher dissolved oxygen levels.

The accumulations of waste from excess fish feed (Ebeling et al., 2006; Hargreaves, 1998) and excreta (Ip et al., 2001; Timmons and Ebeling, 2013) build up to form ammonia, nitrate and nitrite-nitrogen compounds which are toxic to fish and can lead to stress, poor growth,

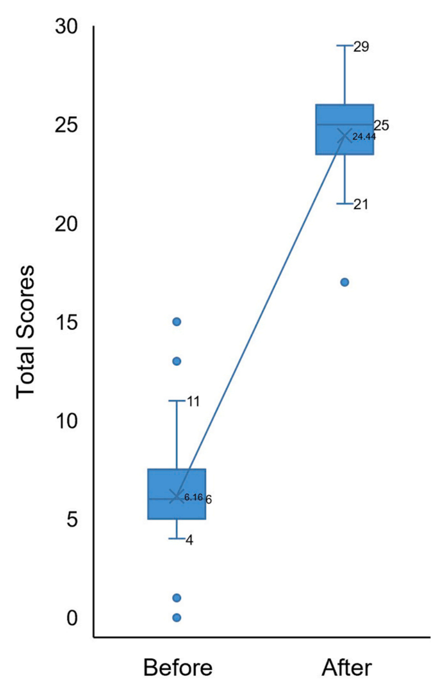

Fig. 8. Box plot depicting aggregated score of all the attributes on Integrated Multi-Trophic Aquaculture (IMTA) before and after the study wherein silver pompano (*Trachinotus blochii*) and green mussel (*Perna viridis*) were reared in an integrated system.

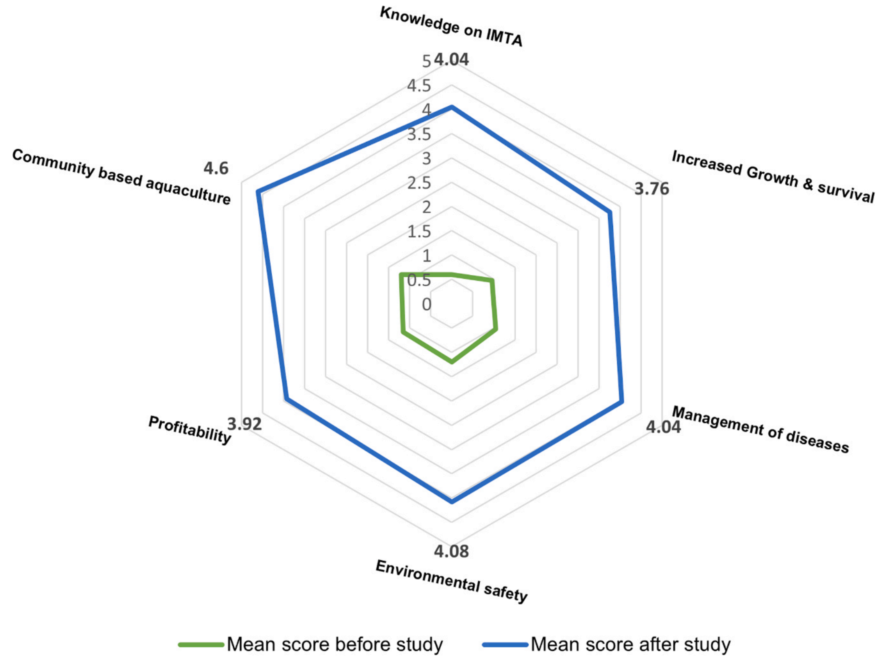

Fig. 9. Radar chart showing perception of farmers for different attributes on Integrated Multi-Trophic Aquaculture (IMTA) before and after the study wherein silver pompano (*Trachinotus blochii*) and green mussel (*Perna viridis*) were reared in an integrated system.

immune suppression. The ammonia and nitrate-nitrogen levels were lower at IMTA sites indicates that the IMTA technology could effectively reduce the nitrogen toxicity in the system. It is proven that elevated temperatures exacerbate ammonia toxicity due to increased metabolic rates and reduced oxygen solubility (Tomasso, 1994; Colt, 2006). Integration of bivalves and macro algae with fish culture had proven positive effect on water quality: water temperature, DO, pH, salinity, turbidity, transparency, NO_2, NO_3, NH_3^+, PO_4^{3+}, and silica (Si) (Cunha et al., 2019; Li et al., 2019; Borges et al., 2020).

4.3. Growth performance

The growth performance parameters evaluated in the present study consistently indicated higher productivity in the IMTA system compared to the control, where fish and mussel farming were undertaken in isolation. Notably, silver pompano attained a greater mean final length and body weight under IMTA conditions, suggesting that trophic integration positively influenced growth dynamics. Growth responses in IMTA systems are governed by a combination of biotic and abiotic factors, including nutrient availability, stocking density, and species compatibility (Chopin et al., 2013), as well as environmental variables such as temperature, salinity, dissolved oxygen, and hydrodynamic conditions (Abreu et al., 2009). The improved performance observed in the IMTA setup may be attributed to enhanced water quality and more stable environmental conditions resulting from nutrient assimilation by extractive species.

Survival of silver pompano was also higher in the IMTA system (84.9%) compared to the control (78.3%), indicating improved culture conditions under integrated farming. Enhanced survivability in IMTA systems is often associated with increased ecological stability, better waste management, and reduced environmental stress. Moreover, species diversification within the system may contribute to greater ecosystem resilience, potentially lowering disease risks through improved environmental buffering and reduced pathogen proliferation (Troell et al., 2009). Collectively, these findings highlight the functional advantages of IMTA in improving both growth performance and survival of cultured species.

In the present investigation, green mussels demonstrated significantly superior growth performance in the Integrated Multi-Trophic Aquaculture (IMTA) system compared to the control site. The higher growth observed under IMTA conditions can be attributed to increased availability of organic and inorganic nutrients derived from uneaten feed and fish faeces (Chopin, 2011; Troell et al., 2009). Such nutrient enrichment likely enhanced food availability for mussels, thereby promoting improved somatic growth.

In addition, the trophic interactions inherent in IMTA systems contribute to improved water quality and ecosystem functioning (Neori et al., 2004; Barrington et al., 2009). As efficient suspension feeders, mussels remove particulate organic matter from the water column, reducing the accumulation of waste and suspended solids. This bioremediation function may have helped maintain more stable environmental conditions, minimizing metabolic stress and optimizing energy allocation toward growth rather than maintenance.

Improved environmental conditions, including reduced turbidity and better oxygen dynamics, could have further contributed to the higher productivity recorded in the IMTA system (Reid et al., 2020). Overall, the enhanced growth of silver pompano and green mussel under IMTA conditions underscores the functional advantages of trophic integration in promoting both productivity and environmental sustainability.

4.4. Economic efficiency

The economic evaluation of the Integrated Multi-Trophic Aquaculture (IMTA) system in comparison with the control revealed marked differences in revenue generation, cost structure, profitability, and overall production efficiency. The IMTA system generated higher total revenue, highlighting its capacity to enhance economic returns through trophic integration. By co-culturing species occupying different trophic niches, IMTA maximizes resource utilization and diversifies marketable outputs, thereby improving production value and financial performance relative to monoculture-based systems (Chopin, 2013). The increased revenue in IMTA can be attributed to its ability to enhance resource efficiency and minimize waste, leading to higher overall productivity (Troell et al., 2009).

The relatively lower capital and operational expenditure associated with mussel farming contributed to its higher benefit–cost ratio (B:C ratio), as mussel culture generally involves minimal external inputs and relies largely on natural filtration and ambient nutrient availability (Ferreira et al., 2012). This observation is consistent with earlier reports identifying mussel aquaculture as both economically viable and environmentally sustainable (Petersen et al., 2016). In contrast, cage culture practiced in isolation recorded the lowest B:C ratio and the highest operating ratio. This may be attributed primarily to elevated feed and maintenance costs, which constitute a substantial proportion of total production expenses in finfish aquaculture systems (Asche et al., 2013; Naylor et al., 2000). Feed costs, in particular, are widely recognized as the dominant recurring expenditure in intensive fish farming operations, thereby exerting significant pressure on profitability.

Although the IMTA system involved comparatively higher operational costs due to the management of multiple species and additional infrastructure requirements (Neori et al., 2004), it achieved a higher B:C ratio than monoculture cage farming. This improved economic performance likely reflects enhanced resource-use efficiency and diversified revenue streams arising from co-cultured species. Furthermore, the ecological services provided within IMTA systems—such as nutrient assimilation, waste reduction, and internal nutrient recycling—contribute to improved environmental performance and long-term sustainability (Chopin, 2011; Biswas et al., 2019).

4.5. Farmers' perception

The farmers actively participated in observing the harvesting process and expressed a strong appreciation for the superior growth performance, higher survival rates, and overall improved productivity of both fish and mussels cultured under the Integrated Multi-Trophic Aquaculture (IMTA) system when compared to the conventional monoculture approach. Their positive perception underscores the potential of IMTA as an ideal model for community-based aquaculture, particularly in the coastal regions of Karnataka, India.

By integrating mussel and fish cage farming within a single setup rather than maintaining them as isolated systems the nutrient-rich waste and uneaten feed from fish culture can be efficiently utilized by the filter-feeding mussels. This synergistic relationship results in multiple benefits: improved water quality, reduced environmental impact, enhanced survival and growth of cultured organisms, and a lower risk of disease outbreaks. The dual advantage of environmental sustainability and economic gains makes IMTA a highly attractive model for coastal communities.

5. Conclusion

The present study demonstrates the bio-economic feasibility of integrating silver pompano and green mussels under an IMTA system. The results indicate that IMTA outperformed monoculture systems in terms of growth, survival, profitability, and environmental performance. Improved water quality and efficient nutrient recycling within the integrated system likely contributed to enhanced productivity and sustainability. However, key environmental drivers such as hydrodynamic regimes, chlorophyll-a concentration, and particulate organic carbon (POC), which can substantially influence carrying capacity and system performance in open-water farming environments, were not explicitly quantified in the present study. Future investigations incorporating these parameters would enable a more comprehensive understanding of ecosystem processes and optimize site-specific IMTA design and management. For wider adoption, particularly among small-scale fishers, supportive leasing policies and promotion of community-based IMTA models are essential to ensure equitable access, economic resilience, and sustainable coastal aquaculture development.

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CRediT authorship contribution statement

Grinson George: Writing – review & editing. **Rajesh K. M.:** Writing – original draft, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sujitha Thomas:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Viswambharan Divya:** Writing – review & editing. **Akhila U.:** Formal analysis, Data curation. **Harshitha R.:** Formal analysis, Data curation. **Narasimha Murthy L N:** Writing – review & editing. **Ail Sunil Kumar S:** Writing – original draft, Methodology, Formal analysis. **Dharshan K. S:** Formal analysis, Data curation. **Dineshbabu A. P.:** Writing – review & editing, Methodology.

Declaration of Competing Interest

The authors have no relevant financial or non-financial interests to disclose.

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Data Availability

Data will be made available on request.

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