



Comparative assessment of Open-Sea and Integrated Mangrove Aquaculture Systems (IMAS) for Asian seabass (*Lates calcarifer*) culture: implications for growth performance, physicochemical characteristics and mangrove cover assessment

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Abstract

The present study compared the growth performance, feed utilization, water quality, primary productivity and sediment characteristics of Asian seabass (*Lates calcarifer*) cultured in an Open-Sea Cage culture system (OSC) and two Integrated Mangrove Aquaculture Systems (MP₁ and MP₂). Asian seabass were stocked at 10 fish m⁻³ in six HAPAs within each culture system and reared for 60 days. Growth, feed-utilization indices, water-quality parameters, primary productivity and sediment characteristics were monitored throughout the culture period. Body weight increased progressively in all systems, with significantly higher final weight in MP₂ (27.01±0.34 g) than in MP₁ (25.83±0.30 g) and OSC (23.22±0.11 g). MP₂ recorded the highest weight gain, specific growth rate, feed conversion efficiency and protein efficiency ratio, while feed conversion ratio was lowest. Water-quality and productivity characteristics differed significantly among systems and sampling periods, with MP₂ showing higher gross and net primary productivity and chlorophyll-*a*. Sediment characteristics also differed significantly with MP₂ recording higher organic carbon, organic matter, total nitrogen and carbon stock. The findings highlight IMAS as a promising production-with-ecological-conservation approach enhancing aquaculture performance while retaining mangrove-based ecosystem functions, thereby supporting environmentally responsible seafood production and progress towards the SDGs.

Keywords: Asian seabass; growth performance; IMAS; mangrove cover; primary productivity; sediment quality

1 | INTRODUCTION

Aquaculture has emerged as a key driver of global aquatic food production, contributing to food security, nutritional well-being, employment generation and livelihood development (FAO 2026). Global aquatic animal production reached approximately 195 million tonnes in 2024, of which 103 million tonnes were produced through aquaculture (FAO 2026). Accounting for 53% of total aquatic animal production and more than 59% of aquatic animal food production, aquaculture represents a major contributor to the global aquatic food supply (FAO 2026). With continued expansion of the sector, particularly in coastal and marine environments, pivotal attention is now being directed towards production systems that can sustain biological productivity while maintaining ecological resilience (Yue 2025). Among the commercially important marine and brackishwater finfishes, Asian seabass, *Lates calcarifer*, is considered a versatile species for aquaculture because of its adaptability to a broad range of salinity conditions, rapid growth potential, high market value, suitability for diverse production systems and its wider adaptability has supported its development as a candidate species for marine and brackishwater aquaculture (Yue 2025).

In India, open-sea and marine cage culture of *L. calcarifer* has been successfully demonstrated along the different coastal regions, reporting successful growth, survival and production under floating cage systems (Joseph *et al.* 2011; Mojjada *et al.* 2013; Philipose *et al.* 2013). Growth performance in cage culture can, however, vary with culture practices, stocking conditions and the environmental characteristics of the farming site (Loka *et al.* 2016; Ghosh *et al.* 2026). Consequently, assessing fish production alongside the environmental characteristics of the culture system is essential for understanding seabass performance under different coastal aquaculture conditions. Environmental conditions can influence fish metabolism, growth and survival, and may vary spatially and temporally according to the farming site and culture system (Loka *et al.* 2016). Therefore, environmental monitoring is important for evaluating production performance and identifying changes associated with aquaculture activities.

In parallel with the expansion of coastal aquaculture, integrated approaches involving mangrove vegetation have gained attention owing to their potential to combine aquaculture production with the ecological functions of mangrove ecosystems (McSherry *et al.* 2023). Integrated Mangrove Aquaculture System represents a production approach to combine aquatic food production with mangrove conservation and associated ecosystem functions (Primavera 2000). Mangrove vegetation can interact with the surrounding aquatic environment through nutrient uptake, organic matter processing, sediment trapping and other biogeochemical processes, po-

tentially influencing water-quality conditions within integrated production systems (Primavera 2000; Bosma *et al.* 2016), thereby serving as an alternative approach to conventional aquaculture systems. Various experimental and field-based studies have demonstrated the potential of mangrove integration in modifying environmental conditions in aquaculture systems, although the magnitude and direction of these effects depend largely on mangrove characteristics, system configuration and local environmental conditions (Alongi *et al.* 2003; Bosma *et al.* 2016; Venkatachalam *et al.* 2018).

Previous studies have largely focused either on open-sea cage culture and associated environmental conditions or on comparisons between a single mangrove-integrated system and a non-mangrove system (Joseph *et al.* 2011; Mojjada *et al.* 2013; Loka *et al.* 2016; Venkatachalam *et al.* 2018). Despite these findings, comparative evaluation of Asian seabass performance across contrasting levels of mangrove integration within a common experimental framework remains limited. A broader assessment incorporating multiple mangrove-integrated systems together with growth performance, water-quality characteristics and biological productivity can provide a more comprehensive understanding of how system configuration is associated with seabass culture performance. Such an approach is particularly relevant where mangrove-integrated systems differ in their extent or structural characteristics, as environmental responses may vary with the degree of mangrove integration.

Therefore, the present study comparatively assessed the growth performance of Asian seabass cultured under an Open-sea Cage culture system (OSC) and Integrated Mangrove Aquaculture Systems (IMAS). The study evaluated growth performance, feed-utilization characteristics and survival of hapa-cultured seabass in conjunction with water-quality and chlorophyll/productivity characteristics of the respective culture systems. Associated environmental characteristics, including selected sediment and mangrove-system parameters, were also assessed to provide a broader comparison of the contrasting aquaculture environments. The study was undertaken to determine the comparative performance of Asian seabass under open-sea and mangrove-integrated aquaculture systems and to examine the environmental characteristics associated with their culture conditions.

2 | METHODOLOGY

2.1 Study area

The present study was carried out at the ICAR–Central Marine Fisheries Research Institute (ICAR–CMFRI), Tuticorin Regional Station (TRS), Thoothukudi, Tamil Nadu, India (8°46′49.03N 78°09′34.21″E). The experimental system comprised an Open-Sea cage (OSC) situated in the Tuticorin Bay (8°46′57.71″N 78°9′38.26″E) and an Inte-

grated Mangrove Aquaculture System (IMAS) established at the ICAR–CMFRI experimental mangrove pond facility. The IMAS consisted of two mangrove filtration units, Mangrove Filtration Unit 1 (8°46′52.27″N 78°9′35.54″E) with area of 40.5 m² and Mangrove Filtration Unit 2 (8°46′51.15″N 78°09′35.34″E) with area of 440.1 m², hydraulically connected to their respective mangrove-bunded culture ponds, designated as Mangrove Pond 1 (MP₁) (8°46′52.29″N 78°9′35.27″E) with area of 158.65 m² and Mangrove Pond 2 (MP₂) with area of 210.3 m²

(8°47′13.52″N 78°09′35.38″E). The IMAS consisted of tidal-fed mangrove filtration units hydraulically connected to mangrove-bunded culture ponds. During high tide, seawater enters the mangrove filtration unit through natural tidal inflow, passes through the mangrove vegetation and subsequently enters the culture pond, facilitating tidal water renewal and natural biofiltration. The geographical location and experimental layout of the study site are presented in Figure 1.

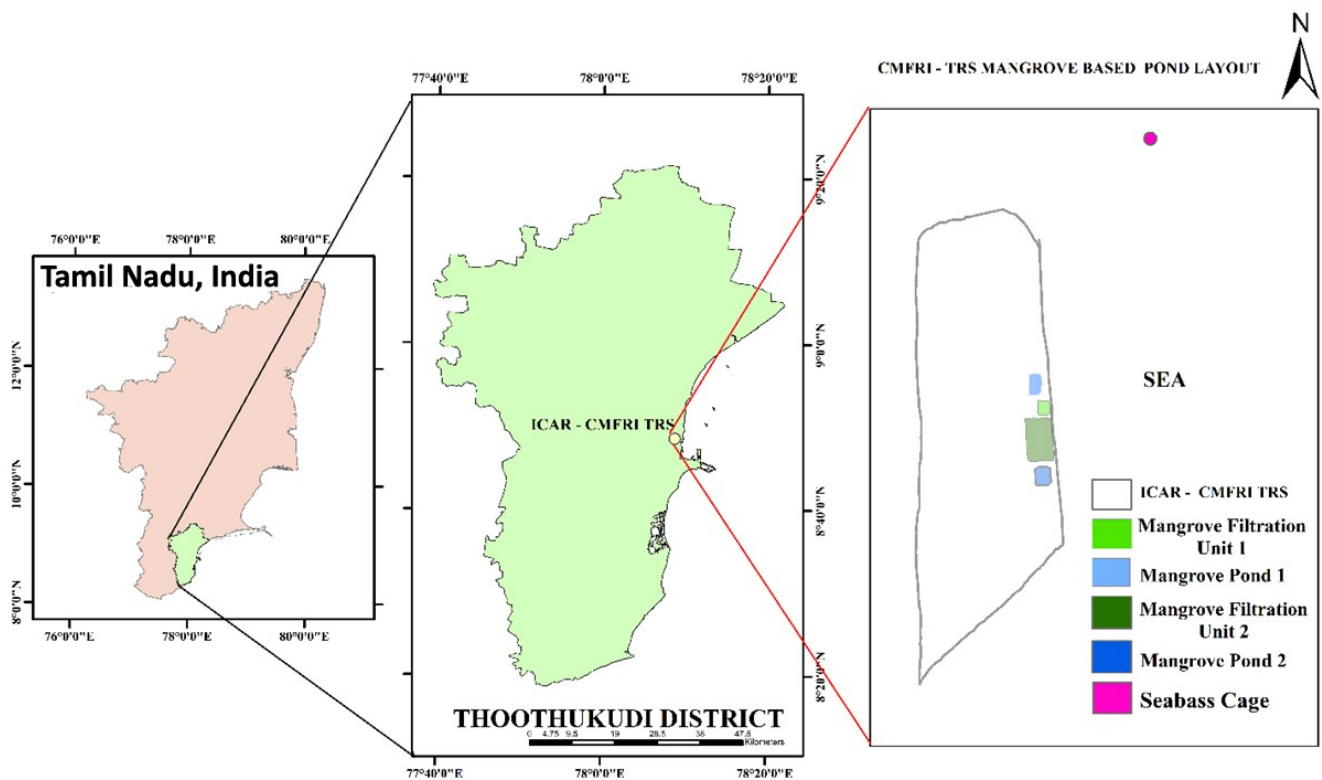


FIGURE 1 Geographical location and spatial arrangement of the Open-sea and IMAS in ICAR–CMFRI Tuticorin Regional Station.

2.2 Experimental design and aquaculture management

The Open Sea Cage is a circular floating GI cage of 7 m diameter, supported by six pressurized HDPE barrels for buoyancy, fitted with a 20 m HDPE bottom ring to maintain cage geometry and anchored using a mooring system. The cage was fitted with an outer cage net of 30 mm HDPE mesh and an inner cage net of 15 mm HDPE mesh. Asian seabass juveniles of 10–11 g size were reared in rectangular HAPA nets measuring 1.0 m × 1.0 m × 1.0 m, fabricated from knotless HDPE netting with a mesh size of 10 mm. Six HAPAs were maintained in the open-sea cage culture system (OSC), and six HAPAs were maintained in each of the two mangrove-integrated aquaculture systems, MP₁ and MP₂. Fishes were stocked in each HAPA at a density of 10 fish m⁻³, resulting in 60 fish per system

and a total of 180 fish across the three systems. The fish were fed a commercial floating pellet diet (Growel Nutrila Seabass Feed; Growel Feeds Pvt. Ltd., Eluru District, Andhra Pradesh, India) containing 45% crude protein, with a pellet size of 1.8 mm. The feeding ration was adjusted according to biomass and was maintained at 4% of body weight during days 1–15, 3% during days 16–30, 2.5% during days 31–45 and 1.5% during days 46–60. The daily ration was divided into two equal meals and provided at 10:00 and 17:00 hrs. The culture experiment was conducted for 60 days, from 25 June to 23 August 2026.

2.3 Growth performance assessment

Growth performance of Asian seabass was evaluated at 15-day intervals and performance indices, including

weight gain (WG), length gain (LG), average daily gain (ADG), specific growth rate (SGR), feed conversion ratio (FCR), feed conversion efficiency (FCE), protein efficiency ratio (PER), survival rate (%) and condition factor (K), were calculated using the relevant formulae described by De Silva and Anderson (1995) to compare Asian seabass performance among OSC, MP₁ and MP₂.

2.4 Water-quality and productivity assessment

Water-quality and primary productivity parameters were monitored throughout the experimental period in all three experimental systems (OSC, MP₁ and MP₂). In each system, water samples were collected separately from three different locations to account for spatial variation. The parameters assessed include Water temperature by mercury thermometer, pH using Hanna HI98121 water-proof pH tester, salinity using a hand-held refractometer (Atago 2361 AL-21), dissolved oxygen (DO) estimated by the Winkler titrimetric method, ammonia (NH₃), nitrite (NO₂⁻), nitrate (NO₃⁻) using the phenol-hypochlorite, sulphanilamide-NED and cadmium reduction-sulphanilamide-NED methods, sulphide (H₂S) using methylene blue method, gross primary productivity (GPP), net primary productivity (NPP) were estimated using the Gaarder and Gran light-and-dark bottle method by following the standard procedures described by APHA, AWWA and WEF (2017). Chlorophyll-*a* concentration was determined using the spectrophotometric acetone-extraction method described by Parsons *et al.* (1984). A thoroughly mixed water sample (500 mL) was filtered through a 47-mm GF/C filter paper to collect phytoplankton. The filter paper was transferred to a centrifuge tube containing 10 mL of 90% (v/v) acetone, and pigment extraction was carried out at low temperature in the dark for 20 h. The extract was centrifuged at 6,000 rpm for 8 min, and the supernatant was used for spectrophotometric analysis. Absorbance was measured at 750, 664, 647 and 630 nm, with the 750-nm reading used for correction. Chlorophyll-*a* concentration was calculated using the equation of Jeffrey and Humphrey (1975), as described by Parsons *et al.* (1984).

2.5 Sediment-quality assessment

Sediment samples were assessed in triplicate from the respective culture systems (OSC, MP₁ and MP₂) during the monitoring period. Sediment pH and EC were determined using a 1:2.5 sediment-to-water suspension following Jackson (1973). Dry bulk density was estimated using the cylindrical core method described by Blake and Hartge (1986). Particle-size distribution, including coarse sand, fine sand, silt and clay fractions, was determined using the hydrometer method (Bouyoucos 1962). Total organic carbon (TOC) was determined using the chromic-acid wet oxidation method of Walkley and Black (1934), while total organic matter (TOM) was estimated from TOC using the

Van Bemmelen conversion factor of 1.724 (Nelson and Sommers 1996). Total nitrogen (TN) was determined using the Kjeldahl digestion and distillation method (Bremner 1996). Available phosphorus was determined by sodium bicarbonate extraction followed by the Olsen colorimetric method (Olsen *et al.* 1954). Organic carbon stock was calculated from sediment bulk density, TOC concentration and sediment depth following standard procedures (IPCC 2003).

2.6 Mangrove community structure assessment

The mangrove community structure associated with the IMAS was assessed separately in the two mangrove-bunded culture ponds (MP₁ and MP₂) and their respective mangrove filtration units (MFU1 and MFU2) using the Point-Centred Quarter Method (PCQM) (Cottam and Curtis 1956). A total of ten sampling points were established for each pond-filtration unit system, comprising four sampling points in the mangrove-bunded culture pond and six sampling points in the associated mangrove filtration unit. At each sampling point, the surrounding area was divided into four quadrants, and the nearest mangrove tree in each quadrant was identified. The distance from the sampling point to the nearest tree, species identity, tree height (m) and diameter at breast height (DBH, cm) were recorded for each sampled tree (Cottam and Curtis 1956). Tree density and mangrove cover density were estimated using the PCQM following Indriyanto (2010). Tree volume was estimated using tree diameter at breast height (DBH), total tree height and a tree form factor of 0.6, following Brown (1997). Five 2 × 2 m quadrats were established in the mangrove vegetation associated with each culture pond and its corresponding mangrove filtration unit. Relative density (RD), relative frequency (RF) and relative coverage (RC) were calculated following Swangjang and Panishkan (2021) and the Importance Value Index (IVI) for each mangrove species was calculated following Curtis and McIntosh (1950). Above-ground biomass (AGB) and below-ground biomass (BGB) were estimated using species-specific allometric equations proposed by Komiyama *et al.* (2005). Carbon stock was estimated by multiplying total biomass by a carbon conversion factor of 0.47 (Fithria *et al.* 2025), while CO₂ sequestration potential was estimated by multiplying carbon stock by a conversion factor of 3.67 (Kauffman and Donato 2012).

2.7 Data analysis

All experimental data were expressed as mean ± standard deviation (SD). Statistical analyses were performed using IBM SPSS Statistics version 20.0 (IBM Corp., Armonk, NY, USA), while graphs and data visualizations were prepared using GraphPad Prism version 8.0.1 (GraphPad Software, San Diego, CA, USA). Prior to statistical analysis, data were assessed for normality and homogeneity of vari-

ance. For variables not meeting the assumptions of parametric analysis, an appropriate non-parametric alternative was applied. For Asian seabass growth data, six HAPAs were maintained within each culture system. The six HAPAs in OSC were located within a single floating cage, whereas those in MP₁ and MP₂ were located within one pond per system providing within-system observations of fish performance. Repeated observations collected from the same experimental units during the culture period were analysed using repeated-measures analysis of variance (ANOVA), with experimental system as the between-subject factor and sampling period as the within-subject factor. Where significant differences were detected among experimental systems, Duncan's Multiple Range Test (DMRT) was used for multiple comparisons. For parameters assessed at a single level among experimental units, one-way ANOVA followed by the appropriate post-hoc multiple-comparison test was used where applicable. Relationships between selected environmental variables and seabass growth parameters were assessed using correlation analysis where appropriate. Principal component analysis (PCA) was used to examine the overall pattern of variation among OSC, MP₁ and MP₂ based on selected environmental and growth variables. Statistical significance was considered at $p < 0.05$.

3 | RESULTS

3.1 Growth performance

Body weight increased progressively throughout the culture period in all three experimental systems (Table 1, Figure 2). At Day 60, mean body weight was highest in MP₂ (27.01±0.34 g), followed by MP₁ (25.83±0.30 g) and OSC (23.22±0.11 g). Significant differences among systems were observed from Day 15 onwards ($p < 0.01$), whereas no significant difference was detected at Day 0 ($p = 0.802$). The repeated-measures analysis also showed significant effects of culture period and the System × Day

interaction ($p < 0.01$). Growth indices and feed-utilization parameters are presented in Table 2.

Weight gain, percentage weight gain, ADG, SGR, FCE and PER were higher in the mangrove-integrated systems, whereas feed conversion ratio was lower, with the most favourable values generally recorded in MP₂. Length gain and condition factor did not show significant differences among the experimental systems. Principal component analysis showed clear separation of the three experimental systems based on the combined growth-performance variables. PC1 and PC2 explained 53.94% and 25.14% of the total variance, respectively, accounting for 79.08% of the cumulative variance. The mangrove-integrated systems were positioned positively along PC1 and were associated with higher weight gain, ADG, PWG, SGR and FCE, whereas OSC was positioned in the negative direction of PC1 and associated with FCR. Length gain and condition factor contributed mainly to PC2 (Figure 3).

TABLE 1 Body weight of Asian seabass during the experimental period.

Experimental system	Days				
	0	15	30	45	60
OSC	11.02±0.014 ^a	13.91±0.007 ^c	16.97±0.169 ^c	20.14±0.249 ^c	23.22±0.111 ^c
MP ₁	11.03±0.013 ^a	14.61±0.133 ^b	18.35±0.217 ^b	22.02±0.275 ^b	25.83±0.304 ^b
MP ₂	11.03±0.011 ^a	14.85±0.204 ^a	18.76±0.208 ^a	22.81±0.314 ^a	27.01±0.335 ^a
<i>F</i> -value	0.228	11.860	22.363	23.892	52.033
<i>p</i> -value	0.8024	0.0082	0.0017	0.0014	0.0002

Values are mean ± SD ($n = 6$). Different superscript letters within a column indicate significant differences among experimental systems ($p < 0.05$). OSC, Open-sea cage culture system; MP₁, Mangrove pond 1; MP₂, Mangrove pond 2

TABLE 2 Growth and feed-utilization indices of Asian seabass.

Growth index	OSC	MP ₁	MP ₂	<i>F</i> -value	<i>p</i> -value
Length gain (cm)	3.390±0.177 ^{ab}	3.595±0.220 ^{ab}	3.866±0.127 ^a	1.784	0.2466
Weight gain (g)	12.212±0.123 ^c	14.794±0.308 ^b	15.977±0.335 ^a	50.044	0.0002
ADG (g/day)	0.2033±0.0019 ^c	0.2466±0.0051 ^b	0.2663±0.0056 ^a	51.099	0.0002
PWG (%)	110.69±1.14 ^c	134.10±2.85 ^b	144.84±3.03 ^a	49.175	0.0002
SGR (%/day)	1.2428±0.0091 ^c	1.4174±0.0202 ^b	1.4923±0.0209 ^a	53.092	0.0002
FCR	1.4915±0.0152 ^c	1.3704±0.0128 ^b	1.2722±0.0271 ^a	32.056	0.0006
FCE (%)	0.6710±0.0067 ^c	0.7298±0.0068 ^b	0.7866±0.0165 ^a	27.584	0.0009
PER	1.4918±0.0157 ^c	1.6218±0.0151 ^b	1.7480±0.0366 ^a	27.139	0.0010
K initial	1.1371±0.0347 ^a	1.1244±0.0347 ^a	1.1319±0.0314 ^a	0.036	0.9648
K final	0.9910±0.0437 ^a	1.0440±0.0557 ^a	1.0329±0.0364 ^a	0.370	0.7055

Values are expressed as mean ± standard deviation ($n = 6$). Different superscript letters within a row indicate significant differences among experimental systems ($p < 0.05$). OSC, Open-sea cage culture system; MP₁, Mangrove pond 1; MP₂, Mangrove pond 2; ADG, average daily gain; FCE, feed conversion efficiency; FCR, feed conversion ratio; K, condition factor; PER, protein efficiency ratio; PWG, percentage weight gain; SGR, specific growth rate.

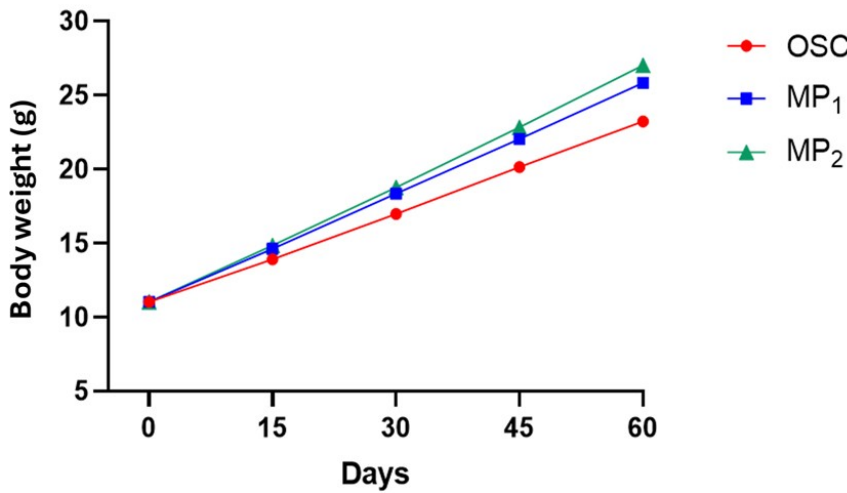


FIGURE 2 Body-weight growth curve of Asian seabass during the experimental period.

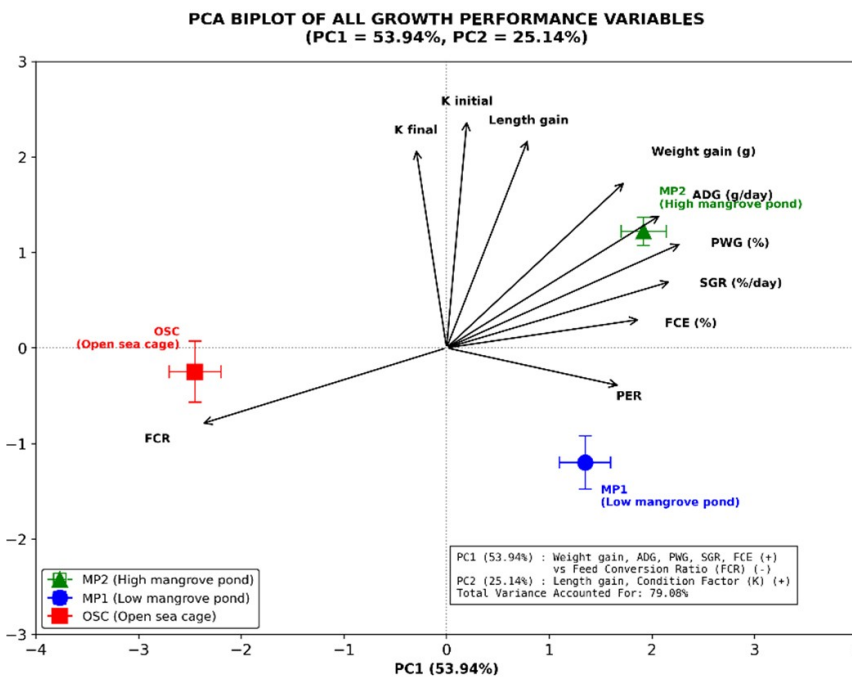


FIGURE 3 Principal component analysis (PCA) biplot of growth-performance variables.

3.2 Water-quality and productivity assessment

Water-quality parameters varied significantly among the experimental systems and across the culture period. Significant differences among the experimental systems were observed for all measured parameters. Water temperature, salinity and pH were highest in OSC, followed by MP₁ and MP₂. Dissolved oxygen (DO), ammonia and nitrite concentrations were also highest in OSC, whereas nitrate was highest in MP₁, followed by MP₂ and OSC. Sulphide concentrations differed among systems, remaining below the detection limit in OSC throughout the monitoring period. Mean GPP was markedly higher in MP₂ ($4794.28 \pm 43.14 \text{ mg C m}^{-3} \text{ d}^{-1}$), followed by MP₁ ($2959.83 \pm 41.25 \text{ mg C m}^{-3} \text{ d}^{-1}$) and OSC (2181.88 ± 74.31

$\text{mg C m}^{-3} \text{ d}^{-1}$) (Table 3). Net primary productivity (NPP) was also highest in MP₂ ($2131.01 \pm 38.15 \text{ mg C m}^{-3} \text{ d}^{-1}$), followed by MP₁ ($1886.88 \pm 26.54 \text{ mg C m}^{-3} \text{ d}^{-1}$) and OSC ($1310.16 \pm 37.19 \text{ mg C m}^{-3} \text{ d}^{-1}$). Chlorophyll-*a* was highest in MP₂ ($2.621 \pm 0.104 \text{ mg m}^{-3}$). Repeated-measures analysis showed significant effects of culture period and significant System $\times$ Day interactions for all parameters (Figure 4). The corresponding *F*-values, *p*-values and partial eta-squared (η^2) values are presented in Table 4.

3.3 Sediment quality characteristics

Sediment quality parameters differed among the three experimental systems and varied across the 60-day culture period (Table 5). Total organic carbon (TOC) and total

organic matter (TOM) showed higher values in MP₂ (0.552±0.009% and 0.951±0.016%, respectively) than in MP₁ (0.425±0.041% and 0.733±0.070%) and OSC (0.425±0.040% and 0.732±0.069%). Total nitrogen (TN) was also highest in MP₂ (0.054±0.001%), whereas MP₁ and OSC showed lower and similar values (0.025±0.002%). The repeated-measures analysis showed significant effects of experimental system and culture period on all sediment parameters assessed ($p < 0.001$). Significant System × Day interactions were also observed for sediment pH, TOC, TOM, TN, available phosphorus

and bulk density ($p \leq 0.002$) and the System × Day interaction for sediment EC was not significant ($F = 0.036$, $p = 1.000$) (Table 6). The PCA further differentiated the three experimental systems based on the sediment quality variables. PC1 explained 60.50% and PC2 explained 31.72% of the total variation, together accounting for 92.22% of the variance. MP₂ was positioned in the positive PC1–PC2 region, MP₁ in the positive PC1 and negative PC2 region, whereas OSC was positioned toward the negative PC1 region (Figure 5).

TABLE 3 Water-quality parameters across the experimental systems.

Parameters	Values (mean ± SD)			F-value	p-value
	OSC	MP ₁	MP ₂		
SST (°C)	30.937 ± 0.118 ^a	30.234 ± 0.063 ^b	29.705 ± 0.111 ^c	124.62	<0.001
Salinity (ppt)	35.124 ± 0.457 ^a	33.466 ± 0.095 ^b	32.472 ± 0.180 ^c	24.18	<0.001
pH	8.213 ± 0.033 ^a	8.183 ± 0.011 ^b	8.090 ± 0.017 ^c	78.43	<0.001
DO (mg L ⁻¹)	6.994 ± 0.062 ^a	5.582 ± 0.038 ^b	5.609 ± 0.091 ^b	75.31	<0.001
NH ₃ (mg L ⁻¹)	0.040 ± 0.005 ^a	0.020 ± 0.003 ^b	0.014 ± 0.001 ^c	25.86	<0.001
NO ₂ ⁻ (mg L ⁻¹)	0.044 ± 0.005 ^a	0.016 ± 0.003 ^b	0.013 ± 0.001 ^c	22.45	<0.001
NO ₃ ⁻ (mg L ⁻¹)	0.066 ± 0.006 ^c	0.110 ± 0.011 ^a	0.097 ± 0.006 ^b	10.92	0.002
H ₂ S (mg L ⁻¹)	BDL [*]	0.032 ± 0.001 ^a	0.021 ± 0.001 ^b	441.56	<0.001
GPP (mg C m ⁻³ d ⁻¹)	2181.88 ± 74.31 ^c	2959.83 ± 41.25 ^b	4794.28 ± 43.14 ^a	985.40	<0.001
NPP (mg C m ⁻³ d ⁻¹)	1310.16 ± 37.19 ^c	1886.88 ± 26.54 ^b	2131.01 ± 38.15 ^a	246.12	<0.001
Chl- <i>a</i> (mg m ⁻³)	1.228 ± 0.088 ^c	1.305 ± 0.063 ^b	2.621 ± 0.104 ^a	114.73	<0.001

Values are mean ± SD ($n = 3$). Different superscript letters within a row indicate significant differences among experimental systems ($p < 0.05$). OSC, Open-sea cage culture system; MP₁, Mangrove pond 1; MP₂, Mangrove pond 2 *BDL: Below Detection Limit (< 0.001 mg L⁻¹).

TABLE 4 Effects of experimental system, culture period and their interaction on water-quality parameters.

Parameter	Culture system effect			Sampling day effect			Interaction effect (System × Day)		
	F	p	ηp ²	F	p	ηp ²	F	p	ηp ²
SST	350.005	<0.001	0.992	79.933	<0.001	0.930	27.395	0.001	0.901
Salinity	44.777	<0.001	0.937	35.698	<0.001	0.856	31.960	<0.001	0.914
pH	52.261	<0.001	0.946	376.246	<0.001	0.984	45.165	<0.001	0.938
DO	97.477	<0.001	0.970	8.878	0.017	0.597	29.625	<0.001	0.908
NH ₃	82.229	<0.001	0.965	449.800	<0.001	0.987	91.838	<0.001	0.968
NO ₂	145.723	<0.001	0.980	409.041	<0.001	0.986	97.129	<0.001	0.970
NO ₃	7.428	0.024	0.712	126.703	0.007	0.955	230.764	<0.001	0.987
H ₂ S	185.370	<0.001	0.984	1719.540	<0.001	0.997	436.782	<0.001	0.993
GPP	3513.059	<0.001	0.999	109.461	<0.001	0.948	17.087	<0.001	0.851
NPP	1229.083	<0.001	0.998	183.563	<0.001	0.968	20.846	<0.001	0.874
Chl- <i>a</i>	403.837	<0.001	0.993	36.454	<0.001	0.859	45.226	<0.001	0.938

F-statistic; p , probability value; ηp^2 , partial eta-squared. System represents the experimental culture system (OSC, MP₁ and MP₂); Day represents the sampling period (0, 15, 30, 45 and 60 days); System × Day represents their interaction.

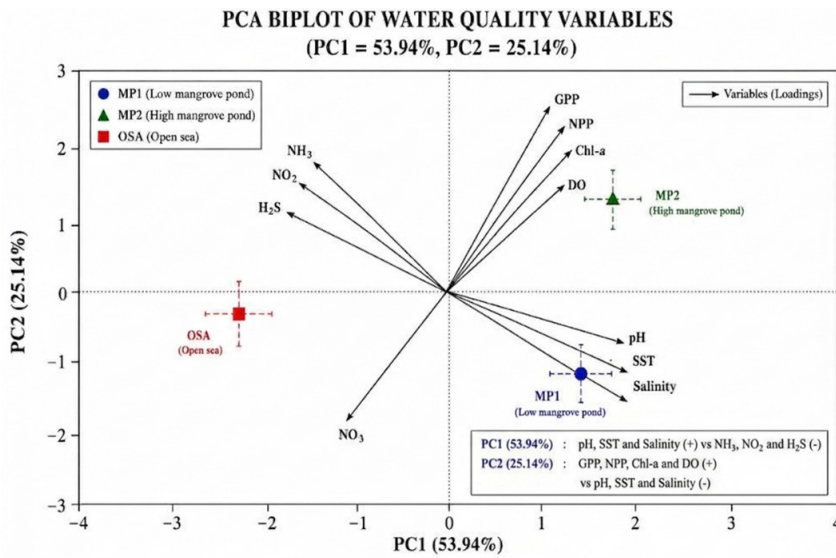


FIGURE 4 Principal component analysis (PCA) biplot of water-quality variables.

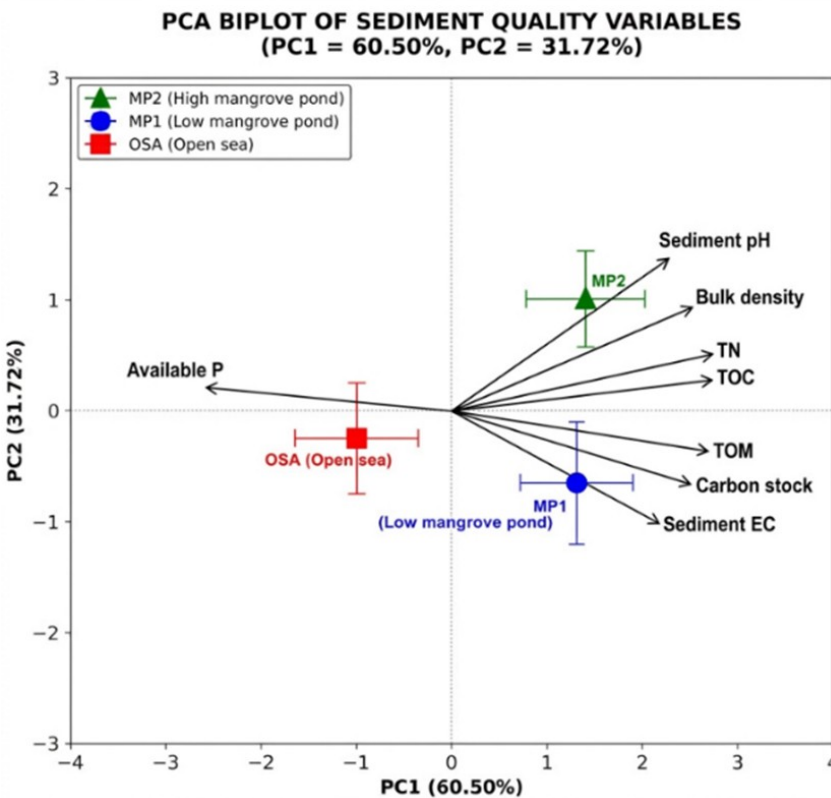


FIGURE 5 Principal component analysis (PCA) biplot of sediment quality variables.

TABLE 5 Sediment quality parameters across the experimental systems.

Parameter	Values (mean $\pm$ SD)			F-value	p-value
	OSC	MP ₁	MP ₂		
Sediment pH	7.639 $\pm$ 0.041 ^b	7.604 $\pm$ 0.052 ^b	8.019 $\pm$ 0.005 ^a	35.76	<0.001
TOC (%)	0.425 $\pm$ 0.040 ^b	0.425 $\pm$ 0.041 ^b	0.552 $\pm$ 0.009 ^a	4.85	0.013
TOM (%)	0.732 $\pm$ 0.069 ^b	0.733 $\pm$ 0.070 ^b	0.951 $\pm$ 0.016 ^a	4.89	0.013
TN (%)	0.025 $\pm$ 0.002 ^b	0.025 $\pm$ 0.002 ^b	0.054 $\pm$ 0.001 ^a	99.84	<0.001
Available P (mg kg ⁻¹)	5.701 $\pm$ 0.019 ^b	8.411 $\pm$ 0.599 ^a	7.424 $\pm$ 0.101 ^a	15.27	<0.001
Bulk density (g cm ⁻³)	1.289 $\pm$ 0.019 ^b	1.293 $\pm$ 0.019 ^b	1.503 $\pm$ 0.004 ^a	59.19	<0.001
Carbon stock (Mg ha ⁻¹)	0.537 $\pm$ 0.167 ^b	0.539 $\pm$ 0.172 ^b	0.829 $\pm$ 0.046 ^a	21.21	<0.001
Sediment EC (mS cm ⁻¹)	4.759 $\pm$ 0.094 ^b	4.756 $\pm$ 0.098 ^b	6.639 $\pm$ 0.092 ^a	132.29	<0.001

Values are mean $\pm$ SD ($n = 3$). Different superscript letters within a row indicate significant differences among experimental systems ($p < 0.05$). OSC, Open-sea cage culture system; MP₁, Mangrove pond 1; MP₂, Mangrove pond 2

TABLE 6 Effects of experimental system, culture period and their interaction on sediment quality parameters.

Parameter	Culture system			Sampling day			Interaction (system× day)		
	<i>F</i>	<i>p</i>	ηp^2	<i>F</i>	<i>p</i>	ηp^2	<i>F</i>	<i>p</i>	ηp^2
Sediment pH	1041.530	<0.001	0.986	207.789	<0.001	0.965	45.249	<0.001	0.923
TOC (%)	126.553	<0.001	0.894	215.507	<0.001	0.966	25.449	<0.001	0.872
TOM (%)	126.431	<0.001	0.894	215.386	<0.001	0.966	25.467	<0.001	0.872
TN (%)	764.336	<0.001	0.981	64.862	<0.001	0.896	4.012	0.002	0.517
Available P (mg kg ⁻¹)	359.833	<0.001	0.960	108.533	<0.001	0.935	65.695	<0.001	0.946
Bulk density (g cm ⁻³)	628.636	<0.001	0.977	82.378	<0.001	0.917	10.815	<0.001	0.743
Carbon stock (Mg ha ⁻¹)	598.105	<0.001	0.976	239.348	<0.001	0.970	24.681	<0.001	0.868
Sediment EC (mS cm ⁻¹)	2140.960	<0.001	0.993	162.364	<0.001	0.956	0.036	1.000	0.010

F-statistic; *p*, probability value; ηp^2 , partial eta-squared. System represents the experimental culture system (OSC, MP₁ and MP₂); Day represents the sampling period (0, 15, 30, 45 and 60 days); System × Day represents their interaction.

3.4 Mangrove community structure assessment

Mangrove structural characteristics varied among the experimental units (Table 7). Mean tree height was highest in MFU₂ (3.4540 m), followed by MFU₁ (1.6400 m) and MP₁ (1.6285 m), while MP₂ recorded the lowest value (1.0577 m). Above-ground biomass, below-ground biomass and total biomass showed significant differences among the units ($p < 0.001$), with the highest values recorded in MFU₂ (48.5090, 22.7982 and 71.3072 kg tree⁻¹, respectively) and the lowest in MP₂ (3.4551, 2.1133 and 5.5684 kg tree⁻¹, respectively). Carbon stock and CO₂ sequestration potential followed a similar pattern, with MFU₂ recording the highest values (33.5144 kg C tree⁻¹ and 122.9977 kg CO₂-eq tree⁻¹, respectively), while MP₂ recorded the lowest values (2.6171 kg C tree⁻¹ and 9.6049 kg CO₂-eq tree⁻¹, respectively) ($p < 0.001$). Estimated tree density was highest in MFU₂ (20,514.59 trees ha⁻¹), followed by MP₁ (10,168.77 trees ha⁻¹), MFU₁ (6,332.28 trees

ha⁻¹) and MP₂ (5,962.94 trees ha⁻¹).

The mangrove community comprised *Avicennia marina* and *Rhizophora mucronata*, with *A. marina* occurring across all four experimental units (Table 8). MP₁ showed complete dominance of *A. marina*, with relative density, frequency and coverage each at 100% and an Importance Value Index (IVI) of 300.00. In MFU₁, *A. marina* had higher relative density (88.00%), frequency (62.50%) and coverage (61.43%) than *R. mucronata* (12.00%, 37.50% and 38.57%, respectively), resulting in IVI values of 211.93 and 88.07, respectively. In MP₂, *A. marina* showed greater relative density (80.00%) and coverage (94.92%) than *R. mucronata* (20.00% and 5.08%, respectively), with IVI values of 230.47 and 69.53, respectively. MFU₂ showed equal relative density and frequency for both species (50.00% each), while *A. marina* had higher relative coverage (73.18%) than *R. mucronata* (26.82%), resulting in IVI values of 173.18 and 126.82, respectively.

TABLE 7 Structural, biomass and carbon characteristics of mangrove vegetation across the experimental units.

Parameter	MP ₁	MFU ₁	MP ₂	MFU ₂	<i>F</i> -value	<i>p</i> -value
Mean tree height (m)	1.6285 ^b	1.6400 ^b	1.0577 ^c	3.4540 ^a	41.28	<0.001
Mean DBH (cm)	5.8719 ^b	4.5664 ^b	3.6000 ^c	10.7667 ^a	32.55	<0.001
Tree density (trees ha ⁻¹)	10,168.77	6,332.28	5,962.94	20,514.59	—	—
Above-ground biomass (kg tree ⁻¹)	10.7836 ^b	6.7250 ^c	3.4551 ^d	48.5090 ^a	24.16	<0.001
Below-ground biomass (kg tree ⁻¹)	5.8628 ^b	3.7745 ^c	2.1133 ^d	22.7982 ^a	21.09	<0.001
Total biomass (kg tree ⁻¹)	16.6464 ^b	10.4995 ^c	5.5684 ^d	71.3072 ^a	22.94	<0.001
Carbon stock (kg C tree ⁻¹)	7.8238 ^b	4.9347 ^c	2.6171 ^d	33.5144 ^a	22.95	<0.001
CO ₂ sequestration potential (kg CO ₂ -e tree ⁻¹)	28.7134 ^b	18.1104 ^c	9.6049 ^d	122.9977 ^a	22.95	<0.001

4 | DISCUSSION

4.1 Growth performance and feed utilization of Asian seabass

The present study demonstrated differences in the growth performance and feed utilization of Asian seabass among OSC, MP₁ and MP₂, with MP₂ recording the highest values for most growth and feed-utilization parameters. Initial body weight did not differ significantly among sys-

tems ($p = 0.802$), indicating comparable stocking weights. Body weight increased throughout the 60-day culture period, with significant differences among systems from Day 15 onwards ($p < 0.01$) and a significant System × Day interaction. By Day 60, mean body weight reached 27.01±0.34 g in MP₂, 25.83±0.30 g in MP₁ and 23.22±0.11 g in OSC.

These findings are consistent with previous studies

demonstrating the influence of culture environments and management conditions on Asian seabass growth (Anil *et al.* 2011; Philipose *et al.* 2013; Mostofa *et al.* 2024; Thomas *et al.* 2026). Venkatachalam *et al.* (2018) also reported differences in survival and growth between mangrove-integrated and open-aquaculture systems. In

the present study, differences in water quality, sediment characteristics, primary productivity and chlorophyll-*a* among the systems may have contributed to the observed growth patterns. However, the individual contributions of these environmental factors cannot be established from the present results alone.

TABLE 8 Mangrove community structure and Importance Value Index across the experimental units.

Parameter	MP ₁	MFU ₁	MP ₂	MFU ₂
Total trees included in community analysis (<i>n</i>)	49	25	20	63
Relative density (RD, %)				
<i>Avicennia marina</i>	100.00	88.00	80.00	50.00
<i>Rhizophora mucronata</i>	0.00	12.00	20.00	50.00
Relative frequency (RF, %)				
<i>Avicennia marina</i>	100	62.50	55.56	50
<i>Rhizophora mucronata</i>	0	37.50	44.44	50
Relative coverage (RC, %)				
<i>Avicennia marina</i>	100.00	61.43	94.92	73.18
<i>Rhizophora mucronata</i>	0.00	38.57	5.08	26.82
IVI – <i>Avicennia marina</i>	300.00	211.93	230.47	173.18
IVI – <i>Rhizophora mucronata</i>	0.00	88.07	69.53	126.82

Feed utilization was also more favorable in the mangrove-integrated systems, particularly MP₂. Previous studies have shown that culture conditions and stocking density can influence seabass growth and production characteristics (Mostofa *et al.* 2024; Thomas *et al.* 2026). The observed differences may reflect the combined influence of environmental conditions and fish physiological performance. Natural food resources from microbial, planktonic and benthic communities may also have contributed to feed utilization; however, this possibility remains unconfirmed because natural food availability was not quantified. Differences in hydrodynamics, water residence time and organic matter inputs may likewise have influenced the feeding environment.

The growth advantage was primarily reflected in body-weight gain rather than statistically detectable differences in length gain or condition factor. Principal component analysis (PCA) supported the overall pattern, with variation among systems associated mainly with growth and feed-utilization performance. PC2 was more strongly associated with length gain and condition-factor variables, representing a separate dimension of variation. Overall, the IMAS were characterized by higher growth and more favourable feed-utilization traits, whereas OSC was more closely associated with higher FCR.

4.2 Water quality and primary productivity

Water-quality and primary-productivity characteristics differed among OSC, MP₁ and MP₂ over the 60-day culture period, with significant effects of system, culture period and their interaction. Water temperature, salinity

and pH were consistently higher in OSC than in the pond-based IMAS, potentially reflecting differences in heat exchange, tidal flushing, freshwater influence and evaporation. Significant System × Day interactions indicated that these differences varied over time. Comparable spatial and temporal variability in temperature, salinity and coastal productivity has been reported in the Tuticorin region and the Gulf of Mannar (Pitchaikani and Lipton 2016; Kavitha *et al.* 2026). Although the recorded temperature and salinity ranges did not appear to impose an obvious constraint on seabass performance, salinity-related differences may have contributed to the observed growth patterns without establishing a direct causal relationship (Reza *et al.* 2025).

Dissolved oxygen (DO) was highest in OSC, followed by MP₂, and lowest in MP₁, indicating that open-water mixing and exchange may have promoted oxygen replenishment in OSC. Temporal and spatial variation in water quality has also been reported in Asian seabass cage-culture systems (Prema *et al.* 2011; Loka *et al.* 2016). The higher DO in MP₂ than in MP₁, alongside greater gross primary productivity (GPP), net primary productivity (NPP) and chlorophyll-*a*, suggests an association between biological productivity and oxygen availability, consistent with observations from Tuticorin Bay (Kavitha *et al.* 2026).

Nitrogenous nutrient concentrations also differed among systems, with ammonia and nitrite highest in OSC, whereas nitrate was highest in MP₁, followed by MP₂ and OSC. Nutrient dynamics in aquaculture systems are influenced by feed inputs, fish metabolism, microbial transformations, plant uptake, sediment interactions and wa-

ter exchange (Tabrett *et al.* 2024). Although water movement can disperse dissolved wastes in open-sea cages, feed residues and faecal material may contribute to local nutrient loading and sediment enrichment (Holmer 2010). Temporal variation in nitrogenous nutrients has been documented in Asian seabass cage systems (Prema *et al.* 2011; Loka *et al.* 2016), while mangrove-integrated and silvofishery systems can modify dissolved inorganic nitrogen and phosphorus concentrations through nutrient uptake and processing (Peng *et al.* 2009; De-León-Herrera *et al.* 2015; Zheng *et al.* 2022). Mangrove sediments may also act as sinks for dissolved inorganic nitrogen through processes such as denitrification (Rivera-Monroy *et al.* 1999).

GPP, NPP and chlorophyll-*a* were higher in MP₂, followed by MP₁, indicating greater measured primary productivity in the IMAS than in OSC. Relationships among nutrient availability, phytoplankton abundance, chlorophyll-*a* and primary productivity have been documented in the Gulf of Mannar and Asian seabass cage-culture environments (Prema *et al.* 2011; Pitchaikani and Lipton 2016). Mangrove-associated systems may influence nutrient availability and biological productivity through nutrient cycling and interactions with sediments (Peng *et al.* 2009; Zheng *et al.* 2022; Huang *et al.* 2026). The higher productivity observed in MP₂ coincided with superior seabass growth; however, this association does not establish a direct causal relationship. Differences between MP₁ and MP₂ may reflect mangrove structure, vegetation density, nutrient processing, water-residence characteristics or other site-specific factors. Previous studies indicate that environmental effects vary with mangrove species, planting arrangements and system configuration (Peng *et al.* 2009; Zheng *et al.* 2022). Therefore, the benefits of mangrove integration should be assessed across multiple water-quality and productivity indicators rather than assuming that all parameters improve simultaneously.

4.3 Sediment quality characteristics

Sediment characteristics differed among OSC, MP₁ and MP₂ throughout the 60-day culture period. MP₂ recorded higher total organic carbon (TOC), total organic matter (TOM), total nitrogen (TN), estimated carbon stock, sediment pH, bulk density and electrical conductivity (EC), whereas available phosphorus was higher in both mangrove-integrated systems. These differences indicate distinct sediment environments, reflecting the combined influences of aquaculture-derived organic matter and nutrients and mangrove-associated processes. TOC and TOM were significantly higher in MP₂ than in OSC and MP₁, potentially reflecting inputs from feed residues, fish excretion, mangrove litter, root turnover and microbial biomass. Previous studies have demonstrated that mangrove integration can modify organic-matter and nutrient

dynamics in aquaculture systems (Peng *et al.* 2009; Zheng *et al.* 2022).

The higher TOC and TN concentrations in MP₂ coincided with the highest estimated sediment carbon stock. Mangrove ecosystems are important carbon reservoirs, and sediment organic carbon is a major component of their carbon storage. Recent research has also examined relationships between integrated mangrove aquaculture, sediment characteristics and ecosystem productivity (Huang *et al.* 2026). In the present study, the higher estimated carbon stock in MP₂ was consistent with its higher TOC and bulk density. Nevertheless, the estimate represents carbon stored within the sediment depth used for the calculation, and limited data are available on total ecosystem carbon storage.

Available phosphorus was significantly higher in MP₁ and MP₂ than in OSC, indicating differences in sediment phosphorus availability among the experimental systems (Peng *et al.* 2009; Zheng *et al.* 2022). However, the present study did not directly assess the processes responsible for these differences or determine whether mangrove-aquaculture integration affected reactive phosphorus accumulation in the culture water.

All sediment parameters showed significant culture-period effects, indicating temporal changes during the 60-day experiment. Significant System × Day interactions for sediment pH, TOC, TOM, TN, available phosphorus, bulk density and carbon stock further indicated that temporal patterns differed among systems. In contrast, sediment EC showed no significant System × Day interaction, suggesting a comparatively consistent temporal pattern despite differences among systems. These changes may reflect the progressive development of sediment conditions during culture, although the underlying processes were not directly measured.

The strongest sediment differences were observed in MP₂, which also showed greater mangrove structural development among the integrated systems. Mangrove roots, litter deposition and sediment–water interactions can influence sediment characteristics, while aquaculture contributes additional organic matter and nutrients. The simultaneous occurrence of greater mangrove development and higher sediment carbon and nutrient concentrations in MP₂ is consistent with a more developed mangrove-aquaculture sediment environment, although this association does not establish a direct causal relationship.

5 | CONCLUSIONS

The present study demonstrated that mangrove-integrated aquaculture, particularly MP₂, a mangrove-bunded culture pond hydraulically connected to Mangrove Filtration Unit 2 (MFU₂), where *Avicennia marina* and *Rhizophora mucronata* were recorded, showed improved growth performance and feed utilization of Asian

seabass compared with the open-sea cage system. These findings suggest that integrated mangrove aquaculture has the potential to combine aquaculture production with mangrove-associated environmental functions. However, the results should be interpreted within the context of the 60-day experimental period and the specific culture conditions evaluated. Although the improved biological performance observed in MP₂ indicates potential production benefits, the long-term sustainability, contribution to mangrove conservation, and economic viability of the system cannot be established from the present study alone. Further long-term studies incorporating ecological monitoring, economic analysis, and assessments of fish health and physiological responses are required to determine the broader applicability and sustainability of IMAS.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHORS' CONTRIBUTION

Kingston Jeyaashree: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. L. Loveson Edward: Resources, Project administration, Supervision, Writing – review & editing. Saminathan Athithan: Supervision, Validation, Writing – review & editing. Lakshmanan Ranjith: Formal analysis, Software, Validation, Writing – review & editing.

AI-USE STATEMENT

The authors used artificial intelligence (AI)-based tools only for language editing and improvement of clarity during the preparation of this manuscript. The authors take full responsibility for the accuracy, originality, interpretation, and final content of the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on a reasonable request from the corresponding authors.

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