Effects of Stocking Density on Fish and Rice Yields in Semi-intensive Rice-fish Culture of Climbing Perch (*Anabas testudineus*) in Rain-fed Rice Paddies

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ABSTRACT

We investigated the feasibility of culturing air-breathing carnivorous fish, climbing perch (*Anabas testudineus*), in a semi-intensive rice-fish system in Northeast Thailand. Fingerlings of two initial size classes (ca.1 and 6 g per fish) were reared for 2.5 or 3.5 months to evaluate the effects of stocking density (0–80 fish·m^{-2}) on fish growth, fish yield, and rice yield. Fish reached market size (100 mm total length and 20 g wet weight) at all stocking densities. Total fish yield increased proportionally with stocking density, at least up to 60 fish·m^{-2}, yielding 1.8–2.0 kg·m^{-2}, indicating that climbing perch did not experience density-related constraints within this range. Trade-off existed between fish and rice yields, with rice yield declining significantly at stocking densities of ≥20 fish·m^{-2} (mean: 200 g·m^{-2}) compared to the no-fish control and 10 fish·m^{-2} treatments (mean: 520 g·m^{-2}). Fish revenue was comparable to, or slightly lower than, the combined costs of fingerling purchase and feed under concurrent culture conditions, with fingerling costs accounting for nearly 40% of this production cost. Overall, this study demonstrates that semi-intensive rice-fish culture of climbing perch is feasible in terms of fish production; however, further optimization of culture conditions is necessary to sustain both fish and rice yields at higher stocking densities. Specifically, extending the culture duration and/or improving fish growth performance are necessary to enhance profitability.

Keywords: Air-breathing, Indochinese Peninsula, Integrated culture, Rice field, Tropical savanna climate

INTRODUCTION

Rice-fish culture is a co-culture system that integrates fish production into rice paddies and has been widely practiced in East and Southeast Asia (Halwart and Gupta, 2004). In this culture system, fish fingerlings are stocked after rice transplanting and cultured until shortly after rice harvest (Halwart and Gupta, 2004). Fish presence can enhance rice production by supplying nutrients through excretion and by resuspending soil nutrients through substrate disturbance (Tsuruta *et al*., 2011; Xie *et al*., 2011; Arunrat and Sereenonchai, 2022). Consequently, the use of both fertilizers and water can be reduced in rice-fish culture systems, compared with rice monoculture (Berg *et al*., 2023). In addition, fish can suppress weed and insect pests (Rothuis *et al*., 1999; Tsuruta *et al*., 2011; Xie *et al*., 2011), thereby contributing to reduced pesticide and herbicide use and improving the environmental sustainability of rice production systems (Xie *et al*., 2011; Bashir *et al*., 2020).

In the Lower Mekong Basin, rice-fish culture traditionally targets herbivorous or omnivorous species such as Nile tilapia (*Oreochromis niloticus*)

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and cyprinids, including silver barb (*Barbonymus gonionotus*) and common carp (*Cyprinus carpio*) (Vromant *et al*., 2002; Kaewpuangdee *et al*., 2024). Owing to their low-trophic levels, these species can effectively utilize natural food resources available in rice paddies, such as periphyton, zooplankton, and aquatic invertebrates (Saowakoon *et al*., 2021; U-kerd and Srifa, 2024). Their growth performance is generally satisfactory under extensive conditions, allowing fish culture to be completed within a single rice cropping period of three to four months (Mohanty *et al*., 2004). However, fish yield of some common omnivorous species may plateau at relatively low densities (2–6 fish·m^{-2}) due to density-dependent effects (Mohanty *et al*., 2009).

The introduction of air-breathing species may provide an opportunity for sustainably intensifying rice-fish culture systems. Many wetland species native to the Lower Mekong Basin possess respiratory systems that enable direct air uptake, allowing survival and growth in stagnant or hypoxic water, particularly during the half-year dry season under tropical savanna climates. Representative air-breathing species include native walking catfish (*Clarias* spp.), snakeheads (*Channa* spp.), gouramies (*Trichopodus* spp.), and swamp eels (*Monopterus* spp.), all of which are widely cultured and economically important in Southeast Asia (Lefevre *et al*., 2014; Bayley *et al*., 2020; Nagao Natural Environmental Foundation, 2021). These species also account for a substantial proportion of rice field capture fisheries in the region, in terms of both quantity and economic value (Amilhat *et al*., 2009a; 2009b; Freed *et al*., 2020). Fishes naturally recruited to rice paddies are harvested by draining water from fish refuge ponds, usually in the early dry season (mainly in November and December) (Little *et al*., 1996; Iwata *et al*., 2003). The presence of such fishing activity and the abundance of fish in fish refuge ponds until fish harvest, in terms of both species richness and biomass, indicate that air-breathing species are well adapted to the secondary wetland habitats created by rice cultivation. Accordingly, air-breathing species may be cultured at higher densities than conventional target species in rice fields, without aeration.

Climbing perch (*Anabas testudineus*) is an air-breathing perciform species with high potential for rice-fish culture. This species is native to Southeast Asia and commonly inhabits wetlands, including rice paddies, especially during the wet season (Iwata *et al*., 2003; Nagao Natural Environmental Foundation, 2021). In the wild, climbing perch typically attains a total length (hereafter TL) of around 15 cm (Satrawaha and Pilasamorn, 2009; Jalilah *et al*., 2025), whereas cultured strains generally exhibit faster growth and can reach up to 25 cm TL (Piwpong *et al*., 2016; Jalilah *et al*., 2025). Like many other air-breathing species, climbing perch commands a high price in local fresh markets (Mekong River Commission, 2015; Tomojiri *et al*., 2021). Despite this economic value, the cultured production of this species remains substantially smaller than that of other air-breathing species native to Southeast Asia, such as snakeskin gourami (*Trichopodus pectoralis*) or striped snakehead (*Channa striata*) (Bayley *et al*., 2020; FAO, 2024). Its relatively small maximum size and short time to maturity (Jalilah *et al*., 2025), however, make climbing perch well suited to the short culture period available in rice paddies.

Previous studies have evaluated the feasibility of rice-fish culture targeting climbing perch under extensive conditions. Vongvichith *et al*. (2018) reported satisfactory growth in rain-fed rice paddies in central Laos at low fish densities (0.3–2.0 fish·m^{-2}), even without supplemental feeding, and the growth performance was further improved when commercial pellets were supplied. Saharia *et al*. (2018) reported fish yields of approximately 500–600 kg·ha^{-1} at a stocking density of 2 fish·m^{-2} and a culture period of 2.5–3 months in Assam region of Northeast India. The productivity of rice-fish culture systems targeting this species could be further enhanced through semi-intensive management, including feeding and increased stocking density. Under earthen pond conditions, climbing perch can be cultured at densities of 5–30 fish·m^{-2} without aeration (Chakraborty, 2016; Ahamed *et al*., 2018; Noodang and Kakkew, 2020), and even at densities of up to 80 fish·m^{-2} in small floating cages without substantial reduction in

survival (Vongvichith *et al*., 2020; Debnath *et al*., 2022). Nevertheless, high density stocking negatively affects fish physiological conditions, fish growth, and fish yield, even in air-breathing species (Debnath *et al*., 2022; Diao *et al*., 2023). Therefore, the relationship between stocking density and fish yield should be examined to identify feasible and sustainable culture settings.

Northeast Thailand is a representative region with a rain-fed rice cropping system on the Indochinese Peninsula. Although Northeast Thailand accounts for nearly 60% of the national rice field area (6.1 million ha), rice production remains at 45% (13 million t·year^{-1}) of the national total (OAE, 2025b). Over 90% of these rice paddies are rain-fed because of water scarcity during the half-year dry season under a tropical savanna climate and the low water-carrying capacity of sandy soil in the region (Homma and Horie, 2009). Consequently, a single crop of rice is produced during the rainy season (mainly between June and November; Suwanmontri *et al*., 2021). Northeast Thailand was historically a focal region for the promotion of rice-fish culture, and the practice is still maintained today (Little *et al*., 1996; Arunrat and Sereenonchai, 2022). These geographical and socio-ecological conditions make Northeast Thailand a representative and promising location for examining intensified rice-fish culture systems.

In this study, we investigated the feasibility of an intensified rice-fish culture system targeting climbing perch under a tropical savanna climate on the Indochinese Peninsula. We hypothesized that this air-breathing species can be grown to market size in rain-fed rice paddies under semi-intensive conditions with feeding. Specifically, we evaluated the effect of fish stocking density on individual fish growth, fish yield, and rice production.

MATERIALS AND METHODS

Rice field and rice

On-site experiments were conducted under predominantly rain-fed conditions at two sites in Ubon Ratchathani Province, Northeast Thailand, between July and December 2024 (Figure 1; Table 1). In Experiment 1, an existing rice paddy at the Nong Bua Hi Farming and Aquaculture Training Center (Phibun Mangsahan District, Ubon Ratchathani Province) was divided into six plots, each measuring 5×10 m (50 m^2), by constructing 50 cm-high dikes (Figure 2). In Experiment 2, two existing earthen ponds at the Ubon Ratchathani University fish farm were subdivided into four plots of the same dimensions (5×10 m, 50 m^2; Figure 2), of which six plots were used in the experiment. The earthen ponds used in Experiment 2 lacked topsoil for rice cultivation; therefore, topsoil was transported from nearby rice paddies to fill the pond bottoms to a depth of 30 cm and to construct dikes separating the plots. The structure and dimensions of the individual rice paddy plots were identical in Experiment 1 and Experiment 2.

Table 1. Experiment schedule and duration.

Activity/fingerling size metric	Exp. 1 (smaller stocking size)	Exp. 2 (larger stocking size)
Rice transplanting	early July	mid September
Fish stocking	early August	late September
Rice harvest	early November	NA
Fish harvest	mid November	early December
Rice cropping period	123 days (4 months)	NA
Fish culture period	101 days (3.5 months)	76 days (2.5 months)
TL at stocking (mm)	38	68
WW at stocking (g)	1.1	5.8

Note: NA = Rice data not available due to flooding; TL = Mean total length; WW = Mean wet weight.

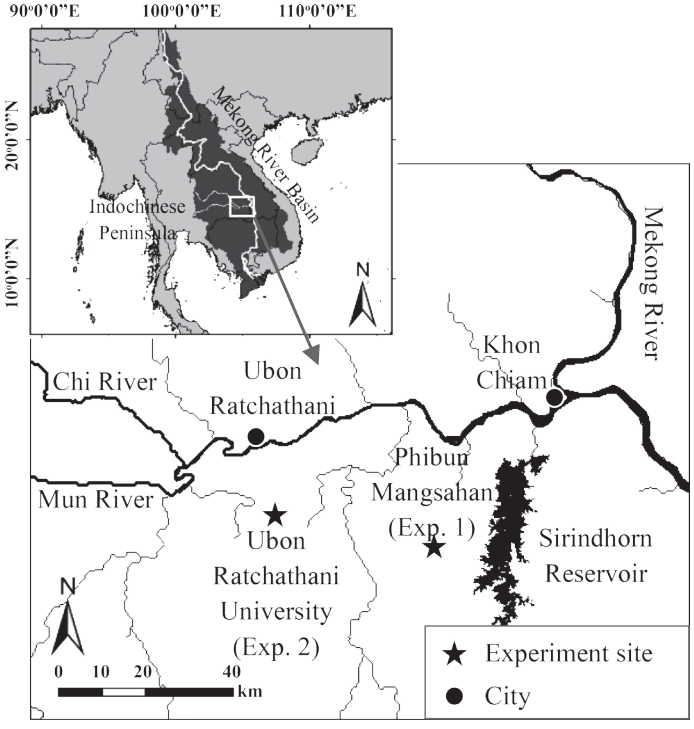


Figure 1. Map showing the experimental sites in Ubon Ratchathani Province, Northeast Thailand. The dark shaded area in the upper-left map indicates the Mekong River Basin.

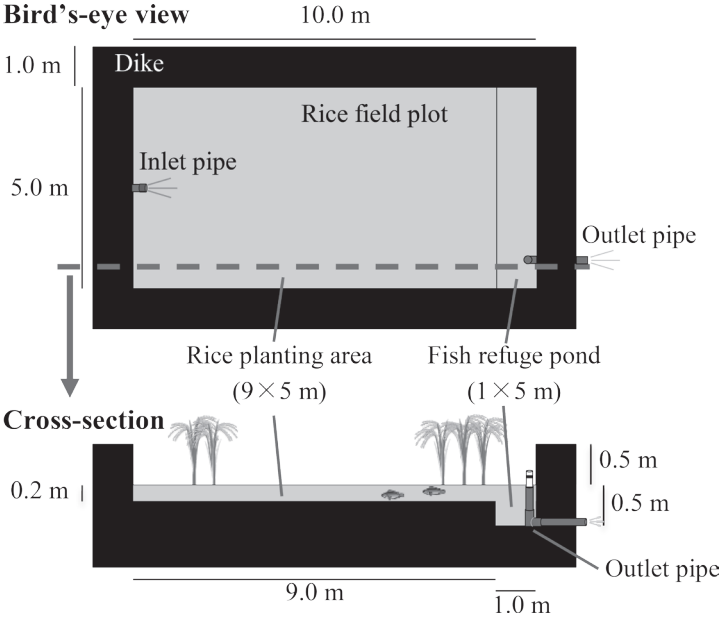


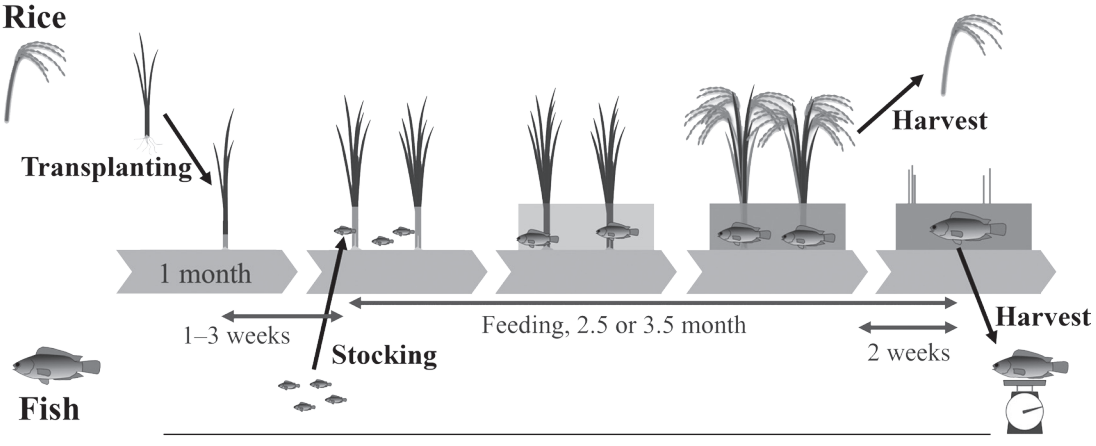
Figure 2. Bird's-eye view (top) and cross-section (bottom) diagrams of an experimental rice paddy plot. The structure and dimensions of the individual plots were identical in Experiment 1 and Experiment 2. Each plot consisted of a rice-planted area and a fish refuge pond. Note that the cross-section diagram is vertically exaggerated by 200% to improve legibility.

A fish refuge pond (1×5 m) was excavated at the lower end of each plot following customary rice-fish practice in the region (Figure 2). Maximum water depth was maintained at approximately 20 cm in the rice-planted area and 50 cm in the fish refuge pond, by allowing excess water to overflow through an outlet pipe (Figure 2). After the rainy season and following rice harvest, water was supplemented from a nearby earthen pond at both sites to maintain a water depth of at least 10 cm in the rice-planted area. Fence nets (1.5 mm square mesh, 0.9 m high) were installed around each plot to prevent fish movement among plots and to reduce potential predation by wild animals.

Soil was plowed twice before rice transplanting. Urea was applied as basal fertilizer at a rate of 10 $g \cdot m^{-2}$ (4.6 g $N \cdot m^{-2}$). Rice seedlings (approximately 30 days after germination, cultivar *Khor kor* 15 (RD15), a long-grained non-glutinous rice variety designated as *Hom Mali* fragrant rice) were transplanted to each plot at 20×20 cm intervals (rice-planted area: 45 m^2 per plot; Figure 2) as a rainy-season crop in early July in Experiment 1 and in mid-September in Experiment 2 (Table 1).

Fish

Fingerlings from the same hatchery batch, weighing around 1 g per fish (ca. 30 days post-hatching), were transported from a private hatchery in Ubon Ratchathani Province to the experiment sites in early August. The Chumphon strain was selected because of its favorable growth performance (Piwpong *et al*., 2016) and wide availability in Northeast Thailand. Six fish stocking densities (0, 10, 20, 40, 60, and 80 fish$\cdot m^{-2}$; values based on the total area of each rice paddy plot) were established to evaluate their effects on fish growth, fish yield, and rice yield. In Experiment 1, fingerlings were stocked directly into each plot in early August (Figure 3; Table 1). In Experiment 2, fingerlings were reared to about 6 g per individual in outdoor plastic tanks placed under roofing, by feeding them commercial juvenile feed ad libitum (Table S1) until fish stocking in late September (Figure 3; Table 1). Only a single replicate of each stocking density was prepared in each experiment/site, due to the difficulty in securing and maintaining individually controllable experimental rice paddy plots of identical dimensions and water conditions.



Exp.	Rice transplanting	Fish stocking	Rice harvest	Fish harvest
Exp. 1	Early-Jul	Early-Aug	Early-Nov	Mid-Nov
Exp. 2	Mid-Sep	Late-Sep	NA*	Early-Dec

Figure 3. Schematic diagram illustrating the flow of rice cropping and fish culture in the experimental rice-fish system. Rice was not harvested in Experiment 2, because of flooding.

Fish were fed twice daily between 09:00–10:00 a.m. and 04:00–05:00 p.m.. Feed amounts were adjusted after each biweekly fish sampling. Feeding rates were set at 10, 9, 8, 6, 4, 4, and 4% of fish wet weight (WW) in Experiment 1 and at 6, 6, 4, 4, and 4% in Experiment 2 across the first to seventh or fifth successive biweekly periods, following customary feeding practice in the region. In Experiment 1, commercial juvenile pellets were used exclusively during the first four weeks (Table S1). During the fifth week, juvenile and catfish feeds were provided in equal proportions, and from the sixth week onward, only catfish feed was used (Table S1). In Experiment 2, catfish feed was used exclusively after fish stocking into rice paddy plots (Table S1). Fish were cultured for 101 days (3.5 months) until harvest in mid-November in Experiment 1 and for 76 days (2.5 months) until early December in Experiment 2 (Figure 3; Table 1).

Twenty fish were sampled from each plot at two-week intervals. TL and WW were recorded individually after gently removing surface water with a microfiber cloth, after which fish were returned to their original plots. Fish survival and total yield were recorded at final harvest.

Environment

Water quality was measured monthly and at fish harvest. Temperature, pH, dissolved oxygen, and turbidity were measured at the mid-water column at three equidistant positions within each rice paddy plot (up-slope, center, and fish refuge pond) using a multiparameter water quality meter (WQC-30, Toa DKK, Tokyo, Japan) and an optical dissolved oxygen meter (DO850, Apera Instruments, Columbus, USA). Surface water samples (50 mL) were collected from fish refuge ponds and stored frozen until analysis. Ammonium-N and nitrite-N concentrations were determined by the indophenol blue and N-(1-naphthyl)ethylenediamine methods, using a spectrophotometer (UV-1280, Shimadzu, Kyoto, Japan).

Data analyses

Specific growth rate (SGR, G; % WW increase per unit time; Houde and Schekter, 1981) between fish stocking and harvest was calculated following the recommendations of Crane *et al*. (2020):

$$G = 100(e^{g} - 1)$$

where the instantaneous growth rate, g, was calculated as follows:

$$g = \frac{\ln(w_2) - \ln(w_1)}{\Delta_t}$$

Here, w_2 and w_1, are mean fish weights (g) at harvest and stocking, respectively, and Δ_t denotes culture duration (days).

Feed conversion ratio (FCR) over the entire culture period was calculated as:

$$FCR = \frac{F}{w_2 - w_1}$$

where F is the total feed input (g).

Fish size at harvest was compared among stocking densities using the Steel-Dwass test. Total rice yield and individual rice yield parameters were also compared among treatments using the Steel-Dwass test. The relationship between stocking density and total fish yield was analyzed using generalized additive models (GAMs; Wood, 2006), which relax the linearity assumption in generalized linear models (GLMs) by incorporating smooth terms. The effective degrees of freedom (EDF) indicate the degree of non-linearity of the fitted curve, with the minimum value of one corresponding to a linear relationship. In the present analysis, EDF values greater than one indicate non-proportional changes in total fish yield relative to stocking density. The response variable was assumed to follow a normal distribution with an identity link function, as the total fish yield from each 50 m^2 plot would not take values near zero and likely provide a reliable estimate of actual fish production in each plot. Separate models were fitted for Experiment 1 and Experiment 2. The maximum basis dimension (k) was restricted to five, to reflect the limited sample size.

All statistical analyses were performed using R ver. 4.4.1 (R Core Team, 2024). The packages PMCMRplus and rcompanion were used for the Steel-Dwass test, and mgcv was used for GAM analyses. Statistical significance was assessed at a two-sided α level of 0.05.

The relationship between production costs and revenue from fish and rice was calculated and compared based on our data and published information. Fish price (120 THB·kg^{-1}; 1 USD= 34.8–35.1 THB during 2022–2023) was based on interview surveys conducted at four fresh markets in Ubon Ratchathani Province in 2022 and 2023. Market size of climbing perch was defined as 100 mm TL and 20 g WW, as this size represented the threshold for a marked increase in market price (60–70 vs. 100–130 THB·kg^{-1}); similar size-dependent differences have been reported by the Mekong River Commission (2015). Rice revenue was calculated based on public statistics (OAE, 2025a), using the price for *Hom Mali* rice at 15% moisture content (14,927 THB·t^{-1}). Total rice yield in the experiment was adjusted to a 15% moisture-equivalent basis in this economic analysis. Rice production costs were obtained from surveys by Arunrat *et al*. (2021) conducted in Thailand between 2017 and 2018, using values for "individual farming" in Northeast Thailand (29,625 THB·ha^{-1}·year^{-1}). These costs were adjusted for inflation from 2018 to 2024 based on the annual consumer price index for Thailand (IMF, 2026), resulting in an estimated cost of 32,229 THB·ha^{-1}·year^{-1}.

RESULTS

Summaries of water quality parameters are shown in Table 2, whereas their time-series trends are shown in Figure 4 and Figure S1. Water temperature ranged from 26.5 to 34.5 °C during

Table 2. Minimum, maximum, and mean values of water quality parameters in each treatment in the rice-fish culture experiments.

Exp.	Stocking density (n·m^{-2})	Temperature (°C)	pH	Dissolved oxygen (mg·L^{-1})	Turbidity (NTU)	NH_4^+-N (mg·L^{-1})	NO_2^--N (mg·L^{-1})
Exp. 1	0	26.5–34.4	6.6–7.8	2.2–8.8	8–24.9	0.0–1.2	0–0.00
		(29.4)	(7.3)	(5.4)	(15.9)	(0.7)	(0.00)
	10	27.4–34.1	6.8–7.7	3.7–15.7	2.5–80.7	0.3–6.4	0–0.08
		(29.6)	(7.3)	(9.8)	(44.1)	(2.4)	(0.03)
	20	27.1–34	6.8–7.6	1.0–8.1	7.5–43.1	0.2–24.5	0–0.05
		(29.5)	(7.2)	(4.6)	(25.0)	(8.6)	(0.01)
	40	26.3–33.3	6.7–7.8	0.2–14.6	1.9–35.4	0.0–33.3	0–0.05
		(29.1)	(7.2)	(7.4)	(15.1)	(12.3)	(0.01)
	60	27.1–34.3	6.9–7.5	0.7–9.1	7.0–224.0	0.1–57.6	0–0.08
		(29.7)	(7.2)	(4.8)	(67.0)	(25.2)	(0.02)
	80	27.5–34.5	6.8–7.5	0.2–8.8	13.4–243.0	0.5–62.7	0–0.04
		(30.0)	(7.2)	(5.7)	(75.8)	(29.8)	(0.01)
Exp. 2	0	26.5–31.8	7.2–7.9	6.2–8.6	0.3–107.3	0.1–2.8	0–0.00
		(28.5)	(7.5)	(7.6)	(40.6)	(1.2)	(0.00)
	10	27.1–30.9	7.0–7.8	4.4–16.3	9.9–278.7	0.0–1.1	0–0.02
		(28.9)	(7.4)	(9.9)	(131.4)	(0.6)	(0.01)
	20	28.2–31.1	6.8–7.9	4.7–16.5	0.7–162.3	0.0–1.8	0–0.00
		(29.1)	(7.4)	(11.0)	(87.4)	(0.7)	(0.00)
	40	27.6–32.1	7.5–8.4	4.7–14.2	1.3–239.7	1.3–13.9	0–0.05
		(29.3)	(7.8)	(10.0)	(108.6)	(5.1)	(0.01)
	60	28.3–31.4	7.1–7.8	0.4–19.4	0.9–461.0	2.5–23.2	0.02–0.06
		(29.6)	(7.4)	(9.0)	(210.8)	(11.6)	(0.04)
	80	28.0–32.2	7.1–8.0	4.5–13.4	0.1–354.7	2.7–9.6	0–0.02
		(29.6)	(7.6)	(8.7)	(164.8)	(6.2)	(0.01)

Note: Figures in parentheses indicate mean values.

the experiment. pH was neutral to weakly basic, ranging from 6.6 to 8.4. Hypoxia was rarely recorded in the mid-water column. The range of dissolved oxygen concentration tended to be wider in the fish stocked treatments compared to the no-fish control, especially in Experiment 2. Turbidity and ammonium-N concentrations tended to be higher in the higher-density fish treatments, especially during the later part of the experiment. Ammonium-N concentrations exceeded 40 mg·L^{-1} in the 40–80 fish·m^{-2} treatments at harvest in Experiment 1, whereas this was not observed in Experiment 2 with the shorter culture period in rice paddy plots (Figure 4). Nitrite-N concentrations were higher in the fish stocked treatments at harvest in Experiment 1, when rice panicles had been harvested.

In Experiment 1, in which fish were stocked at a smaller initial size, fish survival ranged from 44.6 to 82.5%, with the lowest survival observed at a stocking density of 10 fish·m^{-2} (Table 3). Fish grew to sizes exceeding the market size of 100 mm TL and 20 g WW at all stocking densities (Figure 5 and 6). Fish size at harvest was significantly larger at 10 fish·m^{-2} than at 40–80 fish·m^{-2} (Table 3; Steel-Dwass test, $p<0.05$), a trend also confirmed by weight gain per surviving fish individual (Table 3). Total fish yield increased nearly proportionally to stocking density up to 60 fish·m^{-2} (Figure 7). However, total fish yield was similar between 60 and 80 fish·m^{-2}, as indicated by the fitted GAM and its effective degree of freedom exceeding one. This pattern was consistent with the lower weight gain per surviving individual observed at 80 fish·m^{-2} (Table 3). FCR was the lowest at 40 fish·m^{-2}, whereas the highest FCR was recorded at 10 fish·m^{-2}, corresponding to the plot with the lowest survival.

In Experiment 2, in which fish were stocked at a larger initial size, survival exceeded 90% across all five stocking density treatments (Table 3). As in Experiment 1, fish reached sizes exceeding the market size at all stocking densities (Figures 5 and 6). In contrast to Experiment 1, fish size at harvest was smaller at 10 fish·m^{-2} than at 40–80 fish·m^{-2} treatments (Table 3; Steel-Dwass test, $p<0.05$), whereas weight gain per surviving individual was highest at 10 fish·m^{-2} (Table 3). Total fish yield increased proportionally with stocking density, as indicated by the linear GAM fit (Figure 7). Consequently, total weight gain and fish yield were greatest at 80 fish·m^{-2} (Table 3). FCR values were lower at 10 and 20 fish·m^{-2} than at higher stocking densities.

Lodging of rice plants occurred at both experimental sites after a storm event in early October, with higher proportions observed in fish-

Table 3. Summary of fish growth and yield parameters in Experiment 1 and Experiment 2.

Exp	Fish stocking density (m^{-2})	TL at stocking† (mm)	TL at harvest† (mm)	WW at stocking† (g)	WW at harvest† (g)	Survival (%)	Total fish yield‡ (g·m^{-2})	Weight gain‡ (g·m^{-2})	Weight gain per surviving individual‡ (g)	SGR‡ (G, %·day^{-1})	FCR‡
Exp. 1	10	39±4	150±13^{a}	1.2±0.4	87.9±24.6^{a}	44.6	331	319	73.0	4.19	4.23
	20	38±2	140±14^{ab}	1.0±0.2	64.9±20.3^{b}	64.4	697	677	53.1	4.06	2.60
	40	38±2	129±11^{b}	1.1±0.3	47.5±13.6^{c}	76.1	1,214	1,172	38.8	3.66	2.43
	60	39±4	132±9^{b}	1.1±0.4	51.0±11.4^{bc}	82.5	1,987	1,919	39.0	3.59	2.56
	80	39±2	129±10^{b}	1.1±0.2	47.6±11.1^{bc}	79.4	2,025	1,941	30.8	3.43	2.65
Exp. 2	10	66±6	115±9^{b}	5.2±1.1	29.8±7.4^{c}	92.0	306	254	28.1	2.54	1.82
	20	70±4	122±11^{ab}	6.2±1.2	36.3±11.3^{bc}	96.4	623	499	26.1	2.31	1.86
	40	66±5	130±12^{a}	5.3±1.0	45.6±13.1^{ab}	96.0	1,191	979	25.7	2.46	2.07
	60	71±4	130±10^{a}	6.4±1.1	45.5±11.2^{ab}	96.6	1,815	1,431	24.9	2.21	2.24
	80	69±6	132±11^{a}	5.8±1.5	47.8±12.1^{a}	94.5	2,354	1,890	25.3	2.31	2.01

Note: †Mean±SD of 20 individual measurements in each plot; ‡Calculated based on total fish yield; Mean±SD in each column with different superscript letters are significantly different (Steel-Dwass test; $p<0.05$) within each experiment.

stocked plots. In Experiment 1, rice plants were bundled the following day to prevent sprouting of the submerged spikelets. In Experiment 2, bundling was not possible because flooding persisted for several days; therefore, representative rice yield samples could not be collected in this experiment.

In Experiment 1, total rice yield was significantly higher in the no-fish control and the 10 fish·m^{-2} treatment than in the higher stocking density treatments (20–80 fish·m^{-2}; Figure 8a; Steel-Dwass test, $p<0.05$). Similarly, rice yield per hill was significantly higher at 10 fish·m^{-2} than in the remaining treatments (Figure 8b; $p<0.05$). Single-grain weight was greater in the no-fish control and 10 fish·m^{-2} than at the highest fish density (80 fish·m^{-2}; Figure 8c; $p<0.05$). The number of effective panicles per hill was significantly higher at 10 fish·m^{-2} than in the other treatments (Figure 8d; $p<0.05$). The number of spikelets per hill at 10 fish·m^{-2} was higher than at 0 and 80 fish·m^{-2} (Figure 8e; $p<0.05$). The proportions of filled spikelets were significantly higher in the 0 and 10 fish·m^{-2} treatments, showing a pattern similar

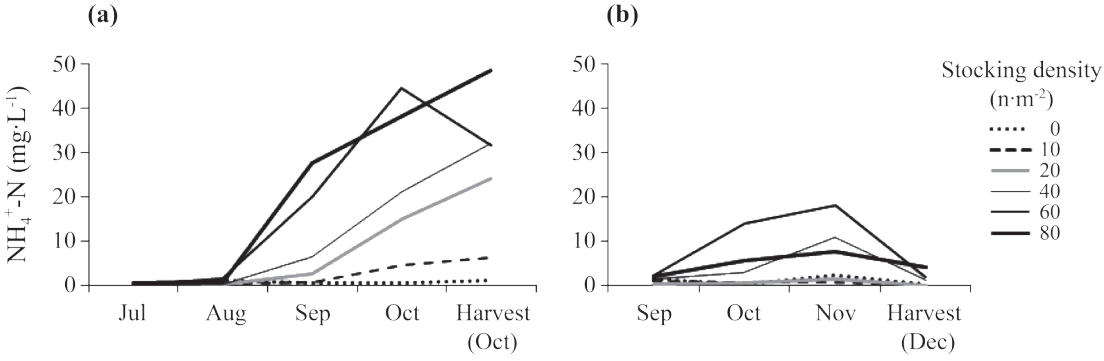


Figure 4. Time-series trends in ammonium-N concentration in each stocking density: (a) Experiment 1; and (b) Experiment 2.

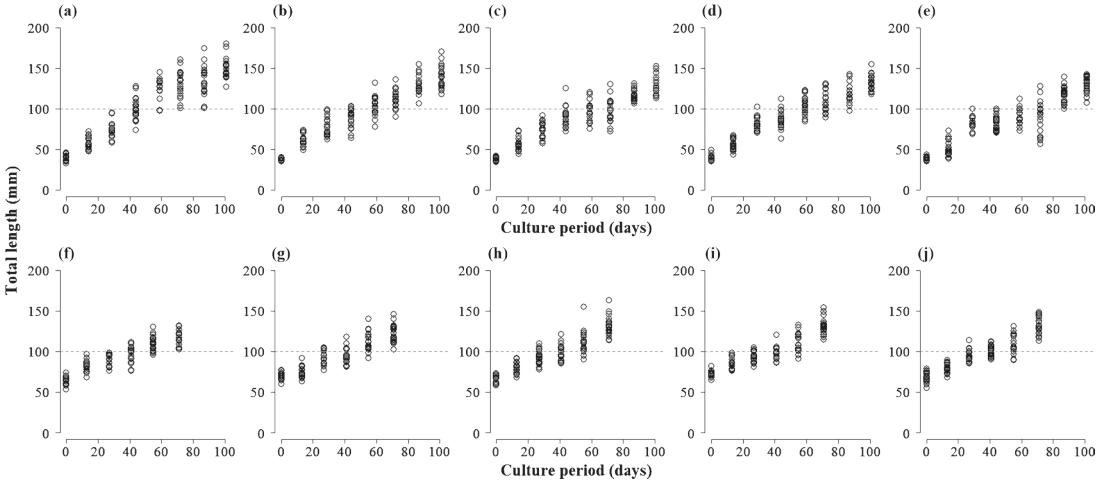


Figure 5. Growth patterns of climbing perch (*Anabas testudineus*) in total length under different stocking densities: (a)–(e) Experiment 1 (top; smaller stocking size); and (f)–(j) Experiment 2 (bottom; larger stocking size). Panels from left to right represent stocking densities of 10, 20, 40, 60, and 80 fish·m^{-2}, respectively. The dashed horizontal line in each graph indicates the commercial size of the species (100 mm total length).

to that of total rice yield (Figure 8f; $p<0.05$). Overall, although fish stocked treatments tended to show higher numbers of spikelets per hill (Figure 8e), the proportions of filled spikelets in the no-fish control and at 10 fish·m^{-2} were approximately twice those observed at higher stocking densities (Figure 8f), resulting in higher rice yield in these plots (Figure 8a).

Cost-to-sales ratios were approximately one at stocking densities of 20–60 fish·m^{-2} when survival ranged from approximately 65 to

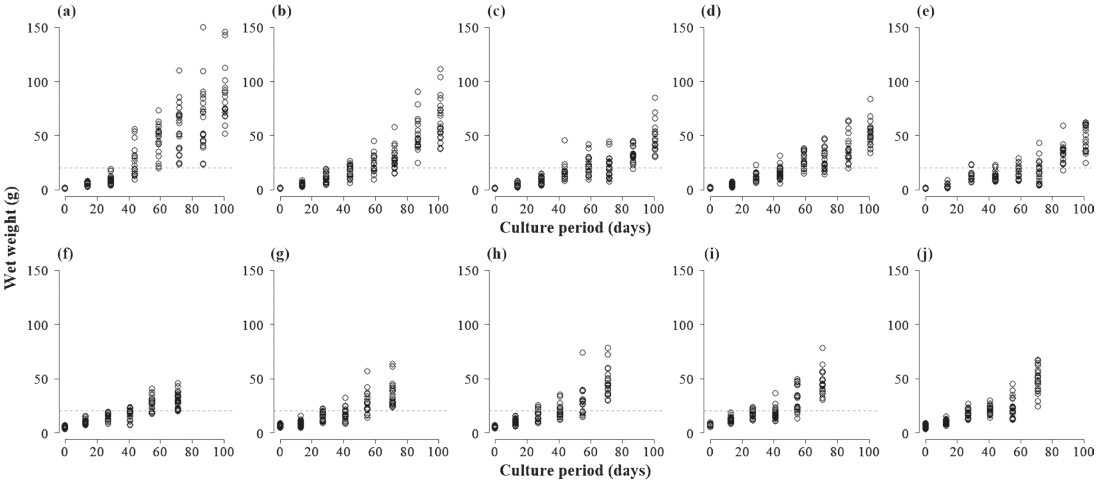


Figure 6. Growth patterns of climbing perch (*Anabas testudineus*) in wet weight under different stocking densities: (a)–(e) Experiment 1 (top); and (f)–(j) Experiment 2 (bottom). Panels from left to right represent stocking densities of 10, 20, 40, 60, and 80 fish·m^{-2}, respectively. The dashed horizontal line in each graph indicates the commercial size of the species (20 g wet weight).

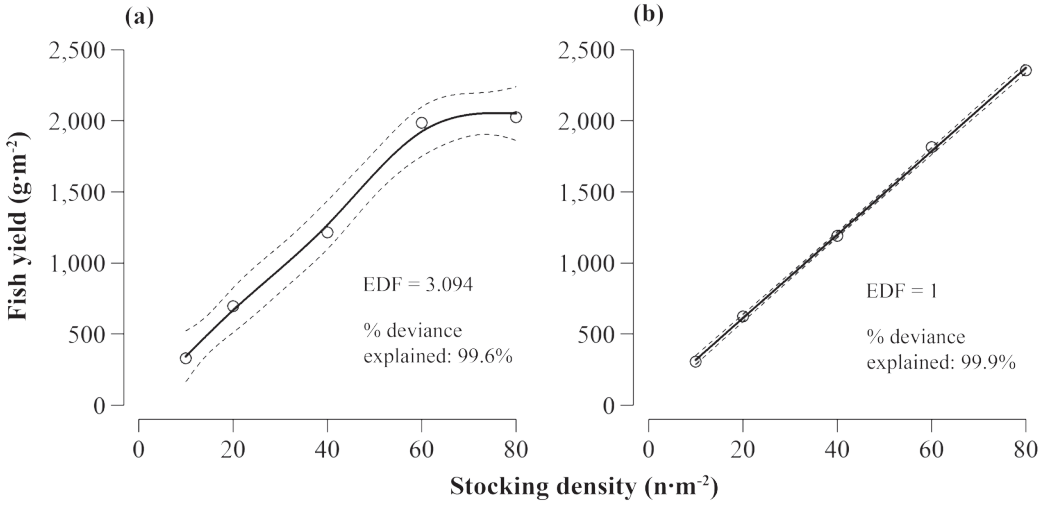


Figure 7. Relationship between stocking density and fish yield in: (a) Experiment 1; and (b) Experiment 2. Open points represent observed values. Relationships were estimated using generalized additive models (GAM) assuming a Gaussian error distribution with an identity link function. Solid and dashed curves in each graph indicate the fitted mean trend and its 95% confidence limits, respectively. Effective degrees of freedom (EDF) represent the degree of non-linearity in each fitted model, with the minimum value of one indicating a linear relationship.

80% (Experiment 1; Figure 9). The ratio was slightly above one when survival exceeded 90% (Experiment 2). Fish income was substantially higher than rice income across all fish-stocked treatments in Experiment 1, the experiment for which rice yield data were available. Fingerlings accounted for approximately 40% of total production costs.

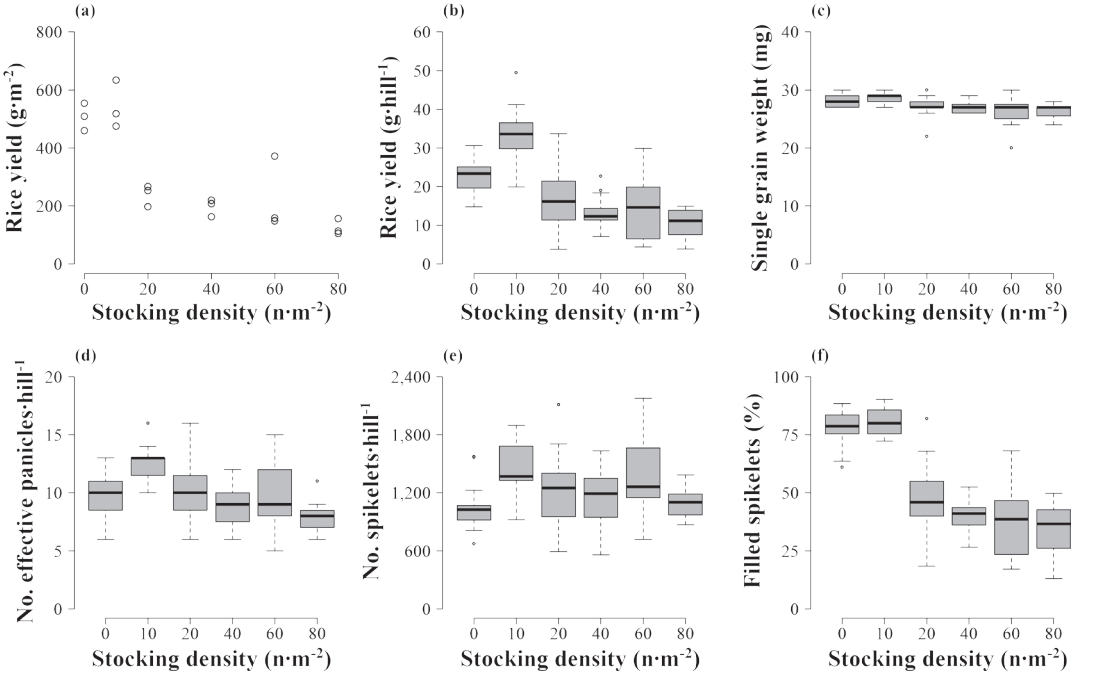


Figure 8. Effects of fish stocking density on rice yield parameters in Experiment 1: (a) rice yield; (b) rice yield per hill; (c) single-grain weight; (d) number of effective panicles per hill; (e) number of spikelets per hill; and (f) percentage of filled spikelets. Rice yield was estimated from all rice hills within each 1×1 m quadrat. Data in panels (b)–(f) were obtained from five hills randomly selected from each quadrat. Grain weight was adjusted to a 14% moisture content. Different letters at the bottom of each panel indicate significant differences among stocking densities based on the Steel-Dwass test ($p<0.05$).

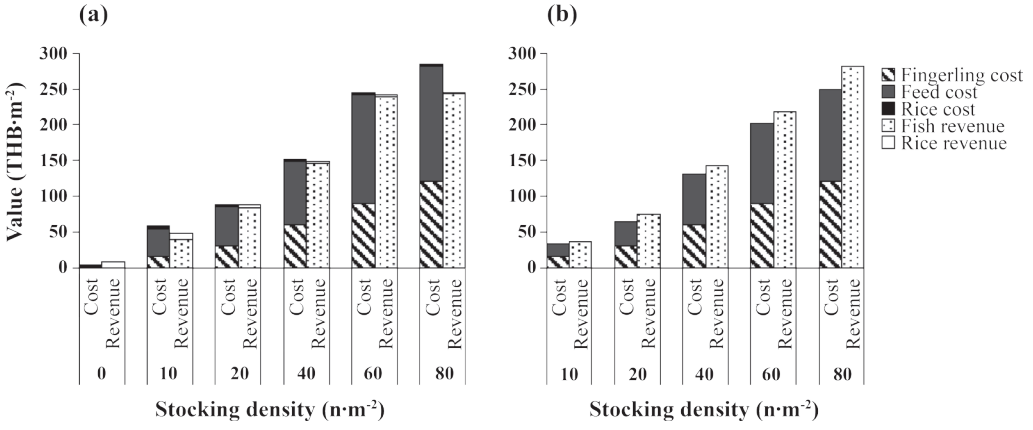


Figure 9. Comparisons of production costs and revenues of fish and rice in the rice-fish culture system: (a) Experiment 1 with smaller stocking size; (b) Experiment 2 with larger stocking size. Rice was not harvested in Experiment 2 because of flooding.

DISCUSSION

The present study demonstrated that climbing perch can be cultured under semi-intensive conditions in a rice-fish culture system without the installation of aeration equipment. Fish yields per unit area obtained in this study (Figure 7) exceed those reported previously for extensive rice-fish culture targeting climbing perch (Saharia *et al*., 2018) as well as for semi-intensive earthen pond culture (Chakraborty, 2016; Ahamed *et al*., 2018; Mumu and Hossain, 2021). These results highlight the high potential of rain-fed rice paddies as a culture environment for climbing perch. Based on the results of Experiment 1, fish stocking density did not negatively affect total fish yield, at least up to 60 fish·m^{-2} during the 3.5-month (approximately 100-day) rice-fish culture period. This threshold is consistent with the findings of Debnath *et al*., (2022), who reported comparable growth rates up to 60 fish·m^{-2} in floating cage culture, followed by growth rate declines at higher densities during a six-month culture period.

In Experiment 2, fish yield increased proportionally with stocking density up to 80 fish·m^{-2}, unlike in Experiment 1 (Figure 7), suggesting that the growth decline observed in Experiment 1 was unlikely to result from density-dependent growth inhibition. Although the temporal resolution of ammonium measurements was limited, the high concentration observed at harvest, which reached nearly 50 mg NH_4^+-N·L^{-1} (Figure 4), suggests that ammonia accumulation may have contributed to the reduced growth in Experiment 1. This value exceeded the < 0.1 mg·L^{-1} typically reported for extensive rice-fish systems (Mohanty *et al*., 2009; Kaewpuangdee *et al*., 2024) but was comparable to levels reported for pond culture of some air-breathing fishes (Lefevre *et al*., 2014; Swangdacharuk and Musig, 2016). Toward the end of the rice-fish culture cycle, ammonia may accumulate more readily because rice plants are absent and water exchange rates decrease with declining precipitation (Cowan *et al*., 1999; Rodmongkoldee *et al*., 2024), in addition to increased excretion associated with fish growth (Lefevre *et al*., 2014; Swangdacharuk and Musig, 2016). Elevated ammonia can impair mitochondrial function and ion transport across membranes, reducing blood oxygen transport capacity and increasing susceptibility to diseases (Boyd and Tucker, 2019; Bayley *et al*., 2020). Air-breathing fishes are generally more tolerant of ammonia than water-breathing species (Bayley *et al*., 2020). Climbing perch can withstand 100 mmol·L^{-1} of NH_4Cl in freshwater at pH 7.0 for six days (Loong *et al*., 2012), equivalent to 1,387 mg NH_4^+-N·L^{-1} and 13 mg NH_3-N·L^{-1}. These findings are consistent with our observation that fish survival was not affected by either increasing stocking density or ammonium concentration. In contrast, the effects of ammonia on fish growth, which typically occurs at concentrations far below acute toxicity, remain poorly understood in air-breathing fishes (Lefevre *et al*., 2014). Koydon *et al*. (2025) reported improved growth of striped snakehead in earthen ponds with more frequent water exchange, suggesting that elevated ammonia may suppress growth by increasing the energetic cost of ammonia excretion. Moreover, the proportion of the more permeable unionized form (NH_3) relative to NH_4^+ fluctuates daily and hourly depending on pH, particularly under outdoor culture conditions (Lefevre *et al*., 2014; Boyd and Tucker, 2019), making inferences from sparse observations uncertain. Further studies should therefore examine the relationship between ammonia concentration and fish growth at higher temporal resolution to better define the physiological limits for optimal growth of climbing perch.

The proportional increase in fish yield with increasing stocking density (Figure 7) was achieved through similar survival rates among most density treatments (Table 3). Exceptions were observed in the 10 and 20 fish·m^{-2} plots in Experiment 1, where lower survival was compensated for by faster individual growth of the surviving fish (Figure 5 and 6; Table 3). This faster growth was likely attributable to higher feed availability per individual, as feed amounts were not adjusted in response to fish mortality. Although fingerlings in both experiments originated from the same hatchery batch, the stocking size in the rice fields was larger in Experiment 2, and survival was consistently high across all density treatments. Fingerling mortality was also observed during the early nursery phase in plastic tanks in Experiment 2

(Saito, personal communication), albeit at lower proportions than observed in Experiment 1. These observations support the notion that early-stage of culturerepresent a critical period for mortality control. Higher mortality during the early culture period may have resulted from transport and handling stress associated with the sudden transfer of fish from concrete tanks to rice paddies and size measurements, together with predation by aquatic insects. These stressors were largely mitigated in Experiment 2 by introducing a tank nursery phase prior to release. Nursery rearing of smaller fingerlings in floating cages or tanks prior to fish stocking may therefore be advisable to ensure higher survival when stocking smaller-sized fingerlings.

Rice yield in the no-fish control and the 10 fish·m^{-2} treatment was higher than in the 20–80 fish·m^{-2} treatments (Figure 8). Under extensive rice-fish culture without feeding, fish presence generally enhances rice yield (Tsuruta *et al*., 2011; Kaewpuangdee *et al*., 2024). In contrast, under semi-intensive conditions, Hu *et al*. (2022) reported reduced rice yield at 30 fish·m^{-2} compared with 15 fish·m^{-2} in deep-water rice-fish culture of yellow catfish (*Peleteobagrus fulvidraco*). Excess nitrogen input typically promotes vegetative growth and increases the number of spikelets, while reducing the proportion of filled spikelets owing to insufficient photoassimilate supply during grain filling (Tanaka, 1972; Zhao *et al*., 2022). A similar trend was also observed in the present study (Figure 8). Excess nitrogen can further increase lodging risk and reduce rice yield (Ohnishi *et al*., 1999). Accordingly, Li *et al*. (2023) emphasized the importance of selecting rice varieties with high lodging resistance for successful rice-fish co-culture. Under the fertilizer application regime and fish culture conditions used in the present study, a stocking density of 10 fish·m^{-2} appears to represent the upper limit at which climbing perch stocking exerts a positive effect on rice yield.

Rain-fed rice paddies in Northeast Thailand are typically managed with low fertilizer inputs, despite inherently low soil fertility (Homma and Horie, 2009). This practice likely reflects farmers' adaptation to unstable water availability, minimizing potential losses when drought occurs in the middle of the rice cultivation season. Mochizuki *et al*. (2006) reported improved nitrogen recovery efficiency and rice yield when sediment from farmer-managed earthen ponds was incorporated into rice fields in combination with chemical fertilizer application (25–25–12.5·ha^{-1} N–P_2O_5–K_2O). An increase in cation exchange capacity, enhancing soil nutrient retention, was suggested as a key mechanism underlying rice yield improvement. Because additional nitrogen and phosphate are supplied through fish culture (Hu *et al*., 2022; Kaewpuangdee *et al*., 2024), sediment accumulated in the fish refuge ponds, together with potassium fertilizer, could be applied to rice fields to achieve similar benefits. Silicon application may further enhance rice yield by maintaining erect leaf posture, thereby suppressing lodging and increasing photoassimilate production during grain filling phase (Takahashi, 1968; Liao *et al*., 2023). Fertilizer management strategies tailored to semi-intensive rice-fish culture should therefore be explored to enhance rice yield under higher fish stocking densities.

The cost-benefit ratio of the semi-intensive rice-fish culture system was approximately 1 at stocking densities of 20–60 fish·m^{-2}, when survival rate ranged from 65 to 80% (Experiment 1), and slightly above 1 when survival rate exceeded 90% (Experiment 2; Figure 9; Table 3). Because costs associated with field preparation, labor, and consumables were not included, further optimization is required to improve profitability. Fish accounted for the majority of both production costs and revenue, indicating that fish culture largely determines the economic performance of semi-intensive rice-fish culture systems. Reducing production costs, particularly fingerling costs, may therefore enhance profitability. Potential approaches include collective procurement to reduce logistics costs and enhance bargaining power, or the establishment of community hatcheries (Barman and Little, 2006), although such approaches require capacity building.

In semi-intensive aquaculture systems, survival, growth, and feed efficiency are the primary determinants of yield and economic outcomes. In the present study, fingerling costs were nearly comparable to the total feed costs, which were substantially higher than the 10–30% reported for

pond culture of climbing perch in Bangladesh (Sarker *et al*., 2014; Chakraborty, 2016; Shofiquzzoha *et al*., 2018). Moreover, fish harvested in this study (Table 3) were smaller than the common harvesting size of the strain (approximately 100 g per fish; ca. 16 cm TL), which can be attained after 4–5 months after stocking under pond culture conditions (Rahman *et al*., 2013; Chakraborty and Haque, 2014; Kohinoor *et al*., 2016; Piwpong *et al*., 2016; Mumu and Hossain, 2021). Dissection of fish after harvesting in Experiment 1 revealed that most individuals had not yet developed gonads (C. Grudpan and Saito, personal communication), indicating potential for further growth. As a conservative estimate, based on the observed FCR of 2.6 in the 20 fish·m^{-2} treatment that recorded 64% survival (Table 3), the feed cost required for 1 kg of weight gain was approximately 70 THB, which is lower than the local market price of the fish (100–130 THB·kg^{-1}). Extending the culture period to achieve larger harvest sizes would therefore likely improve the cost-benefit ratio.

Two main approaches could be employed to increase fish yield after accounting for survival: extension of the culture period and enhancement of growth rate. The culture period could be extended by retaining water in fish refuge ponds after rice harvest, similar to practices in rice field capture fisheries. In the Lower Mekong Basin, naturally recruited fish are often concentrated in refuge ponds and harvested before water bodies dry out, generally in November and December, but fish harvesting could be extended until April under favorable conditions (Little *et al*., 1996; Amilhat *et al*., 2009b). A similar approach could be applied to the rice-fish culture of climbing perch, provided that water quality remains within the species' tolerance range. However, lower water temperatures in December and January are likely to reduce metabolic activity and growth. Mid-December may therefore represent a realistic limit for culture extension.

Fish growth rates may also be enhanced by increasing feeding rates or by identifying feeds better suited to the nutritional requirements of climbing perch. Faster growth observed at lower stocking densities in Experiment 1 (10 and 20 fish·m^{-2}) likely resulted from higher feed availability per individual due to early mortality (Figures 5 and 6; Table 3), suggesting that fish may accept higher feeding levels than those applied in the present study. Walking catfish feed containing 27% protein was used because it was the only carnivorous fish feed widely available in the study area; however, this protein level was likely below the optimum for climbing perch, particularly at intermediate sizes (60–100 mm TL). A reduction in growth rate was observed after switching from juvenile feed (43% protein) to catfish feed in the fifth week of culture in Experiment 1 (Figures 5 and 6; Table S1). Hasan *et al*. (2010) reported faster growth and lower FCR values with 35 and 28% protein feeds compared with 24% protein feeds for climbing perch within a comparable size range to the present study. Similarly, higher growth performance and lower FCR have been reported in earthen pond culture studies with similar fingerling strains, stocking sizes, and culture durations, but using feed with higher protein contents (30–35%; Chakraborty and Haque, 2014; Kohinoor *et al*., 2016; Mumu and Hossain, 2021). Commercial catfish feeds with higher protein contents (30–35%) and barramundi (*Lates calcarifer*) feeds (35–42% protein) are readily available in Central Thailand. Future studies should evaluate the effects of these feeds on climbing perch growth, as well as the relationship between feeding rate and FCR, to identify optimal feeding strategies and further enhance the profitability of semi-intensive rice-fish culture systems. After such modifications, the semi-intensive rice-fish culture system tested in the present study is expected to benefit rice-fish farming in the Lower Mekong Basin, including Laos, Cambodia, and southern Vietnam, where tropical savanna climates, rain-fed rice cropping systems, and rice field fisheries practices are similar to those in Northeast Thailand.

CONCLUSIONS

This study demonstrated that climbing perch can be cultured under semi-intensive conditions in rice-fish culture systems. Fish yield increased proportionally with stocking density up to 60 fish·m^{-2}; however, fish size was smaller at 80 fish·m^{-2}, indicating that excessively high stocking densities may be unsuitable. Rice yield declined

substantially at stocking densities of 20 fish·m^{-2} and above, which was associated with a reduction in the proportion of filled spikelets. Fertilizer management strategies tailored to semi-intensive rice-fish culture should therefore be explored to better utilize the additional nitrogen and phosphate supplied by fish culture and to enhance rice yield at higher fish stocking densities. To ensure profitability, fish should be grown to sizes larger than those observed in the present study (approximately 30–40 g per fish). This may be achieved by extending the culture period and/or by enhancing fish growth rates through increased feeding levels or the use of feeds with higher protein contents.

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LITERATURE CITED

Ahamed, S., K. Hasan, M. Mou and M. Mursalin. 2018. Polyculture of Vietnamese koi (*Anabas testudineus*): Emphasis on seasonal mini water ponds in semi-arid zone of Bangladesh. **Annual Research and Review in Biology** 27: 1–7.

Amilhat, E., K. Lorenzen, E.J. Morales, A. Yakupitiyage and D.C. Little. 2009a. Fisheries production in Southeast Asian farmer managed aquatic systems (FMAS). I. Characterisation of systems. **Aquaculture** 296: 219–226. DOI: 10.1016/j.aquaculture.2009.08.014.

Amilhat, E., K. Lorenzen, E.J. Morales, A. Yakupitiyage and D.C. Little. 2009b. Fisheries production in Southeast Asian farmer managed aquatic systems (FMAS). II. Diversity of aquatic resources and management impacts on catch rates. **Aquaculture** 298: 57–63. DOI: 10.1016/j.aquaculture.2009.09.027.

Arunrat, N., N. Pumijumnong, S. Sereenonchai, U. Chareonwong and C. Wang. 2021. Comparison of GHG emissions and farmers' profit of large-scale and individual farming in rice production across four regions of Thailand. **Journal of Cleaner Production** 278: 123945. DOI: 10.1016/j.jclepro.2020.123945.

Arunrat, N. and S. Sereenonchai. 2022. Assessing ecosystem services of rice-fish co-culture and rice monoculture in Thailand. **Agronomy** 12: 1241. DOI: 10.3390/agronomy12051241.

Barman, B.K. and D.C. Little. 2006. Nile tilapia (*Oreochromis niloticus*) seed production in irrigated rice-fields in Northweast Bangladesh—an approach appropriate for poorer farmers? **Aquaculture** 261: 72–79. DOI: 10.1016/j.aquaculture.2006.06.018.

Bashir, M.A., J. Liu, Y. Geng, H. Wang, J. Pan, D. Zhang, A. Rehim, M. Aon and H. Liu. 2020. Co-culture of rice and aquatic animals: An integrated system to achieve production and environmental sustainability. **Journal of Cleaner Production** 249: 119310. DOI: 10.1016/j.jclepro.2019.119310.

Bayley, M., C. Damsgaard, N.V. Chong, T.P. Nguyen and D.T.T. Huong. 2020. **Aquaculture of air-breathing fishes.** In: Fish Physiology (eds. T.J. Benfey, A.P. Farrell and C.J. Brauner), pp. 313–353. Academic Press, Cambridge, UK.

Berg, H., T.H.P. Lan, N.T. Tam, D.H. Trang, P.H.T. Van, H.N. Duc and C.T. Da. 2023. An ecological economic comparison between integrated rice-fish farming and rice monocultures with low and high dikes in the Mekong Delta, Vietnam. **Ambio** 52: 1462–1474. DOI: 10.1007/s13280-023-01864-x.

Boyd, C.E. and C.S. Tucker. 2019. **Water quality.** In: Aquaculture—Farming Aquatic Animals and Plants, 3rd ed. (eds. J.S. Lucas, P.C. Southgate and C.S. Tucker). pp. 63–92. John Wiley and Sons, Chichester, UK.

Chakraborty, B.K. and S.M. Haque. 2014. Growth, yield and returns to koi, *Anabas testudineus* (Bloch, 1792) under semi-intensive aquaculture system using different seed types in Bangladesh. **Journal of Fisheries and Livestock Production** 2: 1–7.

Chakraborty, B.K. 2016. Sustainable aquaculture practice of climbing perch koi, *Anabas testudineus* (Bloch, 1792) under semi-intensive aquaculture system in Bangladesh. **Proceedings of the Zoological Society** 69: 133–140.

Cowan, V.J., K. Lorenzen and S.J. Funge-Smith. 1999. Impact of culture intensity and monsoon season on water quality in Thai commercial shrimp ponds. **Aquaculture Research** 30: 123–133. DOI: 10.1046/j.1365-2109.1999.00308.x.

Crane, D.P., D.H. Ogle and D.E. Shoup. 2020. Use and misuse of a common growth metric: Guidance for appropriately calculating and reporting specific growth rate. **Reviews in Aquaculture** 12: 1542–1547. DOI: 10.1111/raq.12396.

Debnath, C., S.K. Das and P. Mahanta. 2022. Effect of varying stocking densities on the production attributes of climbing perch (*Anabas testudineus*) in a cage culture environment. **Journal of Inland Fisheries Society India** 54: 190–195.

Diao, W., R. Jia, Y. Hou, Y. Dong, B. Li and J. Zhu. 2023. Effects of stocking density on the growth performance, physiological parameters, antioxidant status and lipid metabolism of *Pelteobagrus fulvidraco* in the integrated rice-fish farming system. **Animals** 13: 1721. DOI: 10.3390/ani13111721.

Food and Agriculture Organization of the United Nations (FAO). 2024. **FishStatJ—Software for fishery and aquaculture statistical time series.** https://www.fao.org/fishery/en/statistics/software/fishstatj. Cited 8 Oct 2024.

Freed, S., Y. Kura, V. Sean, S. Mith, P. Cohen, M. Kim, S. Thay and S. Chhy. 2020. Rice field fisheries: Wild aquatic species diversity, food provision services and contribution to inland fisheries. **Fisheries Research** 229: 105615. DOI: 10.1016/j.fishres.2020.105615.

Halwart, M. and M.V. Gupta. 2004. **Culture of Fish in Rice Fields.** WorldFish Center Contributions No. 1718. The WorldFish Center, Penang, Malaysia. 83 pp.

Hasan, M., A.K.S. Ahammad, M. Mukhlesur and R. Khan. 2010. A preliminary investigation into the production of Thai koi (*Anabas testudineus*) reared in nylon hapas in Bangladesh. **Bangladesh Research Publication Journal** 4: 15–23.

Homma, K. and T. Horie. 2009. **The present situation and the future improvement of fertilizer applications by farmers in rainfed rice culture in Northeast Thailand.** In: Fertilizers: Properties, Applications and Effects (eds. L.R. Elsworth and W.O. Paley), pp. 147–180. Nova Science Publishers, New York, USA.

Houde, E.D. and R.C. Schekter. 1981. Growth rates, rations and cohort consumption of marine fish larvae in relation to prey concentrations. **Rapports et Procès-Verbaux des Réunions** 178: 441–453.

Hu, Y., T. Yang, Y. Liu, F. Li, C. Xu, F. Fang and J. Feng. 2022. High fish stocking density weakens the effects of rice-fish co-culture on water eutrophication and greenhouse gas emissions. **Water, Air and Soil Pollution** 233: 222. DOI: 10.1007/s11270-022-05691-w.

Iwata, A., N. Ohnishi and Y. Kiguchi. 2003. Habitat use of fishes and fishing activity in plain area of southern Laos. **Asian and African Area Studies** 3: 51–86. DOI: 10.14956/asafas.3.51. (in Japanese)

International Monetary Fund (IMF). 2026. **World Economic Outlook (WEO).** International Monetary Fund. https://data.imf.org/en/datasets/IMF.RES:WEO. Cited 6 Jan 2026.

Jalilah, M.S., K. Waiho, H. Manan, M. Suhairi, S. Muda, A.S. Kamaruzzan and H.J. Liew. 2025. Insights into the reproductive biology and age at maturity of climbing perch, *Anabas testudineus* (Bloch, 1792) in Malaysia. **Planetary Sustainability** 3: 45–61. DOI: 10.46754/ps.2025.01.005.

Kaewpuangdee, P., S. Saowakoon, K. Kasamawut, A. Kruapukdee, A. Juatagte and T. Jutagate. 2024. Changes in water quality and soil property in the rice-freshwater animal co-culturing system. **Water** 16: 2890. DOI: 10.3390/w16202890.

Kohinoor, A., M. Moshiur Rahman, M. Shahidul Islam and Y. Mahmud. 2016. Growth and production performance of climbing perch Thai koi and Vietnamese koi strain (*Anabas testudineus*) in Bangladesh. **International Journal of Fisheries and Aquatic Studies** 4: 354–357.

Koydon, S., J. Is-haak and C. Ngamphongsai. 2025. Nitrogen balance of intensive snakehead fish culture in earthen ponds under different water exchange frequencies: a case study of Ang Thong Fisheries and Processing Cooperative. **Burapha Science Journal** 30: 511–528. (in Thai)

Lefevre, S., T. Wang, A. Jensen, N.V. Cong, D.T.T. Huong, N.T. Phuong and M. Bayley. 2014. Air-breathing fishes in aquaculture: What can we learn from physiology? **Journal of Fish Biology** 84: 705–731. DOI: 10.1111/jfb.12302.

Li, M., X. Hu, R. Hu, K. Liang, X. Zhong, J. Pan, Y. Fu, Y. Liu, X. Wang, Q. Ye and Y. Yin. 2023. Evaluating rice varieties for suitability in a rice-fish co-culture system based on lodging resistance and grain yield. **Agronomy** 13(9): 2392. DOI: 10.3390/agronomy13092392.

Liao, P., S.M. Bell, L. Chen, S. Huang, H. Wang and J. Miao. 2023. Improving rice grain yield and reducing lodging risk simultaneously: A meta-analysis. **European Journal of Agronomy** 143: 126709. DOI: 10.1016/j.eja.2022.126709.

Little, D.C., P. Surintaraseree and N. Innes-Taylor. 1996. Fish culture in rainfed rice fields of northeast Thailand. **Aquaculture** 140: 295–321. DOI: 10.1016/0044-8486(95)01208-7.

Loong, A.M., S.F. Chew, W.P. Wong, S.H. Lam, and Y.K. Ip. 2012. Both seawater acclimation and environmental ammonia exposure lead to increases in mRNA expression and protein abundance of Na^+:K^+:2Cl^- cotransporter in the gills of the climbing perch, *Anabas testudineus*. **Journal of Comparative Physiology** B 182: 491–506.

Mekong River Commission. 2015. **Catch and Capture,** Volume 21, No 3. Mekong River Commission, Vientiane, Laos. 48 pp.

Mochizuki, A., K. Homma, T. Horie, T. Shiraiwa, E. Watatsu, N. Supapoj and C. Thongthai. 2006. Increased productivity of rainfed lowland rice by incorporation of pond sediments in Northeast Thailand. **Field Crops Research** 96: 422–427. DOI: 10.1016/j.fcr.2005.08.007.

Mohanty, R.K., H.N. Verma and P.S. Brahmanand. 2004. Performance evaluation of rice-fish integration system in rainfed medium land ecosystem. **Aquaculture** 230: 125–135. DOI: 10.1016/S0044-8486(03)00423-X.

Mohanty, R.K., S.K. Jena, A.K. Thakur and D.U. Patil. 2009. Impact of high-density stocking and selective harvesting on yield and water productivity of deepwater rice-fish systems. **Agricultural Water Management** 96: 1844–1850. DOI: 10.1016/j.agwat.2009.08.006.

Mumu, U.H. and M.N. Hossain. 2021. Sustainable semi-intensive aquaculture of climbing perch (*Anabas testudineus*) in Mymensingh region, Bangladesh: A comparative study. **Asian Journal of Fisheries and Aquatic Research** 11: 8–22. DOI: 10.9734/ajfar/2021/v11i130193.

Nagao Natural Environmental Foundation. 2021. **Fishes of the Indochinese Mekong.** Nagao Natural Environmental Foundation, Tokyo, Japan. 545 pp.

Noodang, S. and S. Nakkew. 2020. **The Situation of Climbing Perch Culture of Farmers in Chiang Mai Province.** Technical Paper No. 1/2020. Chiang Mai Provincial Fisheries Office, Department of Fisheries, Chiang Mai, Thailand. 49 pp. (in Thai)

Office of Agricultural Economics (OAE). 2025a. **Agricultural Economic Report: 1st Quarter 2025 and Outlook for 2025.** Office of Agricultural Economics, Thailand. https://oae.go.th/home/article/474. Cited 6 Oct 2025.

Office of Agricultural Economics (OAE). 2025b. **Rice Yield Statistics 2023/2024.** Office of Agricultural Economics, Thailand. https://oae.go.th/home/article/499. Cited 10 Dec 2025.

Ohnishi, M., T. Horie, K. Homma, N. Supapoj, H. Takano and S. Yamamoto. 1999. Nitrogen management and cultivar effects on rice yield and nitrogen use efficiency in Northeast Thailand. **Field Crops Research** 64: 109–120. DOI: 10.1016/S0378-4290(99)00054-4.

Piwpong, N., J. Chiayvareesajja and S. Chiayvareesajja. 2016. Growth and survival of a diallel cross for five strains of climbing perch (*Anabas testudineus* Bloch, 1792) in Thailand. **Agriculture and Natural Resources** 50: 351–356. DOI: 10.1016/j.anres.2016.05.001.

Rahman, S., S. Monir and M.H. Khan. 2013. Culture potentials of climbing perch, Thai koi, *Anabas testudineus* (Bloch) under different stocking densities in northern regions of Bangladesh. **Journal of Experimental Biology and Agricultural Sciences** 1: 202–208.

R Core Team. 2024. **R: A language and environment for statistical computing.** R Foundation for Statistical Computing. https://www.R-project.org/. Cited 2 Oct 2024.

Rodmongkoldee, M., S. Nimitrkul, C. Aranyakanont, U. Na-Nakorn and R. Yoonpund. 2024. Effects of stocking density and water management on stress responses and reproductive performance of bighead catfish (*Clarias macrocephalus*) female broodstock after hormone injection. **Journal of Fisheries and Environment** 48(2): 1–11. DOI: 10.34044/j.jfe.2024.48.2.01.

Rothuis, A.J., N. Vromant, V.T. Xuan, C.J.J.J. Richter and F. Ollevier. 1999. The effect of rice seeding rate on rice and fish production, and weed abundance in direct-seeded rice–fish culture. **Aquaculture** 172: 255–274. DOI: 10.1016/S0044-8486(98)00396-2.

Saharia, P.K., S. Bhuyan, R. Bordoloi, D. Borah, B. Rahman, H. Rabha and P. Deka. 2018. Introduction of climbing perch (*Anabas testudineus*, Bloch) in low-lying rice field as a component of integration for doubling farmers income in Assam. **Journal of Community Mobilization and Sustainable Development** 13: 13–16.

Saowakoon, S., K. Saowakoon, A. Jutagate, M. Hiroki, M. Fukushima and T. Jutagate. 2021. Growth and feeding behavior of fishes in organic rice-fish systems with various species combinations. **Aquaculture Reports** 20: 100630. DOI: 10.1016/j.aqrep.2021.100663.

Sarker, M.A.A., F.M. Arshad, M.F. Alam, Z.A. Mohamed and M.A. Khan. 2014. Economics of Thai koi (climbing perch, *Anabas testudineus*) farming in pond in Bangladesh. **Trends in Agricultural Economics** 7: 26–40. DOI: DOI: 10.3923/tae.2014.26.40.

Satrawaha, R. and C. Pilasamorn. 2009. Length-weight and length-length relationships of fish species from the Chi River, northeastern Thailand. **Journal of Applied Ichthyology** 25: 787–788. DOI: 10.1111/j.1439-0426.2009.01293.x.

Shofiquzzoha, A.F.M.A., M.A. Halim and M.S. Islam. 2018. Growth and production performance of Vietnamese climbing perch (*Anabas testudineus*) at farm level in Jashore, Bangladesh. **Bangladesh Journal of Fisheries** 30: 187–194.

Suwanmontri, P., A. Kamoshita and S. Fukai. 2021. Recent changes in rice production in rainfed lowland and irrigated ecosystems in Thailand. **Plant Production Science** 24: 1–14. DOI: 10.1080/1343943X.2020.1787182.

Swangdacharuk, G. and Y. Musig. 2016. Growth, production, feed conversion ratio, water quality and nutrient budget of hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) cultivation in earthen ponds without water exchange. **Kasetsart University Fisheries Research Bulletin** 40(3): 78–92.

Takahashi, E. 1968. Silica as a nutrient for the rice plant. **Japanese Agricultural Research Quarterly** 3: 1–4.

Tanaka, T. 1972. Issues for improving ripening rate in rice. **Agricultural Technology** 27: 308–312. (in Japanese)

Tomojiri, D., P. Musikasinthorn and A. Iwata. 2021. Utilization and economic importance of native and non-native freshwater fishes in the lowermost Chao Phraya River Basin, Thailand. **Wildlife and Human Society** 9: 35–56. DOI: 10.20798/awhswhs.9.0_35. (in Japanese)

Tsuruta, T., M. Yamaguchi, S. Abe and K. Iguchi. 2011. Effect of fish in rice-fish culture on the rice yield. **Fisheries Science** 77: 95–106.

U-kerd, P. and A. Srifa. 2024. Temporal changes in zooplankton community composition and abundance in chemical and organic rice fields in Buri Ram Province, Thailand. **Journal of Fisheries and Environment** 48(1): 175–188. DOI: 10.34044/j.jfe.2024.48.1.15.

Vongvichith, B., S. Morioka, K. Kawamura and A. Mori. 2018. Factors influencing fish productivity in rice paddy aquaculture: A case study in Vientiane Province, Central Laos. **Japan Agricultural Research Quarterly** 52: 359–366. DOI: 10.6090/jarq.52.359.

Vongvichith, B., S. Morioka, T. Sugita, N. Phousavanh, N. Phetsanghanh, P. Chanthasone, P. Pommachan and S. Nakamura. 2020. Evaluation of the efficacy of aquaculture feeds for the climbing perch *Anabas testudineus*: Replacement of fishmeal by black soldier fly Hermetia illucens prepupae. **Fisheries Science** 86: 145–151. DOI: 10.1007/s12562-019-01381-5.

Vromant, N., L.T. Duong and F. Ollevier. 2002. Effect of fish on the yield and yield components of rice in integrated concurrent rice-fish systems. **Journal of Agricultural Science** 138: 63–71.

Wood, S.N. 2006. **Generalized Additive Models: An Introduction with R.** CRC Press, Boca Raton, USA. 392 pp.

Xie, J., L. Hu, J. Tang, X. Wu, N. Li, Y. Yuan, H. Yang, J. Zhang, S. Luo and X. Chen. 2011. Ecological mechanisms underlying the sustainability of the agricultural heritage rice–fish coculture system. **Proceedings of the National Academy of Sciences of the United States of America** 108(50): E1381–E1387. DOI: 10.1073/pnas.1111043108.

Zhao, C., G. Liu, Y. Chen, Y. Jiang, Q. Dai, Z. Huo, Y. Shi, L. Zhao, P. Liao, W. Wang and K. Xu. 2022. Excessive nitrogen application leads to lower rice yield and grain quality by inhibiting the grain filling of inferior grains. **Agriculture** 12: 962. DOI: 10.3390/agriculture12070962.