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Original Article

Optimizing paddy spacing for co-production: effects on rice-fish yields and soil-water quality in integrated farming systems

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Abstract
Integrated rice-fish farming (IRFF) is a promising agronomic strategy that enhances crop and fish productivity while improving soil health and resource use efficiency. This study aimed to assess the effects of different rice planting spacing on the growth and yield of rice and fish and evaluate soil fertility and water quality within an IRFF system. A field experiment was conducted using four (T1–T4) planting spacing; T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm. Each treatment with three replicates was randomly allocated in a randomized complete block design. Growth and yield parameters of rice and fish were measured along with soil and water quality indices. Data were analyzed using ANOVA and Tukey's test. Spacing influenced both rice and fish performance significantly. The 15×15 cm spacing provided the best balance, supporting high yields for both rice and fish without adverse effects on soil fertility or water quality. Narrower spacing enhanced total rice yield through higher plant density but reduced individual plant performance. Wider spacing improved individual plant growth yet lowered total yield. Soil nutrient levels (N, P, and K) and organic matter (OM) significantly increased across treatments, with T2 showing the highest enrichment. Water quality parameters (pH, EC, temperature, DO, NO_3^-, NH_3) remained within non-toxic limits. This study suggests that 15×15 cm spacing optimizes rice-fish yields and enhances soil quality without compromising water quality in IRFF systems.

Keywords: integrated rice-fish farming; rice planting spacing; soil fertility; sustainable agriculture; tilapia; water quality

1 | INTRODUCTION

Global food security remains a pressing challenge amid the projected rise in the global population to 9.7 billion by 2050; Asia alone expects to account for approximately 5.2

billion people (WPP 2022; Asia-Pacific Population and Development Report 2023). Rice (*Oryza sativa* L.) plays a crucial role in global food security, serving as a staple food that provides more than half of the daily caloric intake for billions of people (Tolba *et al.* 2020; Shi *et al.* 2023; Singh and Solanki 2025). It occupies around 155 million hectares and consumes up to 90% of Asia's irrigated water (Cosslett and Cosslett 2018; Liu *et al.* 2019). Global rice demand is projected to increase significantly, with estimates ranging from 584 to 852 million tons by 2050 (Khush 2013; Parshuram *et al.* 2022). However, urbanization, environmental degradation, and overreliance on chemical inputs, which contribute to soil and water pollution, biodiversity loss, and greenhouse gas emissions, constrain the expanding production (Swaminathan 2006; Liu *et al.* 2015).

In Sri Lanka, rice is the staple crop supporting national food security and rural livelihoods. Over 2.1 million farmers cultivate about 1.3 million hectares of rice during the "Maha" (October – March) and "Yala" (April – September) seasons. Rice cultivation primarily relies on irrigation schemes and high-yielding varieties (DOA 2023). However, rice cultivation in Sri Lanka faces significant challenges, including declining soil fertility, erratic rainfall, pest outbreaks, and excessive chemical use, which threaten its sustainability (Silva and Lakshani 2021). Sri Lanka has substantially invested in irrigation infrastructure and extension services. However, the country still imports around 0.7 million metric tons of rice annually to meet domestic demand (Rathnayake *et al.* 2020), reflecting persistent gaps in self-sufficiency and resilience.

Parallel to the rice sector, Sri Lanka's aquaculture industry could also offer complementary food and income opportunities. However, it faces multiple barriers, including high costs of formulated feeds, limited availability of suitable land and water resources, environmental degradation, frequent disease outbreaks, and emissions associated with intensive production systems (Silva *et al.* 2009; Yuan *et al.* 2019). These interlinked restrictions in both rice and aquaculture systems emphasize the urgent need for integrated and resource-efficient production models such as integrated rice-fish farming (IRFF), which can simultaneously enhance productivity, profitability, and environmental sustainability.

Protein deficiency is another longstanding nutritional issue, particularly in rural communities in developing countries. A decade ago, the average daily protein intake was only 44.6 g day^{-1}, of which plant-based sources like rice and pulses provided the majority of protein (Jayawardena *et al.* 2014).

The recent economic crisis has further limited access to animal-based foods due to price hikes and shortages (Sooriyaarachchi and Jayawardena 2023). These deficits cause significant health issues due to limited protein intakes, leading to stunting, anemia, and micronutrient-related disorders. While seafood remains a vital protein source, it is often scarce in inland and rural areas, making inland aquaculture a viable strategy to address both nutrition and rural livelihoods (Willett *et al.* 2019). Inland aquaculture practices, such as culture-based fisheries, pond farming, and IRFF, have been identified as a promising tool to address these challenges in many Asian countries. However, it remains underutilized in Sri Lanka (Kumara *et al.* 2024). Further, integrated aquaculture agriculture approaches have improved food security and household income, especially among women (Ahmed *et al.* 2010; Dey *et al.* 2019) in rural communities.

Thus, IRFF offers a practical, resource-efficient solution to these challenges by combining rice cultivation and aquaculture within the same field. This system enhances nutrient cycling, reduces pest and weed pressure, and improves soil and water quality while providing both rice grain and animal protein (Halwart and Gupta 2004; Ahmed and Garnett 2011; Inayat *et al.* 2023). Studies have shown that IRFF can improve productivity, diversify incomes, and reduce chemical dependency, thereby supporting food security and multiple Sustainable Development Goals including Zero Hunger (SDG 2), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), and Life on Land (SDG 15) (Ahmed and Garnett 2011; Samaddar *et al.* 2025).

Rice planting density is a key factor influencing the success of IRFF, affecting microclimate, nutrient competition, water circulation, fish movement, and growth performance. Closer spacing can improve rice tillering and suppress weeds (Aminpanah 2014); however, it may limit fish movement. Wider spacing can enhance fish performance and resource availability for individual plants (Baloch *et al.* 2002), but there is a possibility of lower yield and high weed density. In traditional rice cultivation in Sri Lanka, farmers typically adopt dense planting methods to maximize rice yield. However, in IRFF systems practiced elsewhere, wider plant spacing is often used to facilitate fish movement, which can compromise rice productivity (Bin *et al.* 2021; Inayat *et al.* 2023).

The Department of Agriculture, Sri Lanka, has established optimum planting spacing for rice based on variety maturity (age class). For example, short-age rice varieties (3 - 3½ months) such as AT 362 are recommended to be transplanted at 15×15 cm spacing under conventional rice monoculture (DOA 2020). These recommendations aim to maximize rice yield in standard paddy cultivation.

However, IRFF, where fish are raised in the flooded rice paddies alongside the crop, introduces a different agro-ecosystem. In Sri Lanka, this integrated approach is not a common practice yet, and no specific planting density recommendations exist for rice grown with fish that balances both rice and fish production in IRFF under the local context. This lack of guidelines represents a clear research gap. Currently, farmers have to rely on monoculture spacing guidelines, which may not be suitable for the unique dynamics of the IRFF system. Further, no prior study in Sri Lanka has focused on rice planting geometry in an integrated system with fish, especially using the popular short-duration rice variety AT 362 and the fish species tilapia.

The present study is the first investigation that evaluates how different planting spacing affect crop fish yield and soil water quality parameters in an integrated setup. The findings will fill the current knowledge gap and provide practical recommendations for farmers and authorities on the optimal planting spacing to be adopted in an IRFF system in Sri Lanka, particularly for the most widely cultivated rice variety. Therefore, this study aimed to (i) evaluate the effects of different rice planting spacing on rice and fish growth and yield, and (ii) assess soil fertility and water quality dynamics in an IRFF system under different rice planting spacings in Sri Lanka.

2 | METHODOLOGY

2.1 Experimental site and duration

The experiment was conducted at the Institute for Agro-Technology and Rural Sciences (UCIARS), Weligatta, Hambantota, Sri Lanka, from December 2024 to March 2025 (Maha season). The study was performed in the dry zone, characterized by temperatures ranging from 28°C to 33°C and average monthly rainfall between 181.5 mm and 205.5 mm.

2.2 Experimental design

A field experiment evaluated the effect of varying rice planting spacing on rice and fish performance in an integrated system. The following four rice planting spacing were used as treatments: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm (control), T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm. The Department of Agriculture (DOA 2020) recommendation for 3½-month rice varieties under rice monoculture (15 × 15 cm spacing) was selected as the control (T2).

Each treatment was replicated thrice in a randomized complete block design to minimize potential variability across plots, resulting in twelve experimental plots (4 × 4 m² each). Soil slope variation across the experimental site was used as the blocking criterion to minimize the effect of topographical differences. Blocks were oriented perpendicular to the main irrigation channel. Within each block, treatment plots were randomly allocated using computer-generated random numbers. Initial soil properties were analyzed before transplanting, and no significant differences were found among the experimental plots, ensuring uniformity at the baseline (Table 1).

Uniform agronomic management practices recommended by the Department of Agriculture (DOA 2020), Sri Lanka, were applied across all treatments, including standardized water management, and regular pest and disease monitoring with uniform control measures where necessary. The entire field was subjected to similar microclimatic conditions, and water was supplied from a single irrigation source while maintaining the same water depth across all plots to ensure consistency. Except for rice planting spacing, all other management practices were maintained identically among all plots. All plots were enclosed with a 2 × 2 cm² mesh to prevent bird predation. The experiment lasted 92 days until rice harvest.

2.3 Paddy nursery and transplantation

Oryza sativa (variety: AT 362) was raised in a wet-bed nursery and transplanted when 14 days old. Two seedlings were transplanted per hill, and the hill density varied by spacing: 72/m² (T1), 30/m² (T2), 18/m² (T3), and 11/m² (T4).

2.4 Land preparation and ditch construction

The field was manually ploughed twice (14 and 04 days before transplanting) with 5 to 10 cm of water maintained to aid organic matter decomposition. Peripheral ditches were lined with polythene to prevent seepage (Figure 1; Lokuhetti *et al.* 2025).

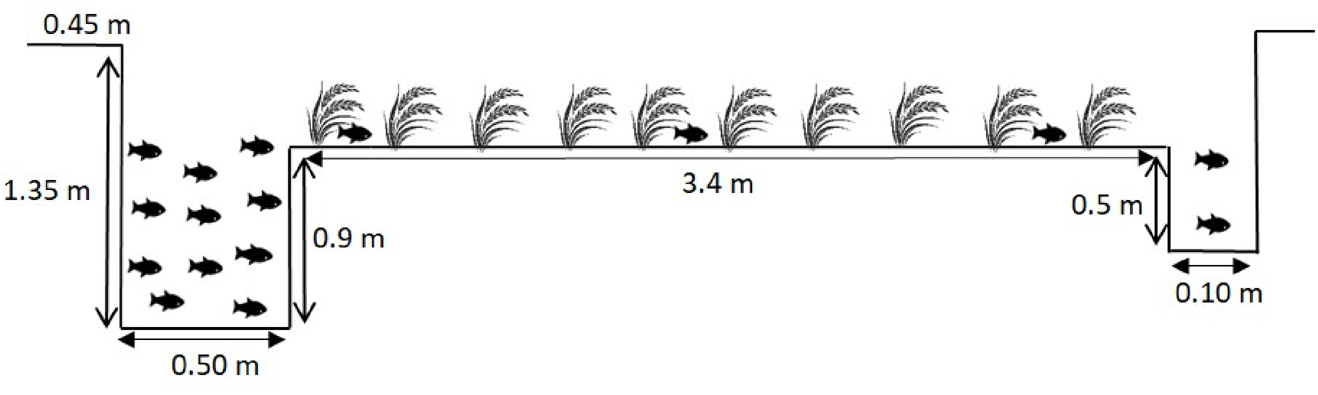

FIGURE 1 Diagrammatic representation of the cross-section of a plot.

2.5 Fertilizer application

Organic fertilizer was applied after the first plowing at the following rates: 0.5 kg m^{-2} paddy straw, 0.4 kg m^{-2} cow dung, and 0.1 kg m^{-2} *Gliricidia* leaves, in accordance with the Department of Agriculture guidelines (DOA 2020). Additionally, 0.06 kg m^{-2} of biochar was incorporated after the second plowing. No chemical fertilizers or top dressing were used throughout the experiment.

2.6 Fish species, stocking, and feeding

Oreochromis niloticus fingerlings (average weight 35 ± 2.0 g) were sourced from a certified hatchery and acclimatized for two weeks in cement tanks. They were fed commercial feed (32% crude protein) at 3% body weight. Fish were stocked at 2.2 m^{-2} (35 per plot), two weeks post-transplanting, and fed twice daily, adjusting for growth.

2.7 Water and fish management

During the first 15 days, water depth was maintained at 2 to 5 cm, then increased to 5 to 15 cm thereafter. Standard DOA recommended agronomic practices were followed.

2.8 Data collection

2.8.1 Rice growth and yield

Growth parameters, such as plant height, stem diameter, number of leaves, tillers, flag leaf dimensions, and days to flowering, were measured biweekly. Yield components, including effective tillers, grains per panicle, filled grains, 1000-grain weight, grain yield, straw yield, and biological yield, were recorded using standard procedures at harvest (Gomez 1972; Mirhaj *et al.* 2013).

Biological yield and harvest index were computed as follows: harvest index (%) = (Grain yield) / (Biological yield) × 100; biological yield (t ha^{-1}) = Grain yield + Straw yield.

2.8.2 Fish growth and survival

Initial weights of fish (g) were measured using a top-loading balance; thereafter, weight was measured fortnightly by sampling ten fish randomly from each plot. At harvest, all fish were collected, counted, and weighed individually to assess survival, yield, and weight gain (g day^{-1}).

2.8.3 Soil and water quality analysis

Soil samples were analyzed monthly for pH (dS m^{-1}), EC (dS m^{-1}), organic matter (%), N (%), P (mg kg^{-1}), and K (mg kg^{-1}) at the Hambantota District Soil Laboratory (DOA). Potassium content was measured using a flame photometer (M410, Sherwood Scientific; UK), while phosphorus content was analyzed by the Olsen method using a spectrophotometer (DR3900, Hach; USA). Soil pH was determined using a pH meter (HQ11d, Hach; USA), and electrical conductivity (EC) was measured using an EC meter (HQ14d, Hach; USA). Total soil nitrogen content was analyzed using the Kjeldahl method with a Kjeldahl system (UDK169, Velp Scientifica; Italy). Soil organic content was measured by the Walkley and Black method. The baseline soil quality parameters are as follows (Table 1).

TABLE 1 Baseline soil quality parameters for different treatments (T1 – T4) before transplanting in the integrated rice-fish farming experiment.

Soil characteristics	Treatments				*p*-value
	T1	T2	T3	T4	
pH	7.10±0.10[a]	6.96±0.06[a]	7.13±0.03[a]	7.03±0.06[a]	0.406
EC (ds/$m^{-1.5}$)	0.07±0.003[a]	0.06±0.003[a]	0.07±0.003[a]	0.07±0.003[a]	0.441
N (%)	0.274±0.001[a]	0.276±0.002[a]	0.275±0.002[a]	0.277±0.003[a]	0.856
P (ppm)	5.58±0.15[a]	5.63±0.11[a]	5.67±0.10[a]	5.70±0.07[a]	0.901
K (ppm)	80.46±0.48[a]	80.23±0.76[a]	79.90±0.92[a]	79.70±0.79[a]	0.892
OM (%)	2.89±0.04[a]	2.91±0.04[a]	2.93±0.03[a]	2.92±0.04[a]	0.862

Similar superscript letter indicate no differences across treatments. Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

Water quality parameters, including pH, electrical conductivity (EC; µS cm^{-1}), dissolved oxygen (DO; mg L^{-1}), nitrate (NO_3^-; mg L^{-1}), and ammonia (NH_3, mg L^{-1}), were measured bi-weekly using calibrated instruments. NO_3^- concentrations were determined using a multiparameter water quality meter (HI9829, Hanna Instruments, Romania) while pH and EC were measured with a pH/EC meter (EUTEC Cyberscan PC300, Singapore). DO levels were assessed using a DO meter (HI98194, Hanna Instruments, Romania), and NH_3 concentrations were determined following the APHA Standard Methods (APHA 2017).

The baseline values were as follows: pH (7.36 ± 0.02), electrical conductivity (EC: 356 ± 8.79 µS cm^{-1}), temperature (29.3 ± 0.08°C), dissolved oxygen (DO: 5.66 ± 0.02 mg L^{-1}), ammonia (NH_3: 0.14 ± 0.008 mg L^{-1}), and nitrate (0.32 ± 0.01 mg L^{-1}).

2.8.4 Weeds density

Weed samples were collected at 60 and 90 days using a 1 ft^2 quadrat placed at three random locations per plot.

Weed density was calculated using the following equation, weed density (number of weeds ft^{-2}) = (total number of weeds in sampled area) / (sampled area (ft^2)).

2.9 Data analysis

The data were tested for normality. Statistical comparisons were made using a one-way analysis of variance (one-way ANOVA), followed by Duncan's post hoc test to evaluate mean differences at a significance level of $p \leq 0.05$. Pearson's correlation analysis was conducted to examine variable relationships. All statistical computations were performed using Minitab version 20, and graphical illustrations were created using Microsoft Excel version 2016.

3 | RESULTS AND DISCUSSION

3.1 Growth performances of rice

There was no significant variation in plant height, number of tillers, or number of leaves until four weeks after transplanting (WATP) (Figure 2). However, these parameters showed significant differences among treatments thereafter. Plants cultivated at the narrowest spacing produced the tallest plants, whereas those at the widest spacing recorded the shortest with statistical significance (ANOVA: F = 4.68, p = 0.036) at the final measurement (Figure 2A). This pattern may have resulted from the increased competition for light, which triggered shade avoidance responses and promoted vertical elongation (Cui *et al.* 2023; Gautrat *et al.* 2024). In contrast, plants at the widest spacing remained shorter because the reduced interplant competition minimized the need for vertical growth and favored resource allocation to other organs (Gautrat *et al.* 2024).

Despite being taller, plants in the densest spacing (T1) produced significantly fewer tillers (ANOVA: F =11.87, p = 0.003) and leaves (F = 49.06, p < 0.001) per plant compared to those in wider spacing treatments (Figures 2B and 2C). This suggests an exchange between vertical growth and lateral development when plants are grown in crowded conditions. Wider spacing treatments allowed plants more access to light, nutrients, space, and air circulation, resulting in higher leaf production (Yang *et al.* 2012; Inayat *et al.* 2023). Similarly, stem diameter significantly improved (F = 18.06, p = 0.001) with wider planting spacing at the flowering stage (Figure 3).

These findings are consistent with previous studies that report that higher plant density restricts stem girth due to increased foliar shading and nutrient competition (Baloch *et al.* 2002; Berhanu 2017). Wider spacing enhanced photosynthetic efficiency, supporting better vegetative development and individual plant biomass (Bhaduri *et al.* 2020). Moreover, plant growth parameters, including the number of leaves, tillers, and stem diameter, were further enhanced by the integration of fish, which likely contributed to nutrient cycling and improved microenvironmental conditions.

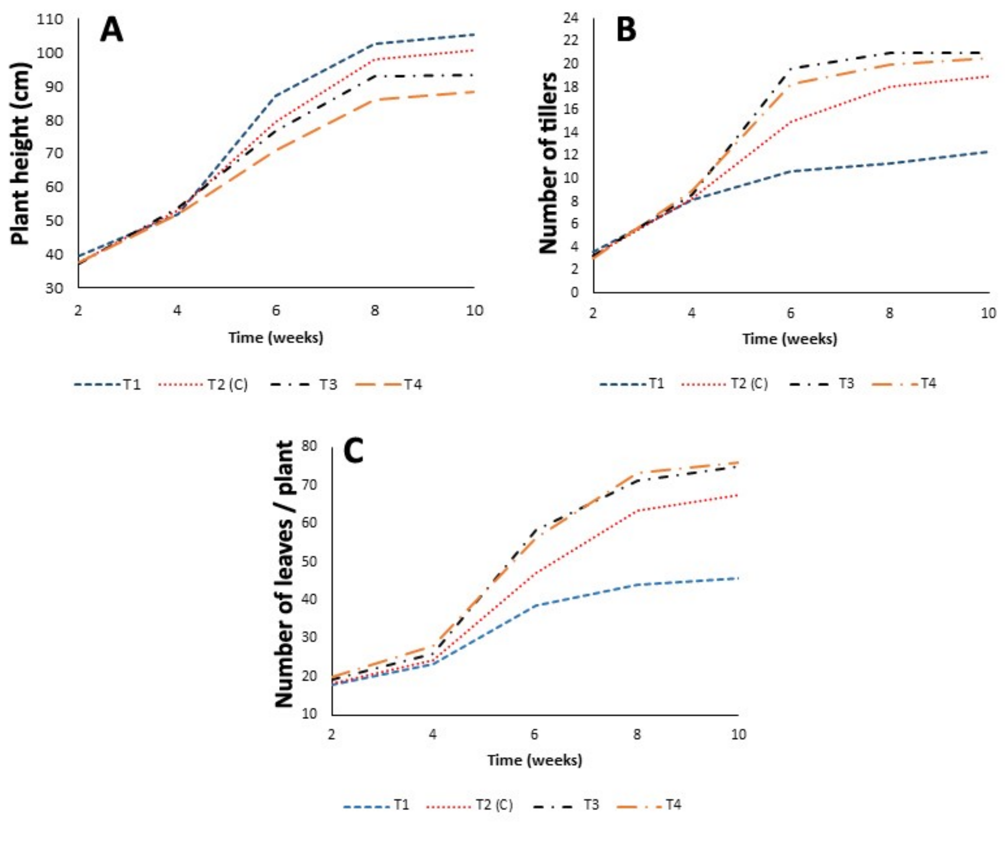

FIGURE 2 Growth performance of paddy plants: (a) plant height, (b) number of tillers, (c) number of leaves. Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

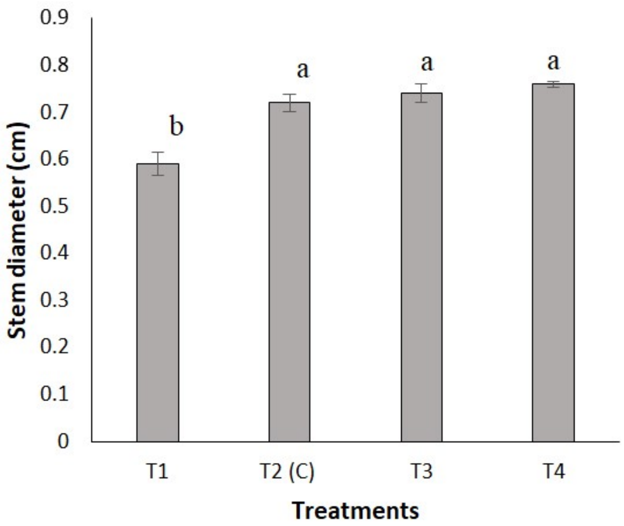

FIGURE 3 Stem diameter of paddy plants across the treatments at the flowering stage. Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

A significant difference was noted in flag leaf length ($F = 8.49$, $p < 0.05$) and the number of days to flowering ($F = 33.14$, $p < 0.05$) among the treatments. However, no significant difference was observed for flag leaf width. T1 and T2 exhibited the shortest flag leaves, while T3 and T4 showed the longest flag leaves (Table 2). The increase in flag leaf length under wider spacing can be attributed to reduced competition for resources, which promotes elongation. Flag leaf width remained unaffected because leaf expansion is genetically constrained and less responsive to planting density (Zhang *et al.* 2015).

Furthermore, T1 flowered earlier compared to wider spacing treatments (Table 2). The possible reason for this phenomenon can be the increased intra-plant competition for light, nutrients, and space, which imposes physiological stress on the plants. Such stress conditions are known to trigger earlier transition into the reproductive phase as a survival strategy (Takeno 2016).

TABLE 2 Flag leaf length, width, and number of days to flower of rice plants (AT 362) in the integrated rice-fish farming system across different rice planting spacings (Mean ± SE, $n = 3$).

Variable	T1	T2 (C)	T3	T4	*p*-value
Flag leaf length (cm)	30.40±2.05[a]	30.65±1.39[a]	39.51±1.97[b]	40.53±2.05[b]	0.007
Flag leaf width (cm)	3.30±0.25[a]	3.47±0.38[a]	3.56±0.25[a]	4.74±1.87[a]	0.320
Number of days to flower	53.66±0.57[b]	60.33±0.57[a]	62.67±2.52[a]	63.66±0.57[a]	<0.001

Different superscript letters in columns indicate differences across treatments ($p < 0.05$). Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

3.2 Yield performance of rice

The number of effective tillers per plant varied significantly among the treatments (ANOVA: $F = 34.94$, $p < 0.05$). Treatments T4 and T3 produced a significantly higher number of effective tillers per plant compared to the control (T2), although they were statistically similar to each other (Figure 4A). A comparable trend was observed in the number of total grains per panicle, which also differed significantly among treatments ($F = 77.34$, $p < 0.05$) (Figure 4B). The number of filled grains per panicle was notably enhanced in T3 and T4 ($F = 133.23$, $p < 0.05$), whereas T1 recorded the lowest values (Figure 4C).

TABLE 3 Correlation results for flag length and number of grains, filled grains per panicle, and 1000-grain weight.

Parameter	*r*-value	*p*-value
Number of grains per panicle	0.834	0.001
Number of filled grains per panicle	0.843	0.001
1000-grain weight (g)	0.514	0.087

r = Pearson correlation value. Significance of the correlation is presented at the 0.05 level.

Table 3 illustrates a strong positive correlation between flag leaf length and some yield components, such as the number of grains and filled grains / panicle, and 1000-grain weight. These results are consistent with the central role of the flag leaf as a primary photosynthetic source during grain filling in rice. The flag leaf supplies a substantial proportion (45 – 60%) of the assimilates required for grain development (Rahman *et al.* 2014). Chandra *et al.* (2009) and Rahman *et al.* (2014) reported positive correlations between flag leaf length and yield components such as panicle length, number of grains, and 1000-grain weight, which are consistent with the findings of this study. Higher chlorophyll in the flag leaf compared to other leaves impacts seed setting rates and other yield components of rice (Rahman *et al.* 2014). However, the final grain yield of wider spacing did not reflect the positive trends observed in the effective tiller number, total grains, and filled grains per panicle.

Rice yield in the widest spacing treatments (T3 and T4) was approximately 25.9% and 28.5% times lower, respectively, compared to the control (T2) (Figure 4D). The integration of tilapia with increasing planting spacing benefited individual plant growth (Figure 5). This outcome reflects a common agronomic trade-off: wider spacing enhances individual plant performance, but it can reduce yield per unit area due to low population density (Sherif *et al.* 2020). Inayat *et al.* (2023) also demonstrated that medium rice spacing in IRFF systems offers the most efficient balance between rice and fish production. Mobasser *et al.* (2007) reported a 20.6% yield increase at 120 plants m^{-2} compared to 20 plants m^{-2}. Similarly, Bozorgi *et al.* (2011) and Mohapatra *et al.* (1989) observed higher yields at 15 × 15 cm and 20 × 20 cm spacing, respectively, supporting the present findings. Although higher planting densities can limit panicle size or spikelet number, the greater number of panicles per unit area often compensates for yield losses caused by individual plant limitations (Chandrakar and Khan 1981; Uddin *et al.* 2011). The rice planting spacing significantly impacts the growth and yield of *O. sativa* (AT 362) since all tested correlations was statistically significant (Table 4).

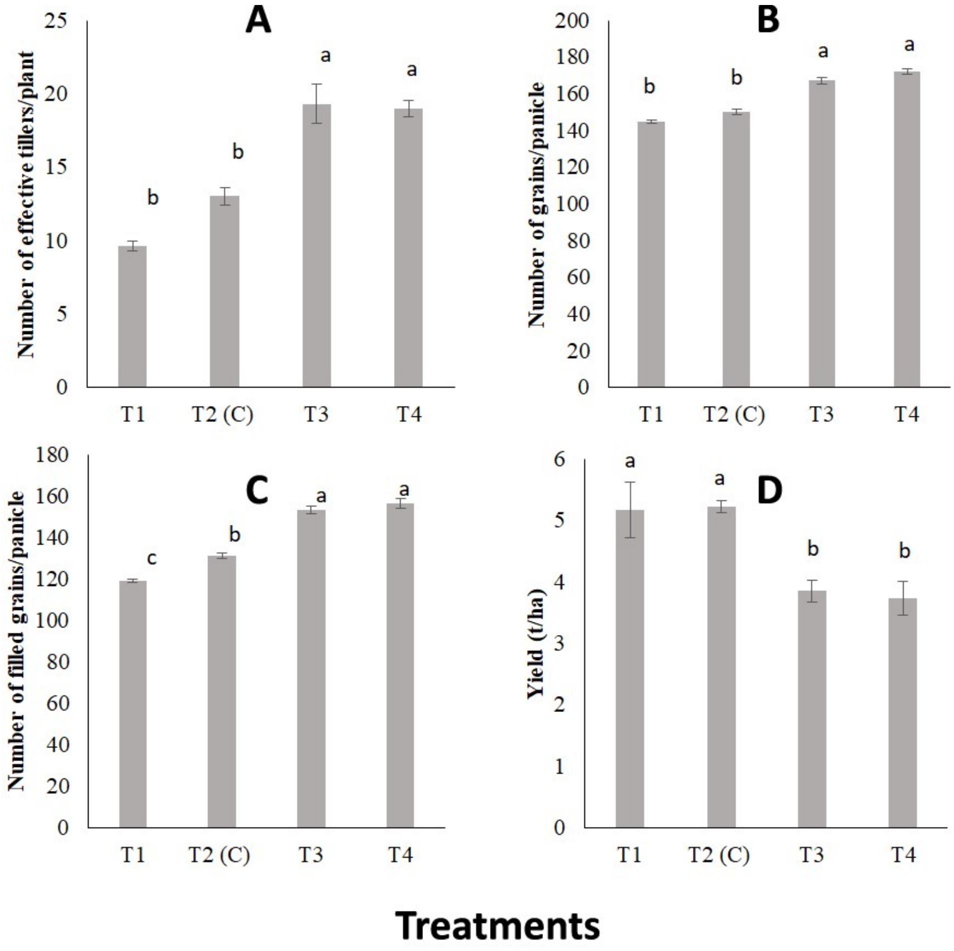

FIGURE 4 Yield performances of paddy plants: (A) number of effective tillers, (B) number of grains, (C) number of filled grains, (D) paddy yield. Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

TABLE 4 Correlation matrixes for planting spacings and growth and yield performances of rice.

Variables	Planting spacing (treatment)	
	Pearson correlation (*r*)	Significance (*p*)
Number of leaves	0.885	<0.001
Number of tillers	0.761	0.004
Plant height (cm)	-0.817	0.001
Stem diameter (cm)	0.830	0.001
Number of grains panicle^{-1}	0.955	<0.001
Number of filled grains panicle^{-1}	0.958	<0.001
Number of effective tillers	0.904	<0.001
Paddy yield (t ha^{-1})	-0.787	<0.001

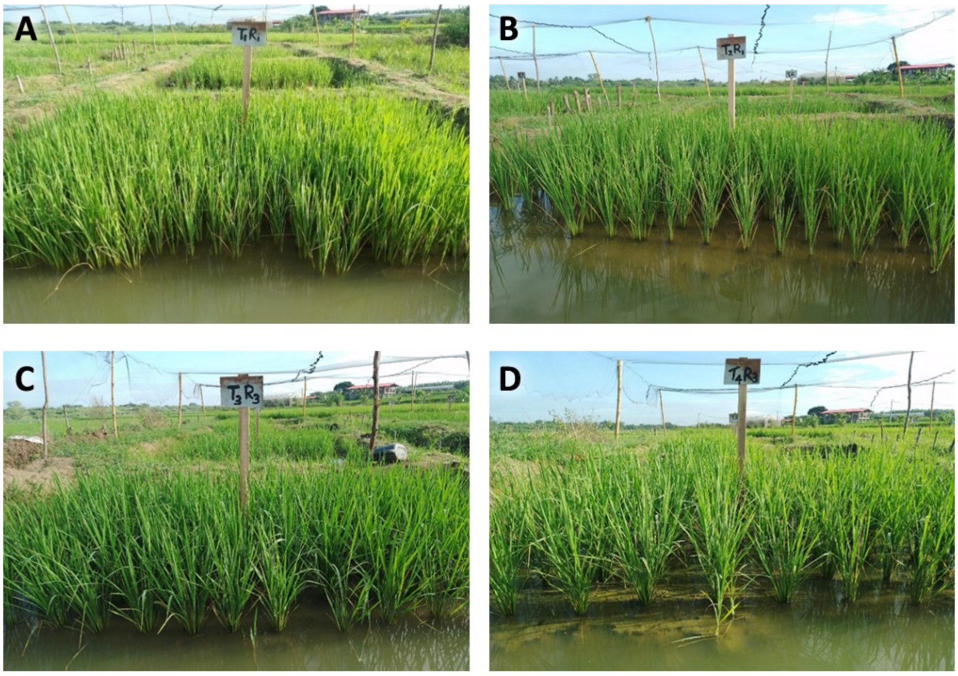

FIGURE 5 Experimental plots: (A) T1: 10 cm × 10 cm, (B) T2: 15 cm × 15 cm (control), (C) T3: 20 cm × 20 cm, (D) T4: 25 cm × 25 cm.

3.3 Weed density

The integration of fish into the rice-based system, along with wider rice planting spacing, significantly increased weed density ($p < 0.05$). Treatments T3 and T4 recorded the highest weed densities at both 60 and 90 days after transplanting (DAT). In contrast, T1 and T2 exhibited the lowest densities at 90 DAT (Figure 6). At 60 DAT, T1 and T2 showed statistically similar densities, both of which were lower than those of T3 and T4. This suggests an optimal balance between canopy coverage, water depth, and fish activity.

The higher weed density under wider spacing is mainly due to enhanced light penetration to the soil surface, which promotes weed emergence. In contrast, narrower spacing facilitated early canopy closure, suppressing weed emergence through the shading effect (Figure 6). These findings are consistent with those of Rao *et al.* (2007), who reported that reduced canopy coverage enhances weed proliferation. The presence of fish such as *Oreochromis* spp. can help to control submerged and floating aquatic weeds through natural grazing (Halwart and Gupta 2004; CABI 2023). Still, this effect may be insufficient to compensate for the increased weed pressure associated with wider spacing.

3.4 Fish growth and survival

Oreochromis niloticus were still in the exponential phase of their growth cycle at the end of the experiment (Figure 7A). The final body weight of tilapia was significantly higher in the control (T2) and T3 treatments. However, there was no statistical difference between these two treatments. The average final weights recorded in T2 and T3 were 140.0 ± 0.40 g and 141.8 ± 0.77 g, respectively. In contrast, the lowest average weight was observed in T1, which had the narrowest planting spacing (Figure 7A).

Similarly, fish yield was significantly higher in T2 and T3, while the yields in T1 and T4 were statistically lower (Figure 7B; ANOVA: $F = 34.20$, $p < 0.05$). A similar trend was noted for weight gain across treatments ($F = 544.77$, $p < 0.05$). In contrast, fish survival rates did not differ significantly among treatments, indicating uniform survival across the experimental conditions (Table 5).

Visual observations indicated that tilapia exhibited frequent and active movement across the rice plots, such as shoaling, foraging, and exploratory movement, particularly in the T2 and T3. These behaviors may have been facilitated by optimal plant spacing for fish navigation, higher dissolved oxygen levels (5.11 mg L^{-1}), moderate water temperatures (28.6°C), and enhanced natural food availability. Additionally, T2 and T3 may have been provided sufficient canopy protection, which could have reduced fish fear responses to aerial or terrestrial predators, thereby supporting more confident movement and feeding (Savino and Stein 1989; Heck and Crowder 1991; Halwart and Gupta 2004; Ibrahim *et al.* 2023).

However, more restricted fish movement appeared in the narrowest spacing treatment (T1), likely due to dense canopy cover, limited space between rows, and lower dissolved oxygen levels (4.72 mg L^{-1}) (Table 6), which may have contributed to stress and restricted movements and access to feed. Although T4 had lower plant density, the reduced canopy cover might have exposed fish to increased sunlight and perceived predation risk, potentially causing behavioral stress (Savino and Stein 1989; Halwart and Gupta 2004; Miah *et al.* 2011). Furthermore, the higher water temperatures observed in T4 (32.6°C) may have suppressed feed intake and fish growth (Boyd and Tucker 2012).

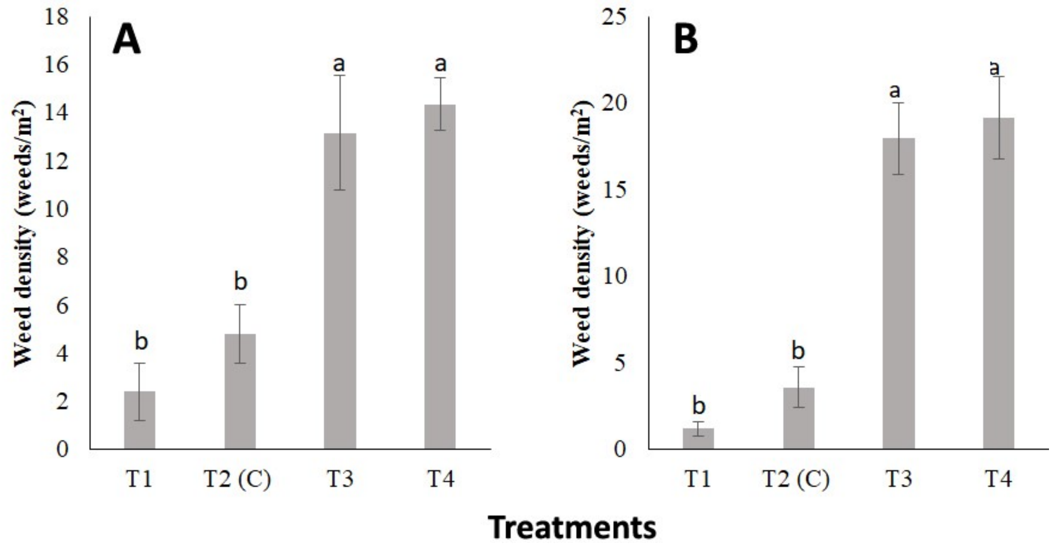

FIGURE 6 Weed density per m^{-2} area in integrated rice-fish farming system: (a) 60 days after transplantation, (b) 90 days after transplantation (weeds m^{-2}). Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

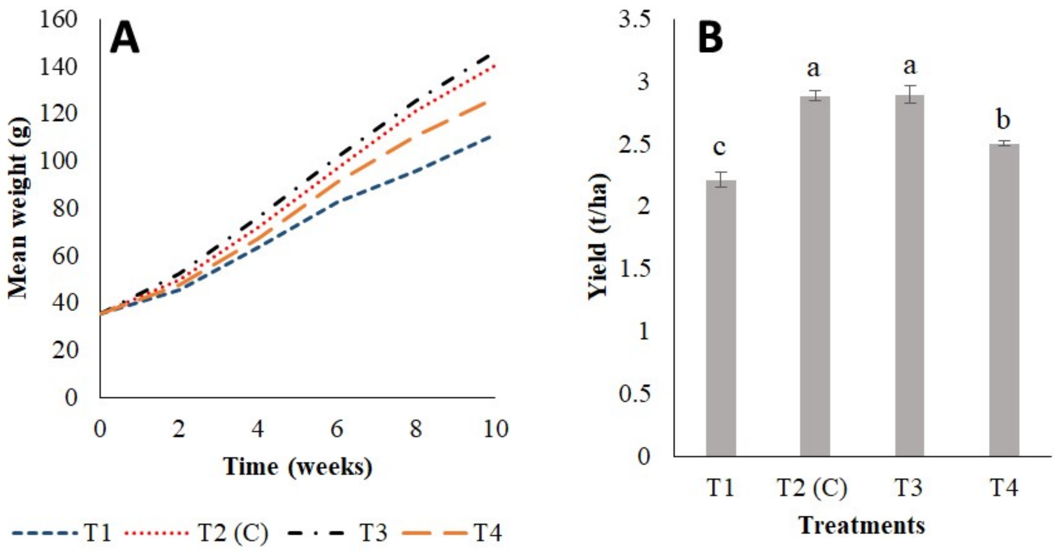

FIGURE 7 Growth and yield performance of *Oreochromis niloticus* in integrated rice-fish farming system: (a) mean weight, (b) fish yield. Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

TABLE 5 Weight gain and survival rate of *Oreochromis niloticus* in integrated rice-fish farming system.

Parameters	Treatments				*p* -value
	T1	T2	T3	T4	
Weight gain (g/day)	0.84±0.01[c]	1.13±0.001[a]	1.15±0.01[a]	0.99±0.01[b]	0.000
Survival (%)	89.52±2.52	94.29±1.65	93.33±1.90	90.47±0.95	0.284

Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

The improved weight gains and final body weight of fish in T2 and T3 support the possibility that moderate spacing provides more favorable conditions for IRFF productivity (Table 5). Medium planting densities may also promote better water quality, including better light penetration (Browman *et al.* 2006), higher dissolved oxygen levels, and increased phytoplankton diversity (Vromant and Chau 2005). These phytoplankton, serving as a natural food source, could have directly contributed to enhanced fish nutrition and growth (Peres and Oliva-Teles 1999). The microbial flora in moderately spaced systems may also have enhanced feed availability. According to Guo *et al.* (2020), such environments are generally more sustainable for fish growth, offering balanced levels of oxygen, temperature, and pH.

Field observations further support this possibility, where fish survival rates remained statistically similar across treatments, suggesting that the basic environmental conditions, including dissolved oxygen, pH, and temperature, remained within acceptable ranges with varied movement and growth (Table 7).

3.5 Soil quality

Initial soil parameters showed no significant differences, confirming plot uniformity. By harvest, N, P, K, and organic matter varied significantly with different planting spacing ($p < 0.05$; Table 6). Soil pH and electrical conductivity (EC) did not differ significantly among treatments. Soil pH ranged from 6.76 to 6.98 and EC from 0.07 to 0.10 dS m^{-1}, indicating stable acidity and salinity across all plots.

TABLE 6 Characteristics of soil at the end of the experiment of integrated rice-fish farming for different rice planting spacings (Mean ± SE, n = 3).

Soil characteristics	Treatments				*p*-value
	T1	T2	T3	T4	
pH	6.98±0.09^{a}	6.88±0.05^{a}	6.76±0.08^{a}	6.96±0.08^{a}	0.270
EC (ds/$m^{-1.5}$)	0.08±0.01^{a}	0.10±0.01^{a}	0.08±0.01^{a}	0.07±0.01^{a}	0.508
N (%)	0.300±0.002^{b}	0.321±0.002^{a}	0.319±0.001^{a}	0.308±0.002^{b}	<0.001
P (ppm)	6.09±0.15^{b}	6.70±0.08^{a}	6.62±0.16^{ab}	6.31±0.07^{ab}	0.033
K (ppm)	85.68±1.86^{b}	97.51±1.53^{a}	94.84±2.72^{ab}	89.48±2.92^{ab}	0.028
OM (%)	3.12±0.01^{c}	3.45±0.03^{a}	3.43±0.02^{a}	3.28±0.02^{b}	<0.001

Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

T2 (control) and T3 treatments recorded the highest values for all key soil fertility parameters, while T1 (10 cm × 10 cm) recorded the lowest, followed by T4. Specifically, total N, P, and K in T1 declined by 6.5%, 9.1%, and 12.1% respectively, compared to T2, likely due to intensified plant competition and limited nutrient retention in denser stands. Organic matter content followed a similar trend, with the lowest level observed in T1.

Despite these treatment-level variations, all plots demonstrated notable post-harvest improvements in N (9.3 to 16.4%), P (9.1 to 19.0%), K (6.5 to 21.5%), and organic matter (8.1 to 18.3%) relative to baseline levels, highlighting the fertility-enhancing potential of the IRFF system.

Previous studies have also demonstrated that IRFF systems significantly enhance soil fertility by improving nutrient cycling. For example, Xie *et al.* (2011) and Nayak *et al.* (2018) observed elevated macronutrient availability in the IRFF system due to continuous deposition of nutrient-rich fish excreta, combined with the stimulation of microbial processes. Halwart (1998) further emphasized that such a system is particularly beneficial under organic and low-input farming conditions. Fish activity may also contribute to soil enrichment by promoting organic matter decomposition and nutrient mineralization (Sinhababu *et al.* 1983). Hossain *et al.* (2015) reported increases of 4 to 11% in sediment N and P under integrated systems. The findings of the present study align with Miao (2010), who quantified the fertilizing effect of fish feces in IRFF systems, and Lu and Li (2006), who confirmed that integration can increase soil nutrient concentrations by up to 38.5%.

3.6 Water quality

Throughout the experimental period, water quality parameters remained within the optimal range for tilapia growth (Boyd and Tucker 1998) (Table 7). Overall, pH, dissolved oxygen (DO), electrical conductivity (EC), temperature, nitrate (NO_3^-), and ammonia (NH_3) levels were maintained at safe thresholds, creating a stable aquatic environment favorable for both rice and fish growth. Nitrate and ammonia concentrations in all treatments remained well below toxic limits, ensuring the fish experienced no stress.

Differences among the treatments reflected the influence of rice planting spacing on aquatic conditions. Decreased plant spacing limited light penetration due to increased canopy cover, which likely lowered water temperature and reduced photosynthetic activity of plankton, thereby decreasing DO levels, which are the conditions known to retard fish growth (Zhang *et al.* 2010). Dense canopies may also have restricted wind-induced surface mixing, further reducing water aeration. Conversely, moderate spacing (T2 and T3) provided balanced canopy coverage and supported favorable water conditions, contributing to improved fish performance.

TABLE 7 Water quality parameters across the treatments in the integrated rice-fish farming system (Mean ± SE, n = 3).

Parameters	Treatment				*p*-value
	T1	T2	T3	T4	
pH	7.90±0.03^{a}	7.85±0.06^{a}	7.70±0.05^{a}	7.95±0.15^{a}	0.290
EC (µS cm^{-1})	371.7±2.03^{bc}	365.6±1.42^{c}	380.8±0.98^{a}	374.5±1.22^{ab}	0.001
Temperature (°C)	28.1±0.03^{c}	28.6±0.03^{c}	31.3±0.49^{b}	32.6±0.05^{a}	<0.001
DO (mg L^{-1})	4.72±0.05^{c}	5.11±0.01^{b}	5.35±0.01^{a}	5.48±0.02^{a}	<0.001
NO_3^- (ppm)	0.71±0.01^{b}	0.83±0.02^{a}	0.84±0.02^{a}	0.72±0.01^{b}	<0.001
NH_3 (ppm)	0.24±0.01^{c}	0.45±0.02^{a}	0.41±0.01^{ab}	0.36±0.02^{b}	<0.001

Spacing: T1: 10 cm × 10 cm, T2: 15 cm × 15 cm, T3: 20 cm × 20 cm, and T4: 25 cm × 25 cm.

In contrast, treatment T4 exhibited slightly higher water temperatures (up to 32.6°C), probably due to excessive sunlight exposure from wider spacing. Although such wide spacing provided more swimming space, elevated temperatures may have negatively influenced feed intake. Small increases in nitrate and ammonia concentrations under wider spacing likely reflected enhanced nutrient inputs from fish excreta but remained below harmful levels, indicating effective ecological buffering. These findings align with previous studies documenting similar nutrient dynamics and environmental stability in IRFF systems (Frei *et al.* 2007; Mirhaj *et al.* 2013; Billah *et al.* 2020).

4 | CONCLUSIONS

The research findings revealed that a 15 × 15 cm rice planting spacing achieved the best balance between total rice yield and fish growth, without compromising soil fertility or water quality. Narrower spacing increased plant density and overall yield but reduced individual plant performance, whereas wider spacing enhanced individual plant growth but lowered total yield. These results confirm that an intermediate spacing can optimize dual production, filling a key research gap and providing practical, field-based evidence for the sustainable intensification of IRFF systems. It is recommended that farmers adopt a 15 cm × 15 cm spacing for rice transplanting in IRFF systems.

Furthermore, this study recommends conducting additional research on microbial activity and changes in soil biodiversity under IRFF conditions, as these factors play a crucial role in maintaining and enhancing soil health. Policymakers and agricultural extension agencies should integrate these findings into training programs, demonstration plots, and support schemes to promote higher farm productivity, efficient resource use, and environmental sustainability.

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ETHICAL APPROVAL

Ethical approval for this study was obtained from the Ethics Review Committee of the Institute of Biology, Sri Lanka (ERC-IOBSL) in 2024, ensuring adherence to animal welfare standards.

CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHORS' CONTRIBUTION

H.K.R.S.K: experimental design and execution, data collection, statistical analysis, interpretation of results and drafting manuscript; M.M.K.I.M & K.S.S.A: supervising, data interpretation and critical revisions to the manuscript; S.S.H & N.P.V: supervising, critically reviewed and edited the manuscript.

DATA AVAILABILITY STATEMENT

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

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