Technical status, financial performance and climate-adaptive pathways of *Artemia franciscana* farming in artisanal solar salterns in Vinh Chau, Soc Trang Province, Vietnam: longitudinal empirical evidence from surveys performed in 2024 and 2026

Nguyen V. Hoa[1], Le T. Tam[2], Tran Q. Khang[3], Duong T. M. Han[1], Le V. Thong[1]

[1] College of Aquaculture and Fisheries, Can Tho University, Can Tho City, Vietnam;
[2] Department of Science and Technology of Ninh Kieu District, Can Tho City, Vietnam;
[3] Grobest Industrial (Vietnam) Co., Ltd., Dong Nai City, Vietnam. Corresponding author: N. V. Hoa, nvhoa@ctu.edu.vn

https://doi.org/10.67784/1018

Abstract. The cultivation of brine shrimp (*Artemia franciscana*) in coastal artisanal solar salterns serves as a vital socioeconomic pillar across Vietnam's Mekong Delta, particularly in Vinh Chau, Soc Trang Province. However, intensifying climate disruptions, extreme thermal anomalies, unseasonal rainfall and estuarine contamination from super-intensive shrimp farms pose severe threats to operational viability. This study presents an authoritative diagnostic evaluation of technical parameters, financial efficiency, operational strengths, structural bottlenecks and climate adaptation pathways by synthesizing comprehensive empirical datasets from 2024 (n = 120 specialised households covering the 2021-2023 production cycles across Vinh Phuoc and Lai Hoa cooperatives) and a diagnostic survey performed in 2026 (n = 25 households during a climate-shock season). The results indicate that *Artemia* farming remains economically superior to alternative coastal land uses, generating a triennial mean net profit of 49.70± 8.46 million VND ha^{-1} $crop^{-1}$ (benefit-cost ratio of 2.49, profit margin of 1.49) during 2021-2023. Nevertheless, mean cyst productivity declined from 61.9 kg ha^{-1} in 2021 to 45.6 kg ha^{-1} in 2023 and then decreased sharply to 6.46±5.45 kg ha^{-1} in the climate-perturbed 2026 season. In response to abnormal weather, 46.7% of farmers transitioned toward modified low-salinity systems (50-70‰), prioritizing the collection of adult live/frozen biomass (623.0-671.5 kg ha^{-1} during 2021-2023; 166.49±139.04 kg ha^{-1} in 2026) and rotational solar salt production (23.6-29.3 t ha^{-1}). Financial analysis in 2026 demonstrated severe margin compression, with mean production costs of 24.37±15.62 million VND ha^{-1} compared with revenues of 14.64±10.80 million VND ha^{-1}, yielding an average net loss of −9.74±18.36 million VND ha^{-1} among capital-intensive operations unable to buffer rainfall dilution. In contrast, resilient holdings achieved net profits of 15.9-22.9 million VND ha^{-1} by leveraging dual-harvesting regimes, deep hypersaline water reserves (> 80‰) and family labour. Key interventions include establishing municipal hydraulic zoning to isolate saltern intakes from aquaculture effluents, expanding dedicated fertilization reservoirs and deploying early stocking calendars.
Keywords: aquaculture economics, *Artemia franciscana*, climate change vulnerability, cyst/biomass productivity, hypersaline salterns, Mekong Delta.

Introduction. Aquaculture in Vietnam's Mekong River Delta (MRD) has expanded rapidly over recent decades, becoming a major driver of rural economic prosperity, food security and foreign-exchange revenue (Anh et al., 1997, 2014; Le et al., 2019, Vinh et al., 2020). In coastal estuarine zones characterised by acid-sulphate soils and pronounced hydrological seasonality, solar salt (NaCl) evaporation has traditionally supported local coastal livelihoods (Baert et al., 1997; Le et al., 2019). However, artisanal salt farming historically kept coastal salt workers in persistent poverty owing to its labour-intensive

nature, low market value and extreme vulnerability to unseasonal precipitation (Brands et al., 1995; Anh et al., 1997).

A transformative innovation emerged in the mid-1980s through scientific collaboration between Can Tho University and the Laboratory of Aquaculture & Artemia Reference Center at Ghent University, Belgium. Researchers acclimated and introduced the SFB brine shrimp (*Artemia franciscana* Kellogg, 1906, San Francisco Bay strain) into seasonal coastal artisanal salterns in Vinh Chau (Soc Trang Province) and Bac Lieu province (Brands et al., 1995; Anh et al., 1997; Le et al., 2019). By converting seasonal artisanal evaporation pans into *Artemia*-intensive, hypersaline-rearing enclosures during the dry season (December through May), coastal households generated financial returns four to five times greater than those from traditional salt monoculture, establishing an internationally acclaimed benchmark for poverty alleviation and community development (Brands et al., 1995; Hoa et al., 2007; Le et al., 2019).

Vinh Chau *Artemia* cysts rapidly achieved worldwide recognition in commercial crustacean and marine fish hatchery industries. The cysts exhibit an exceptionally small naupliar instar-I length (~430 µm), highly synchronised hatching (> 90%) and an optimal biochemical profile rich in highly unsaturated fatty acids (HUFA), particularly eicosapentaenoic acid (EPA, 20:5n-3) (Sorgeloos et al., 2001; Hoa et al., 2007). Ecologically, *Artemia* farming is symbiotic with artisanal solar salt crystallization. Dense populations of filter-feeding brine shrimp consume suspended microalgae, benthic microbial mats and organic detritus, thus clarifying hypersaline brines biologically before they enter crystallization beds. This biological filtration accelerates evaporation and produces sea salt with superior whiteness and chemical purity (> 96% NaCl) (Baert et al., 1997; Hoa et al., 2007; Anh et al., 2014).

Despite these technical and ecological advantages, coastal *Artemia*-salt integrated systems face intensifying ecological and socioeconomic challenges (Anh et al., 2014; Le et al., 2019, Vinh et al., 2020). Climate change has disrupted regional hydrology across the lower Mekong basin (Hong et al., 2021; Anh et al., 2024; Hua et al., 2024). Climatological reconstructions in Soc Trang Province have documented a 0.5°C rise in mean ambient temperatures, along with delayed monsoon cessation, unseasonal downpours during the normally arid dry months (January-March) and shorter evaporation windows (Hong et al., 2021; Anh et al., 2024; Hua et al., 2024). Because oviparous reproduction in *Artemia* (cyst formation) requires continuous hypersaline conditions (≥ 80‰) and high water temperatures, unseasonal rainfall dilutes salinity, induces thermal stratification, triggers lethal osmotic shock and causes cyst harvests to collapse (Lavens & Sorgeloos, 1996; Hoa et al., 2007).

Furthermore, rapid transformations of the coastal landscape - most notably, the proliferation of super-intensive whiteleg shrimp (*Litopenaeus vannamei*) complexes along the Vinh Chau coast - have caused severe contamination of intake canals (Hoa, 2012; Le et al., 2019, Vinh et al., 2020). Effluents discharged from shrimp ponds reduce salinity, introduce chemical residues and biocides and increase organic pathogen loads, thus prolonging the pumping time required to concentrate seawater and heightening disease risks. In response, local farmers have developed diverse coping strategies, including low-salinity rearing (50-70‰), commercial biomass harvesting and rotational wet-season polyculture (Brands et al., 1995; Hoa, 2012; Anh et al., 2014). Nevertheless, systematic investigations of longitudinal farm performance under acute weather anomalies remain fragmented. Therefore, this study synthesises extensive field datasets collected in 2024 (covering 120 households evaluated during 2021-2023) and 2026 (covering 25 households assessed during an extreme weather event) to: (1) evaluate operational parameters and technical dynamics; (2) quantify comparative multi-year financial balance sheets; (3) identify favourable factors, operational bottlenecks and systemic risks; and (4) formulate actionable technical, infrastructural and institutional solutions for long-term sustainability.

Material and Method

Study site and agro-ecological setting. Field surveys were performed across Vinh Chau, Soc Trang Province, located in the southeastern coastal zone of the Vietnamese Mekong

Delta (9°19'-9°35' N, 105°47'-106°05' E) (Hong et al., 2021; Anh et al., 2024; Hua et al., 2024). Vinh Chau has an 83-km coastline along the East Sea, characterised by alluvial mudflats, dense mangrove strips and interconnected tidal estuarine canal networks. The regional climate is tropical monsoonal, with a wet season from May to November, which delivers 85-90% of the annual rainfall, and a dry season from December to April/May, characterised by solar irradiance of 2,400-2,700 hours year^{-1} and evaporation rates of 4.5-6.8 mm day^{-1} (Hong et al., 2021; Anh et al., 2024; Hua et al., 2024). The research focused on two prominent aquaculture cooperatives: Vinh Phuoc Cooperative (Vinh Phuoc ward) and Lai Hoa Cooperative (Lai Hoa commune), which represent the historic core of commercial *Artemia* and solar salt farming in Soc Trang Province (Hoa, 2012). In addition, field investigations performed in 2026 incorporated distinct geographic sub-zones: Biển Trên (Upper Coast), which benefits from deep, high-salinity coastal seawater intakes, and Biển Dưới (Lower Coast), which is heavily exposed to estuarine mixing and discharge from adjacent intensive shrimp-farming complexes.

Sampling framework and empirical data collection. A mixed-methods empirical framework was implemented, integrating multi-year retrospective surveys, on-site pond monitoring, key-informant interviews and institutional data collection (Anh et al., 2014; Le et al., 2019, Vinh et al., 2020):

- 2024 comprehensive longitudinal survey (n = 120): performed from August through December 2024 across the Vinh Phuoc (n = 60) and Lai Hoa (n = 60) cooperatives using stratified random sampling. Face-to-face, semi-structured interviews were administered to household heads who had operated continuously throughout the 2021, 2022 and 2023 dry seasons. Standardised modules documented household sociodemographic characteristics, pond engineering dimensions, fertilization strategies, stocking densities, salinity regimes, itemised financial balance sheets and qualitative perceptions of climate-related disruptions (Hoa, 2012);

- 2026 specialized diagnostic survey (n = 25): performed during the 2026 dry-season (April 2026) production cycle to evaluate farming performance under environmentally stressful conditions. A cohort of 25 specialized *Artemia*-farming households in Vinh Chau was surveyed in detail across two technical management models: traditional earthen salterns (n = 15, relying on ambient evaporation and natural microalgae) versus improved/bio-supplemented ponds (n = 10, using dedicated algal fertilization reservoirs, commercial probiotics and structured fertilization). Detailed, itemised accounting logs were maintained for nine representative farms to evaluate production costs, revenue and net profit margins under severe weather anomalies.

Financial accounting and analytical economic modelling. Financial performance was assessed using farm-budgeting economic accounting frameworks adapted for coastal aquaculture systems (Anh et al., 2014; Han, 2023). All metrics were standardised to per-hectare equivalents (ha^{-1}) for each crop:

$$\text{Total Cost (TC)} = \text{Fixed Costs (FC)} + \text{Variable Costs (VC)}$$

where: FC denotes straight-line depreciation of capital assets (pumps, aerators, sluice gates, earthen dyke earthworks and warehouse structures), and VC denotes operating expenditures for *Artemia* cyst seed/inoculum, organic fertilizers (fermented chicken manure), inorganic fertilizers (urea and DAP), water-conditioning agents (agricultural lime and zeolites), supplemental feedstuffs (shrimp starter crumb, goby feeds and rice bran), fuel (diesel and gasoline), electricity and hired labour (Hoa et al., 2007; Hoa, 2012).

$$\text{Total Revenue (TR)} = \Sigma\ (Qj \times Pj)$$

where: Qj represents the harvested yield (kg ha^{-1}) of commodity j (raw cysts, wet biomass, marine salt, or rotational aquatic species), and Pj denotes the corresponding farm-gate unit price (VND kg^{-1}) (Anh et al., 2014).

Net profit (NP) was calculated as NP = TR − TC; the profit margin (PM) was calculated as PM = NP / TC; and the benefit–cost ratio (BCR) was defined as BCR = TR / TC = 1 + PM (Han, 2023).

Statistical analysis. Data were compiled and analysed using Microsoft Excel and SPSS version 26.0 (IBM Corp., Armonk, NY, USA). The parametric assumptions of normality and homogeneity of variance were verified using the Shapiro–Wilk and Levene's tests. Continuous variables are expressed as arithmetic means±standard deviation (mean± SD), together with percentage distributions. Statistical comparisons between groups across cooperative jurisdictions, technical farming regimes, and multi-year timeframes were performed using independent-samples Student's t-tests and one-way analysis of variance (ANOVA), followed by Tukey's HSD post hoc tests. The significance threshold was set at $p < 0.05$.

Results

Socio-demographic profile of farming households. The socio-demographic characteristics of the surveyed households from both the 2024 cohort (n = 120) and the 2026 cohort (n = 25) are systematically presented in Table 1. The demographic structure indicates an aging and highly experienced rural workforce. In the 2024 survey, household heads aged over 50 years accounted for 62.5% of the farming population, followed by those aged 41-50 (22.5%), 31-40 (11.7%) and a negligible 3.3% aged 21-30 years. Similarly, in the 2026 survey, 60.0% of operators were over 50 years old, with an average of 8.55±7.21 years of vocational experience, ranging up to 28 years. This demographic pattern reflects youth out-migration toward urban industrial hubs, leaving aging landholders to sustain manual saltern operations (Han, 2023). Educational attainment among household heads was generally low: 55.0% had only primary school education or no formal schooling, 36.7% had completed lower secondary school, and only 8.3% had completed upper secondary school or obtained tertiary qualifications. Farming operations relied heavily on family labour, with 91.7% of holdings managed by 1-2 family members. Decision-making was predominantly male (95.0%), reflecting culturally defined divisions of labour in nocturnal pumping, dyke construction and field management, while female family members handled cyst cleaning, dehydration and sorting (Anh et al., 2014).

Table 1

Socio-demographic characteristics of *Artemia*-farming households surveyed in Vinh Chau, Soc Trang Province (2024 survey: n = 120; 2026 survey: n = 25)

Demographic parameter / metric	*2024 Cohort (%) (n = 120)*	*2026 Cohort (%) (n = 25)*
Age structure of household heads		
• 21-30 years old	3.3	4.0
• 31-40 years old	11.7	12.0
• 41-50 years old	22.5	24.0
• Over 50 years old	62.5	60.0
Educational attainment level		
• Primary school or non-formal	55.0	52.0
• Lower secondary school	36.7	40.0
• Upper secondary school and higher	8.3	8.0
Farming experience in saltern *Artemia*		
• 1-5 years	25.9	28.0
• 6-10 years	38.3	36.0
• Over 10 years of continuous experience	35.8	36.0
• Mean experience (years±SD)	9.12±6.45	8.55±7.21
Household labour allocation		
• 1-2 family members per household	91.7	88.0
• More than 2 family members per household	8.3	12.0
Gender allocation of the farm manager		
• Male representation	95.0	96.0
• Female representation	5.0	4.0

Technical characteristics and operating parameters. The operational and spatial metrics of *Artemia* farming complexes are summarised in Table 2. In the 2024 survey, the total farm area was 207.56 ha, with an average operational farm holding of 1.73±1.17 ha household^{-1}. Individual pond sizes varied considerably: 59.2% ranged from 1,000 to 3,000 m^2, 17.5% were smaller than 1,000 m^2 (designated for early nursing, microalgal blooming, or biomass rearing), and 23.3% exceeded 3,000 m^2 (serving as deep evaporation reservoirs or grow-out units). Active rearing areas accounted for approximately 90% of total land holdings, while approximately 10% was allocated to conditioning and fertilization reservoirs (Hoa, 2012). In the 2026 survey, the average operational farm size was 1.20± 0.50 ha (traditional earthen farms: 1.11±0.54 ha; improved bio-supplemented farms: 1.34±0.42 ha).

Dedicated fertilization ponds were maintained by 99.2% of farms in 2024 and 72.0% in 2026. Farmers fermented dried chicken manure and applied inorganic fertilizers (urea and DAP) to promote green microalgal blooms, which were gravity-fed or pumped into grow-out ponds to sustain filter-feeding Artemia populations (Baert et al., 1997; Hoa et al., 2007). Supplemental diets were used by 45.0% of farms in 2024 and 48.0% in 2026, including rice bran, shrimp starter crumbs and formulated goby feeds. Goby feeds provided comparable *Artemia* somatic development at 30-40% lower cost than marine shrimp feeds. Stocking density averaged 6.79±2.77 cans ha^{-1} crop^{-1} in 2024 and 6.28±2.14 cans ha^{-1} crop^{-1} in 2026 (~1.07-1.15 kg dry cysts ha^{-1}) - nearly double the recommended baseline stocking rate of 3.0-4.0 cans ha^{-1} (Hoa et al., 2007). Farmers explained that this elevated stocking rate served as a compensatory buffer against early-season mortality caused by cold fronts and unseasonal rains (Hong et al., 2021; Anh et al., 2024; Hua et al., 2024). Regarding salinity management, 53.3% of farms in 2024 and 60.0% in 2026 operated under traditional high-salinity regimes (≥ 80‰ at stocking), whereas 46.7% in 2024 and 40.0% in 2026 managed low-salinity regimes (50-70‰). Low-salinity culture promotes ovoviviparous reproduction (live nauplii), rapid population growth and adult biomass accumulation, thus providing weekly cash flow while farmers wait for water salinity to exceed 80‰ later in the season (Brands et al., 1995; Hoa, 2012).

Table 2

Comparative technical and operational parameters for *Artemia* farming in Vinh Chau, Soc Trang Province

Technical parameter	*Unit*	*2024 Baseline (n = 120)*	*2026 Baseline (n = 25)*	*Baseline guideline*
Average farm operational holding	ha household^{-1}	1.73±1.17^{ns}	1.20±0.50	1.50-2.00
Culture season duration	days crop^{-1}	125.4±18.2	118.42±29.11	120-150
Stocking rate	cans ha^{-1} crop^{-1}	6.79±2.77^{ns}	6.28±2.14	3.00-4.00
Stocking frequency	cycles crop^{-1}	1.03±0.16^{ns}	1.12±0.33	1.00
Pond size: 500-1,000 m^2	% of ponds	17.5	16.0	N/A
Pond size: 1,000-3,000 m^2	% of ponds	59.2	64.0	Dominant standard
Pond size: > 3,000 m^2	% of ponds	23.3	20.0	Reservoir units
Farms with fertilization ponds	% of holdings	99.2	72.0	100.0%
Supplemental feed application	% of holdings	45.0	48.0	Optional
Traditional high salinity (≥ 80‰)	% of holdings	53.3	60.0	≥ 80.0‰ (standard)
Modified low-salinity (50-70‰)	% of holdings	46.7	40.0	50.0-70.0‰ (adaptive)
Dual harvesting (cyst + biomass)	% of holdings	N/A	88.0	Recommended

ns: not significant difference (p > 0.05); N/A: not available.

Longitudinal production trends: 2021-2023 baseline and the 2026 crop. Longitudinal production dynamics across the triennial 2021-2023 baseline and the 2026

production season are presented in Table 3. During 2021-2023, raw cyst production showed a steady downward trend, declining from 12,848 kg (61.9 kg ha^{-1}) in 2021 and 12,586 kg (60.6 kg ha^{-1}) in 2022 to 9,457 kg (45.6 kg ha^{-1}) in 2023 - a 26.3% contraction. This decline was driven by early rainfall in February and prolonged cloud cover, which reduced pond salinities below the 80‰ threshold required for cyst induction and triggered premature ovoviviparity (Hoa et al., 2007; Hong et al., 2021; Anh et al., 2024; Hua et al., 2024).

Table 3

Aggregate production volumes and unit yields for *Artemia*, rotational sea salt and wet-season aquaculture in Vinh Chau (2021-2026)

Production commodity	*2021*	*2022*	*2023*	*2021-2023 mean*	*2026*
Artemia raw cysts (kg ha^{-1})	61.9	60.6	45.6	56.03±9.07	6.46±5.45
• Traditional earthen salterns	--	--	--	--	7.42±6.39
• Improved/bio-supplemented	--	--	--	--	4.96±3.34
Artemia wet biomass (kg ha^{-1})	663.4	671.5	623.0	652.63±25.96	166.49±139.04
• Traditional earthen salterns	--	--	--	--	153.12±139.18
• Improved/bio-supplemented	--	--	--	--	187.28±144.52
Wet-season polyculture (kg ha^{-1})	282.9	274.4	262.0	273.10±10.51	N/A (wet season)
• *L. vannamei* share (%)	89.0	89.0	89.0	89.0	--
• *P. monodon*/crab/scat (%)	11.0	11.0	11.0	11.0	--
Rotational artisanal salt (t ha^{-1})	23.62	27.65	29.34	26.87±2.94	N/A (late dry)

This climate vulnerability was even more pronounced during the 2026 season. Mean cyst productivity across the 25 surveyed farms declined to 6.46±5.45 kg ha^{-1} (ranging from 0.00 to 20.00 kg ha^{-1}) - an 88.5% decrease relative to the 2021-2023 triennial average of 56.03±9.07 kg ha^{-1}. The 2026 season was characterised by severe weather anomalies, including torrential mid-season rains, thermal fluctuations (pond water temperatures varied from 24 to > 38°C within 48 hours) and high turbidity in the intake canals. Notably, traditional earthen salterns produced higher average cyst yields (7.42±6.39 kg ha^{-1}) than improved bio-supplemented ponds (4.96±3.34 kg ha^{-1}) (Figure 1).

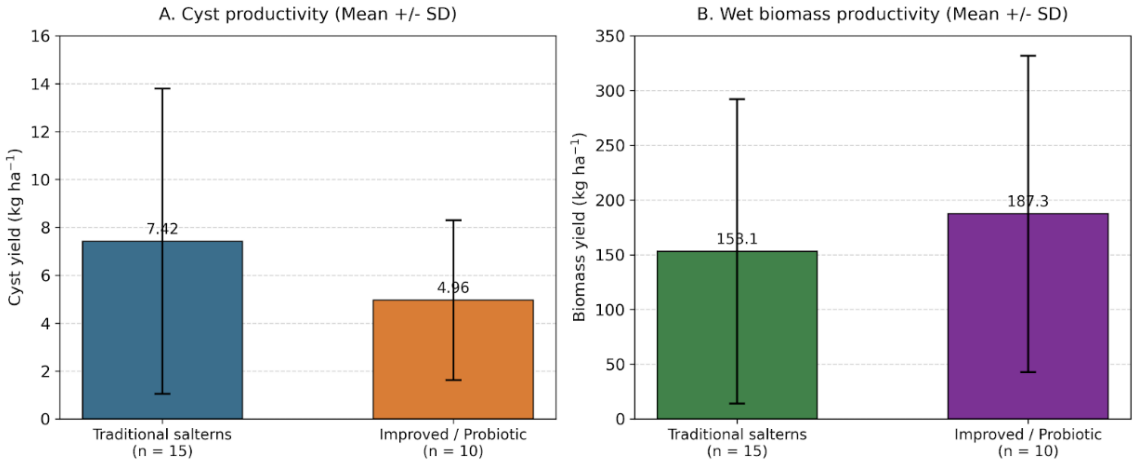


Figure 1. Comparison of *Artemia* cyst and wet biomass productivity (mean±SD) between traditional salterns and improved, bio-supplemented ponds in Vinh Chau during the 2026 crop.

In improved ponds, elevated nutrient inputs combined with lower salinity levels stimulated microalgal blooms that favoured the release of live nauplii over cyst encapsulation. In contrast, harvesting adult *Artemia* wet biomass proved more resilient. In dedicated commercial ponds during 2021-2023, biomass yields remained steady at 623.0-671.5 kg ha^{-1}. In 2026, yields from dual-harvest biomass averaged 166.49±139.04 kg ha^{-1} (187.28±144.52 kg ha^{-1} in improved ponds versus 153.12±139.18 kg ha^{-1} in traditional

salterns). Rotational solar salt production increased from 23,615 kg ha^{-1} in 2021 to 29,343 kg ha^{-1} in 2023, as salt-focused farmers capitalised on late dry-season heatwaves to evaporate biological *Artemia* brine. During the wet season, 84.2% of households rotated into polyculture (whiteleg shrimp, black tiger shrimp, mud crab and spotted scat), producing an average of 273.1 kg ha^{-1} across 179.06 ha (Anh et al., 2014).

Financial balance sheets and economic efficiency. The economic balance sheets for the 2021-2023 baseline period and the 2026 crop are summarised in Tables 4 and 5. During 2021-2023, *Artemia* cultivation demonstrated strong financial profitability. Total production costs averaged 33,323,703±5,604,083 VND ha^{-1} crop^{-1}, gross revenues reached 83,023,967±7,545,297 VND ha^{-1} and net profits averaged 49,700,264± 8,458,944 VND ha^{-1}, resulting in an average profit margin of 1.49 (BCR = 2.49). Net earnings from *Artemia* were approximately three times higher than those from rotational solar salt (13.14 million VND ha^{-1}) and wet-season polyculture (17.05 million VND ha^{-1}), confirming its central role in household income generation (Anh et al., 2014; Le et al., 2019; Vinh et al., 2020).

Table 4

Annual financial balance sheets per hectare for coastal production systems in Vinh Chau (2021-2023 baseline)

Production system and year	*Total cost (VND)*	*Gross revenue (VND)*	*Net profit (VND)*	*Profit margin*
Artemia culture (2021)	39,734,929	85,895,420	46,160,491	1.16
Artemia culture (2022)	29,357,901	88,711,974	59,354,073	2.02
Artemia culture (2023)	30,878,280	74,464,507	43,586,227	1.41
Artemia three-year mean±SD	33,323,703± 5,604,083	83,023,967± 7,545,297	49,700,264± 8,458,944	1.49
Wet polyculture mean±SD	11,358,725± 134,219	28,406,689± 1,469,242	17,047,963± 1,429,399	1.50
Solar salt mean±SD	14,000,000± 1,000,000	27,136,150± 3,081,830	13,136,150± 2,184,027	0.94

In contrast, the 2026 diagnostic audit revealed severe financial distress during a season of adverse weather. Across the 9 fully audited farms, total production costs averaged 24.37± 15.62 million VND ha^{-1}, whereas gross revenues averaged only 14.64±10.80 million VND ha^{-1}, resulting in an average net loss of −9.74±18.36 million VND ha^{-1} (Table 5). Fixed costs accounted for 33.6% of total expenditures (8.19±7.42 million VND ha^{-1}), primarily owing to dyke reconstruction and canal dredging/raking. Variable operational costs accounted for the remaining 66.4% (16.19±12.08 million VND ha^{-1}), with the largest components being cysts used as inoculum (24.9%), fertilizers and feeds (20.0%) and externally hired labour (12.8%).

Of the nine audited households, six operated at a net loss (Figure 2). Losses were concentrated among farms with high fixed investments (> 40-50 million VND ha^{-1}), heavy reliance on hired labour and severe crop damage caused by unseasonal rains (e.g., Household 1: −30.11 million VND ha^{-1}; Household 7: −26.31 million VND ha^{-1}). In contrast, profitable farms achieved positive returns (Household 15: +22.96 million VND ha^{-1}, BCR = 5.23; Household 25: +15.95 million VND ha^{-1}, BCR = 3.47). These successful farms shared common operational strategies: keeping fixed preparation costs low (< 7 million VND ha^{-1}), minimizing hired labour by relying on family workers, maintaining deep hypersaline reserves (> 80‰) to buffer against rainfall and pursuing dual harvests (producing > 15 kg ha^{-1} of cysts alongside > 350 kg ha^{-1} of live biomass). Geographic location also influenced productivity: farms in the Biển Trên (Upper Coast) sector achieved cyst yields of 10.78±0.69 kg ha^{-1} - nearly double the 5.81±5.56 kg ha^{-1} recorded in Biển Dưới (Lower Coast) - owing to their direct access to cleaner marine water intakes.

Table 5

Itemised operational costs, gross revenue and financial returns per hectare in Vinh Chau (2026 survey: n = 9 audited holdings)

Accounting expenditure item (Unit: million VND ha^{-1})	*Mean±SD*	*% of total cost*	*Observed range (min-max)*
1. Fixed capital costs (FC)	8.19±7.42	33.6%	0.00-20.00
• Sluice gate repairs, dyke renovation and earthworks	8.19±7.42	33.6%	0.00-20.00
2. Variable operating costs (VC)	16.19±12.08	66.4%	5.43-36.67
• *Artemia* cyst seed/inoculation stock	6.08±2.91	24.9%	3.30-12.00
• Fertilisers (organic chicken dung + DAP/urea)	4.87±4.47	20.0%	0.00-14.44
• Biosecurity, liming and soil conditioning agents	0.71±1.13	2.9%	0.00-3.33
• Pumping fuel (Diesel, Petrol), electricity	1.73±0.80	7.1%	0.67-3.00
• External hired labour (excavation, harvesting)	3.11±5.13	12.8%	0.00-13.33
Total production cost (TC = FC + VC)	24.37±15.62	100.0%	5.43-50.00
Gross harvest revenue (TR)	14.64±10.80	--	0.00-28.47
Net profit (NP = TR - TC)	−9.74±18.36	--	−30.11-22.96
Benefit-cost ratio (BCR = TR / TC)	1.26±1.83	--	0.00-5.23

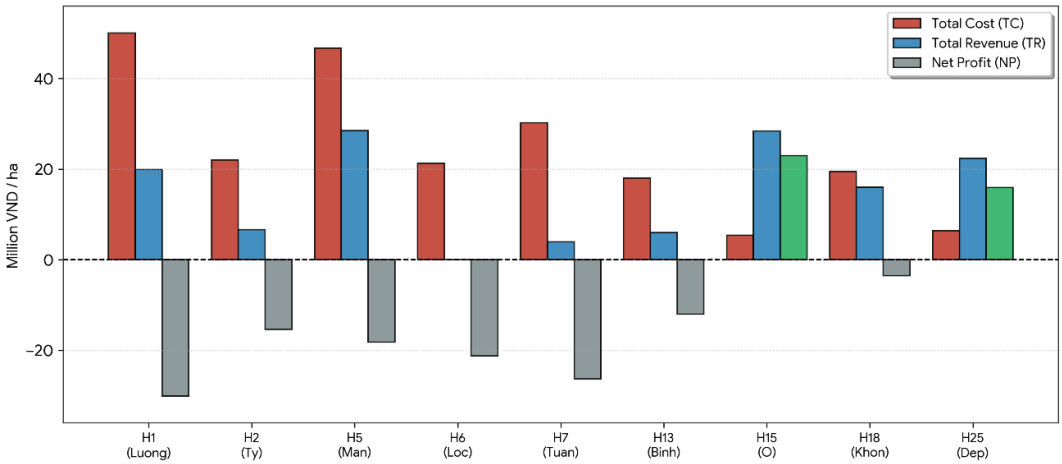


Figure 2. Financial balance sheet (total cost, gross revenue and net profit) per hectare for 9 audited households in Vinh Chau during the climate-affected 2026 crop.

Discussion

Factors favourable to Artemia cultivation in Vinh Chau. Vinh Chau possesses unique natural and geographic advantages that have sustained its reputation for high-quality *Artemia* production for more than 40 years (Anh et al., 1997; Hoa et al., 2007):

1. Favourable macro-climate: the distinct, arid dry season (December-April) is characterised by intense solar irradiance (2,400-2,700 sunshine hours year^{-1}), high ambient temperatures (30-36°C), persistent coastal winds and high evaporation rates, which collectively facilitate the rapid concentration of seawater into hypersaline brine (Brands et al., 1995; Le et al., 2019; Hong et al., 2021; Anh et al., 2024; Hua et al., 2024);

2. Soil and substrate conditions: coastal soils in Vinh Chau consist of dense marine clay loams with low vertical percolation rates, minimizing seepage losses and facilitating the retention of hypersaline water in earthen saltpans (Anh et al., 1997; Hoa et al., 2007);

3. Local knowledge and practical experience: more than three decades of cultivation have fostered deep practical expertise among local farming communities. As shown in Table 1, 74.1% of surveyed farmers have over six years of experience, while 35.8% have farmed *Artemia* for more than a decade. This experience enables farmers to effectively manage water transfers, benthic microalgal mats and salinity adjustments;

4. High economic value: as demonstrated by the 2021-2023 baseline, *Artemia* cultivation generates an average net profit of 49.70 million VND ha^{-1} - substantially exceeding that of traditional salt production and wet-season polyculture.

Operational challenges and systemic bottlenecks. Despite these advantages, household surveys in 2026 identified several major operational bottlenecks that jeopardise system viability (Figure 3):

- weather anomalies and climate disruptions: identified as a critical risk by 100% of respondents in 2026 and 92.5% in 2024. Unseasonal downpours dilute pond surface waters, creating haloclines and thermoclines that cause anoxia, thermal stress and high mortality (Hong et al., 2021; Anh et al., 2024; Hua et al., 2024). In 2026, severe weather shocks reduced average cyst yields to 6.46 kg ha^{-1} - an 88.5% decline from the 2021-2023 baseline of 56.03 kg ha^{-1};

- inconsistent inoculum and seed quality: reported by 76% of farmers in 2026. Substandard commercial cysts with poor hatching synchrony (< 70%) or low larval vigour contribute to early stocking failures, forcing farmers to re-inoculate and increasing seed costs to 6.08±2.91 million VND ha^{-1} (24.9% of total operating costs);

- intake canal contamination: effluents discharged from super-intensive *L. vannamei* shrimp farms introduce suspended solids, chemical residues (disinfectants and chlorine) and lower-salinity water into shared intake canals. This prolongs the pumping time needed to achieve target salinities and increases the risk of microalgal crashes (Hoa, 2012; Le et al., 2019, Vinh et al., 2020);

- technical knowledge and monitoring gaps: despite their experience, 56% of farmers in 2026 and 41.7% in 2024 lacked essential measurement tools, such as optical refractometers (0-150‰) or submersible thermometers. Management decisions are often based on visual observation, leaving systems vulnerable to sudden environmental changes;

- capital constraints and informal debt: more than 56% of farmers identified capital shortages as a major constraint. With limited access to formal bank credit, many rely on informal agricultural loans or deferred-payment credit from feed merchants at high interest rates, reducing farm profitability.

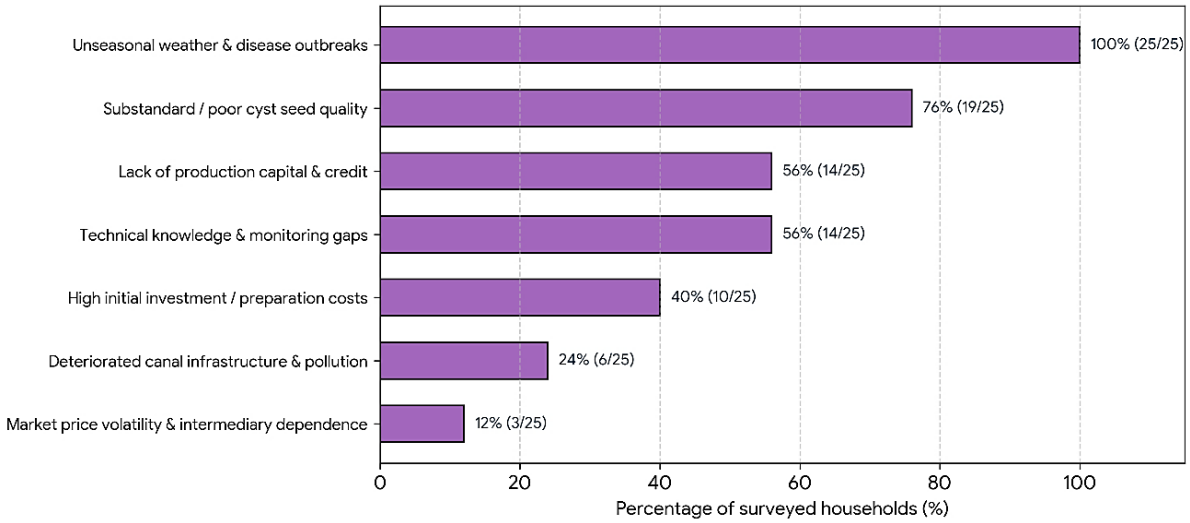


Figure 3. Frequency and proportion of primary operational constraints and risks reported by *Artemia*-farming households in Vinh Chau (2026 survey; n = 25).

Climate-related challenges and environmental threats. Climate change models for the coastal Mekong Delta project an increasing frequency and severity of extreme weather events (Hong et al., 2021; Anh et al., 2024; Hua et al., 2024). Specific environmental threats to the Vinh Chau saltern ecosystem include:

- shortened evaporation windows: a delayed monsoon cessation extending into December and earlier rainfall during the hot, dry season beginning in March or April reduce the reliable *Artemia* production window from 5-6 months to 2.5-3 months (Hong et al., 2021; Anh et al., 2024; Hua et al., 2024);

- thermal extremes: extreme temperatures in early afternoon exceeding 38-40°C in shallow pans (< 15 cm deep) cause lethal thermal stress and trigger systemic physiological collapse in *Artemia* populations (Hoa et al., 2007).

Proposed strategic solutions and adaptive pathways. To address these technical, environmental and financial challenges, we propose an integrated set of strategic solutions (Table 6):

- operational adaptations (deep hypersaline water storage): farmers must establish dedicated hypersaline reserve reservoirs (deeper than 40-50 cm, with salinity of 80-120‰) covering at least 20-25% of the total farm area. During unseasonal rainfall, high-salinity reserve water can be drawn immediately into culture ponds to counteract freshwater dilution, prevent haloclines and preserve oviparous reproduction. In addition, maintaining greater pond water depth (more than 25 cm in grow-out ponds) helps buffer against extreme midday water temperatures (above 38°C);

- harvest diversification (dual cyst and biomass regime): relying only on cyst harvesting increases financial vulnerability to weather disruptions. Transitioning to dual-harvest systems - where adult live or frozen biomass is collected weekly alongside cyst harvesting - provides regular cash flow. Adult *Artemia* biomass sells for approximately 35,000-45,000 VND kg^{-1} as live feed for commercial fish and shrimp hatcheries across the Mekong Delta. As demonstrated by successful farms in 2026, dual harvesting generated gross revenues of 22-28 million VND ha^{-1} even when weather conditions suppressed cyst yields;

- nutrient management and microalgal optimization: the 2026 survey showed that direct, excessive fertilization of culture ponds stimulated green flagellate blooms and reduced salinity, shifting *Artemia* reproduction toward live nauplii rather than cysts. Farmers should restrict organic fertilization (fermented chicken manure) to designated fertilization ponds. Nutrient-rich algal water should be managed and introduced gradually to maintain water transparency (Secchi depth: 25-35 cm), providing sufficient nutrition while preserving the osmotic conditions required for cyst production (Baert et al., 1997; Hoa et al., 2007). Using affordable supplemental feeds, such as goby diets, can also reduce feeding costs by 30-40% compared with marine shrimp starter feeds;

- infrastructure planning (municipal hydraulic zoning): local government authorities (Soc Trang Department of Agriculture and Rural Development) must implement strict hydraulic zoning along the Vinh Chau coast. Primary intake canals for artisanal salterns and *Artemia* farms must be structurally separated from the drainage canals of super-intensive shrimp farming complexes. Requiring commercial shrimp farms to establish effluent settling basins will help protect water quality in shared coastal waterways;

- institutional support and cooperative value chains: cooperatives such as Vinh Phuoc and Lai Hoa should expand bulk purchasing of certified, high-hatching *Artemia* cysts to reduce seed costs and ensure quality. In addition, establishing preferential, low-interest microcredit lines through the Vietnam Bank for Social Policies and commercial agricultural banks will reduce reliance on informal, high-interest loans. Finally, developing guaranteed cooperative off-take agreements with hatchery operators will help stabilise farm-gate prices and protect farmers from fluctuations in intermediary prices.

Table 6

Synthesis of the operational advantages, difficulties, challenges and proposed strategic solutions for *Artemia* farming in Vinh Chau

Thematic dimension	*Empirical field observations and strategic countermeasures*
1. Advantages and favourable factors	• Ideal macro-climate: a prolonged dry season, high solar radiation, persistent winds and high evaporation; • Impermeable marine clay-loam soils that prevent vertical seepage in earthen salterns; • More than 30 years of accumulated local experience in hypersaline water management; • Ecological synergy with solar salt: *Artemia* bio-clarification improves salt purity and grade; • Strong economic profitability: net returns are 2-3 times higher than those of alternative monocultures.

2. Difficulties and bottleneck risks	• Unseasonal rainfall and temperature fluctuations causing pond stratification and mass mortality; • Effluent discharges from intensive shrimp farms contaminating shared water-supply canals; • Substandard cyst-seed quality resulting in low hatching rates and compensatory overstocking; • High initial fixed costs (dyke renovation and excavation) increasing financial risk; • Limited access to formal bank loans, leading to dependence on high-interest informal credit.
3. Long-term challenges	• Global climate change: shorter dry windows, rising sea levels and coastal storm surges; • Demographic shifts: an aging agricultural workforce as younger generations migrate to cities; • Inappropriate nutrient over-enrichment that stimulates live-bearing reproduction rather than cyst formation; • Common-pool water conflicts between intensive shrimp farmers and hypersaline saltern operators.
4. Proposed strategic solutions	• Operational: expand deep hypersaline reservoirs (> 80‰, depth > 40 cm) to buffer declines in salinity; • Management: promote dual harvesting (cysts + live biomass) to diversify revenue streams; • Technical: optimise microalgal fertilization in dedicated ponds; avoid over-fertilizing culture ponds; • Environmental: implement hydraulic zoning to separate shrimp effluent from saltern intakes; • Policy: provide low-interest credit lines and establish cooperative price-stabilization funds.

Conclusions. Synthesizing empirical datasets from 2024 (n = 120) and 2026 (n = 25) in Vinh Chau, Soc Trang, this study identifies four core findings on *Artemia* farming:

- economic viability: highly profitable under favourable weather conditions, generating a triennial net profit of 49.70±8.46 million VND ha^{-1} $crop^{-1}$ during 2021-2023 (profit margin: 1.49), outperforming traditional salt production and polyculture;

- climate vulnerability: extreme weather (unseasonal rain, thermal swings and canal contamination) triggered a 26.3% decline in cyst yield from 2021 to 2023 and a sharp drop to 6.46±5.45 kg ha^{-1} in 2026. Therefore, input-intensive, labour-hiring farms suffered average net losses of −9.74±18.36 million VND ha^{-1};

- adaptive pathways: climate resilience depended on dual harvesting (> 15 kg ha^{-1} cysts and > 350 kg ha^{-1} biomass), deep hypersaline buffers (> 80‰), dedicated external microalgal ponds and lower fixed costs (< 7 million VND ha^{-1} for renovation using family labour);

- policy interventions: sector sustainability requires hydraulic zoning to control shrimp effluents, instrument-based water-monitoring training (salinity, temperature, pH), preferential microcredit and strengthened cooperative value chains.

Acknowledgements. The authors sincerely thank the Management Boards and extension officers of Vinh Phuoc Cooperative and Lai Hoa Cooperative (Vinh Chau town, Soc Trang Province) for facilitating field logistics, survey administration and community engagement. We are grateful to the 120 farming households from the 2024 survey cohort and the 25 households from the 2026 survey cohort for generously sharing their operational logs, financial accounts and practical insights.

Authors Contributions. NVH designed the questionaire, discussed the data, synthesized opinions, wrote the draft, and corected/revised the paper in according to the reviewer's feedback; LTT was responsible for the survey and collecting data; TQK field data collecting;

DTMH data entered and making graphs; LVT was responsible for the survey and collecting data.

Conflict of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding. This study was partially funded and supported by the Department of Science and Technology of Can Tho, Vietnam.

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Received: 09 October 2026. Accepted: 23 October 2026. Published online: 05 November 2026.
Authors:
Nguyen Van Hoa (NVH), College of Aquaculture and Fisheries, Can Tho University, Campus II, 3/2 Street, 94000 Cantho City, Vietnam, e-mail: nvhoa@ctu.edu.vn https://orcid.org/0000-0001-8384-6068
Le Trung Tam (LTT), Department of Science and Technology of Ninh Kieu District, Ly Thuong Kiet Street, No. 02, Ninh Kieu Ward, 94055 Cantho City, Vietnam, e-mail: lttam6@cantho.gov.vn
Tran Quóc Khang (TQK), Grobest Industrial (Vietnam) Co., Ltd., Bien Hoa 2 Industrial Zone, Street 3A, No. 9, Long Hung Ward, 810000 Dong Nai City, Vietnam, e-mail: tranquockhang19012003@gmail.com
Duong Thi My Han (DTMH), College of Aquaculture and Fisheries, Can Tho University, Campus II, 3/2 Street, 94000 Cantho City, Vietnam, e-mail: dtmhan@ctu.edu.vn
Le Van Thong (LVT), College of Aquaculture and Fisheries, Can Tho University, Campus II, 3/2 Street, 94000 Cantho City, Vietnam, e-mail: vanthong@ctu.edu.vn
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How to cite this article:
Hoa, N. V., Tam, L. T., Khang, T. Q., Han, D. T. M., & Thong, L. V. (2026). Technical status, financial performance and climate-adaptive pathways of *Artemia franciscana* farming in artisanal solar salterns in Vinh Chau, Soc Trang Province, Vietnam: longitudinal empirical evidence from surveys performed in 2024 and 2026. *Aquaculture, Aquarium, Conservation & Legislation, 19*(6), 2660-2672. https://doi.org/10.67784/1018