PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–10
https://doi.org/10.14719/pst.5108

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Integrated rice farming systems for improved growth, yield and pest reduction

R Ranjith[1], K Subrahmaniyan[1*], S Elamathi[2], R Manimaran[3], K Manikandan[4] & T Sivasankari devi[5]

[1]Tamil Nadu Rice Research Institute, Tamil Nadu Agricultural University, Aduthurai 612 101, Tamil Nadu, India

[2]Department of Agronomy, Tamil Nadu Rice Research Institute, Tamil Nadu Agricultural University, Aduthurai 612 101, Tamil Nadu, India

[3]Department of Plant Breeding and Genetics, Tamil Nadu Rice Research Institute, Tamil Nadu Agricultural University, Aduthurai 612 101, Tamil Nadu, India

[4]Department of Soil Science and Agricultural Chemistry, V.O.C Agricultural College and Research Institute, Tamil Nadu Agricultural University, Killikulam 628 252, Tamil Nadu, India

[5]Agricultural Microbiology, Tamil Nadu Rice Research Institute, Tamil Nadu Agricultural University, Aduthurai 612 101, Tamil Nadu, India

*Email: subrah_arul@yahoo.com

OPEN ACCESS

ARTICLE HISTORY
Received: 18 September 2024
Accepted: 15 October 2024
Available online
Version 1.0 : 13 December 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Ranjith R, Subrahmaniyan K, Elamathi S, Manimaran R, Manikandan K, Devi TS. Integrated rice farming systems for improved growth, yield and pest reduction. Plant Science Today.2024;11(sp4):01-10. https:/doi.org/10.14719/pst.5108

Abstract

Soil health and environmental degradation are some of the major challenges to the sustainable production of organic rice cultivation. The study utilized farming systems components like *Azolla*, fish and duck as nutrient sources in rice cultivation during *late samba* 2022-23 and 2023-24 at Tamil Nadu Rice Research Institute, Aduthurai, Tamil Nadu. The experiments were conducted with eleven treatments replicated thrice in a randomized block design, the treatments included green manure, fish, *Azolla*, duck and liquid bio fertilizers and their combinations with nano urea foliar spray were compared with RDF. The results demonstrated a significant positive impact of integrating farming system components on rice growth and productivity. GM- Rice + fish + *Azolla* + duck (PSB+KSB+ZSB) along with nano urea foliar spray (0.4 %) recorded the maximum growth and physiological parameters over other treatments. Similar results were also observed in yield attributes of rice *viz.,* the number of panicles (457 m^{-2}), panicle length (31.26 cm), panicle weight (3.94 g), and filled grains $panicle^{-1}$ (331.5). The higher grain (6.06 t ha^{-1}), straw yield (7.81 t ha^{-1}), rice equivalent yield (REY) (22.55 t ha^{-1}), system productivity (61.79 kg ha^{-1} day^{-1}), sustainable yield index (0.881) and relative production efficiency (440.3 %) of rice were recorded in GM- Rice + fish + *Azolla* + duck (PSB+KSB+ZSB) along with nano urea foliar spray (0.4 %). Additionally, lower pest incidences and higher insect pest control efficiency, richness, diversity and evenness indices were observed in green manure, *Azolla*, fish and duck-adopted treatments. The findings of experiments revealed that the inclusion of integrated farming system components significantly improved the yield and reduced pest incidences in rice.

Keywords

azolla; duck; fish; green manure; rice

Introduction

Rice (*Oryza sativa* L.) is the staple food crop in most of South-East Asia. In India, rice is an essential and extensively grown food crop that occupies an area of 47.7 million hectares with a production of 135.7 million tonnes and an average productivity of 2.84 t ha^{-1} (1). Organic agriculture is an eco-friendly approach followed in India, significantly promoting soil health and environmental safety

(2). However, the increasing demand for organic rice has highlighted significant challenges related to soil health. Organic rice farming often encounters issues such as nutrient depletion, soil erosion and reduced microbial activity, which can adversely affect crop yields and sustainability (3). Among these challenges, integrated farming systems offer a promising solution. The integration of rice agriculture with complementary agricultural practices, such as aquaculture and duck farming, can augment soil fertility, enhance nutrient cycling and foster biodiversity (4). This holistic approach not only revitalizes soil health but also optimizes resource use and increases resilience against pests and diseases (5).

Continued rice cultivation with poor crop management practices led to poor soil fertility (6). Therefore, organic nutrient management approaches are vital strategies for augmenting rice productivity, as they also enhance the soil's physical, chemical and biological qualities (7). Nitrogen is regarded as a primary limiting nutrient in paddy fields (8). Thus, a higher amount of nitrogen fertilizer is needed to fulfill the demand for rice production (9). Adoption of green manure cultivation in agroecosystems is an alternative way to solve the problems of excess application of nitrogen fertilizer and to improve rice production (10).

Liquid bio-fertilizers, including Phosphate Solubilizing Bacteria (PSB), Potassium Solubilizing Bacteria (KSB), and Zinc Solubilizing Bacteria (ZSB), enhance soil health by promoting beneficial microbes and diminishing the reliance on chemical fertilizers (11). They enhance nutrient availability through mechanisms such as solubilization of phosphate, potassium and zinc, which are crucial for sustainable agriculture (12).

The rice-fish-*Azolla*-duck integrated farming system could be an effective alternative for transforming conventional systems to organic farming with a reduction in environmental degradation and can be a way forward for developing eco-friendly sustainable agricultural practices (13). Studies reveal that the adoption of diverse integrated farming system components, such as fish, *Azolla* and ducks in rice fields, enhances organic matter content and nutrient availability, greatly increasing rice yield compared to sole rice cultivation (14).

The rice-fish integrated farming systems improve soil productivity by enhancing nutrient supply. This approach reduces the need for synthetic fertilizers and promotes sustainable agricultural practices, ultimately benefiting farmers economically by lowering input costs while maintaining or improving crop yield (15). Rice-fish systems in Southeast Asia use fish to control both weeds and pests in rice paddies (16).

Azolla contributes to soil health by decreasing pH levels, enhancing microbial activity and improving nutrient recycling (17). Organic matter obtained from decomposed *Azolla* enriches the soil, promoting better water retention and reducing weed proliferation (18). The *Azolla* incorporated into the rice fields can lead to improved plant height, increased tiller numbers and ultimately attained higher grain yields (19). Thus, it boosts nitrogen uptake and enhances the overall agronomic efficiency of nitrogen use.

The integration of ducks with rice significantly improved grain productivity, simultaneously offering farmers supplementary income from duck production (meat and eggs) (20). Rice-based farming system approaches attained a higher value of rice equivalent yield and system indices than rice monoculture (21).

Soil applied nutrient losses through leaching, volatilization and runoff, which reduces the nutrient use efficiency (22). Consequently, the foliar application of nano urea at critical crop growth phases significantly improves nitrogen usage efficiency and reduces nutrient losses (23). Integrating farming systems included with nano urea is not only a novel approach but also a necessary evolution in agricultural practices. It enhances nutrient efficiency, promotes environmental sustainability, improves economic viability for farmers, builds resilience against climate change and fosters innovation in agricultural techniques (24).

Rice-fish-duck integrated farming system approach to the control of insect pests is now suggested for the establishment of a chemical-free crop protection option for organic farming (25). A farming system approach had better pest control efficiency and significantly reduced the population density of rice pests such as rice green leaf hoppers, brown plant hoppers, stem borers, leaf folders, whorl maggots and gall midge (26). Integration of fish and duck in rice cultivation noticed higher pest control efficiency, richness index and diversity index than in rice monoculture (27). This study evaluated the impact of integrated rice-based farming system approaches on the growth, yield and pest control of rice.

Materials and Methods

Experimental site

A field experiments were conducted at the South farm field of Tamil Nadu Rice Research Institute (TRRI), Aduthurai, Tamil Nadu during *late samba* (September to January), 2022-23 and 2023-24. The experimental field location is shown in (Fig. 1). It is located in Tamil Nadu's Cauvery Delta Agro-climatic Zone with the coordinates of 11° 01´ N and 79° 48´ E with an altitude of 19.5 meters above mean sea level. The experimental field has a clayey soil with a pH of 7.6, EC of 0.32 dS m^{-1}, low in organic carbon (0.20 %), medium in available nitrogen (275 kg ha^{-1}), high in available phosphorus (45 kg ha^{-1}) and medium in available potassium (324 kg ha^{-1}).

Experimental details

The experiments were carried out under a randomized block design with eleven rice-based integrated farming system approaches of nutrient management under rice cultivation and treatments described in (Table 1). In this experiment, the level of the treatments like fish, *Azolla* and the duck were chosen based on practical considerations from farmers and adapted to the specific agro-climatic region.

Experimental materials

As per the treatments, the green manure (dhaincha) local seed variety was sown at the rate of 40 kg ha^{-1}. The green manure was incorporated into the soil 45 days post-sowing (just prior to flowering) and permitted to decompose for 15

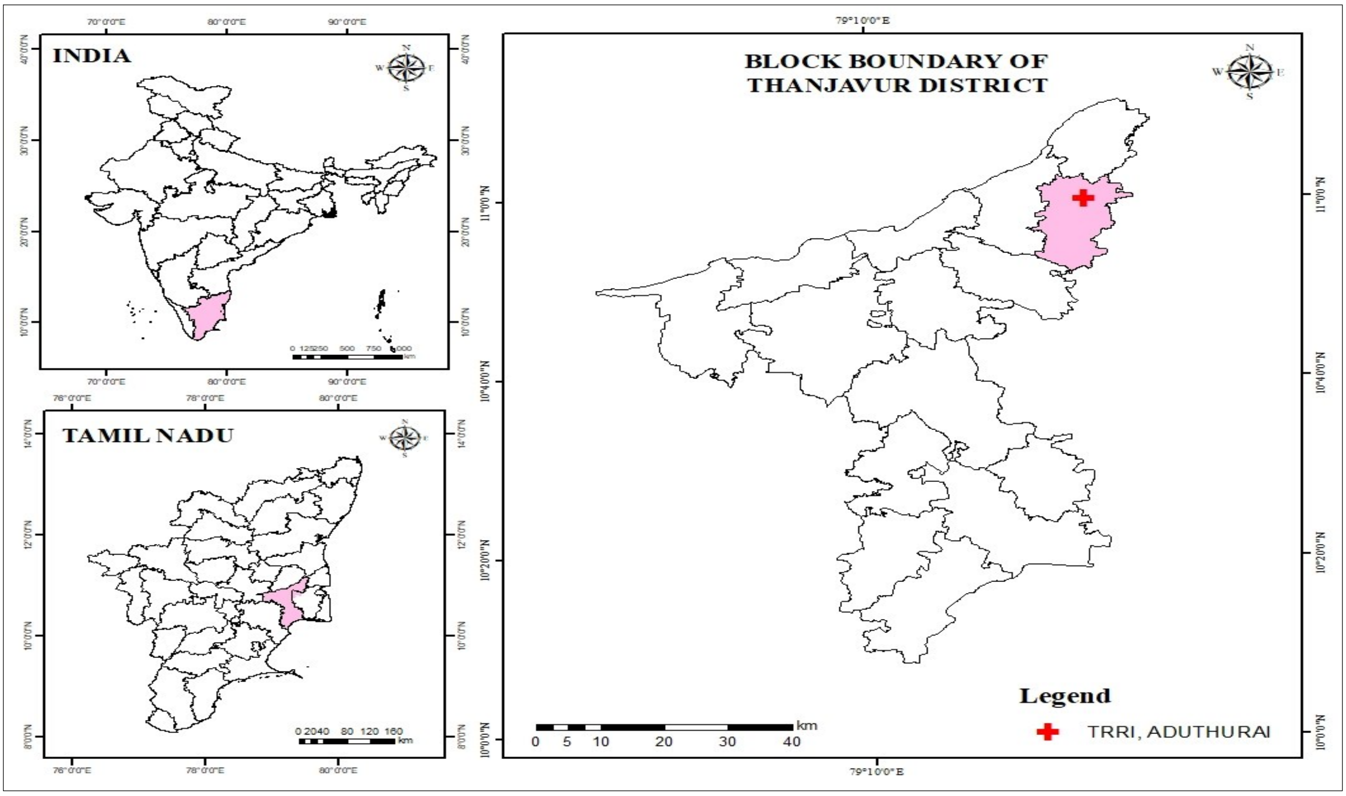

Fig 1. Location of the experimental field in the study.

Table 1: Treatments details of the experiment

T_1	No Green manure - Rice alone (RDF)
T_2	Green manure - Rice alone (PSB + KSB + ZSB)
T_3	T_2+Nano urea (foliar spray at 0.4%)
T_4	Green manure - Rice (PSB + KSB + ZSB) + Fish
T_5	T_4+Nano urea (foliar spray at 0.4%)
T_6	Green manure - Rice (PSB + KSB + ZSB) + Fish + Azolla
T_7	T_6+Nano urea (foliar spray at 0.4%)
T_8	Green manure - Rice (PSB + KSB + ZSB) + Fish + Duck
T_9	T_8+Nano urea (foliar spray at 0.4%)
T_{10}	Green manure - Rice (PSB + KSB + ZSB) + Fish + Azolla + Duck
T_{11}	T_{10}+Nano urea (foliar spray at 0.4%)

days. The liquid biofertilizers, including PSB, KSB and ZSB, were administered via seed treatment at 125 ml ha^{-1}, seedling dipping at 125 ml ha^{-1} and soil application at 500 ml ha^{-1} at basal (before transplanting), 30 and 60 DAT, adhering only to organic methodologies. The various methods of liquid biofertilizer application improve the availability of essential nutrients such as phosphorus, potassium and zinc in the soil. Nano urea foliar spray (0.4 %) twice at 20 DAT and one week before flowering was done in the respective treatments. The foliar spray promotes sustainable farming practices by reducing dependence on chemical fertilizers, enhancing nutrient use efficiency and minimizing environmental impacts. Fish fingerlings of GIFT-Genetically improved farmed tilapia (*Oreochromis niloticus*) and roopchand (*Pampus chinensis*) each at 2000 no's ha^{-1} were released to the rice field at 15 DAT. *Azolla* inoculum at 250 kg ha^{-1} was applied at 10 DAT and it was allowed to grow up to 45 days and then *Azolla* was incorporated. Ducklings of 30 days old at 250 no's ha^{-1} were released to the rice field at 20 DAT. The ducks were kept in rice fields from the up to the flowering stage from the primary tillering stages. The rice variety ADT 54 was used as a test crop. 25 days old seedlings were transplanted manually with a spacing of 20 cm × 15 cm. The recommended dose of fertilizer 150:50:50 kg ha^{-1} of N: P_2O_5: K_2O was adopted only in the inorganic plot. No herbicide and pesticide was applied in rice-based farming system approaches.

Observation taken

The physiological parameters were observed during the vegetative stage of rice. Observation of growth and yield attributes of rice was recorded at the harvest stage. Grain yield and straw yield of rice were recorded from a net plot area and expressed in kg ha^{-1} at 14 % moisture. The different farming system indices, *viz.* rice equivalent yield, system indices, sustainability performance, relative efficiency (%) and resource use efficiency (%) were calculated by as per methods suggested by (28, 29). The insect-pest and predator populations were observed during the vegetative stage of crop growth at randomly selected 10 no. of hills within treatments. The richness index, diversity index and evenness indices of rice pests and predators were calculated as per method followed by (30, 31).

Statistical methods

The experimental data were analyzed statistically as per the standard method (32). Statistical significance was tested by the F test at a critical difference (CD) of 0.05 level of probability. In correlation study, the growth, physiological and yield attributes are correlated based on their data variability and treatment effect on yield. In principal component analysis, the selection of parameters such as green manure, fish, *Azolla* and duck-based treatments are justified by their synergistic effects on pest management through biological control and biodiversity enhancement. The Corrplot and Principal component analysis (PCA) were performed using R studio (Facto extra package software version 3.6.0).

Results and Discussion

Effect of integrated rice-based farming system approaches on growth and physiological parameters of rice

The experimental findings revealed that the inclusion of farming system components had a significant impact on the growth and physiological parameters of rice. The plots treated with fish, *Azolla*, duck and liquid biofertilizer and supplemental application of nano urea foliar spray (T_{11}) exhibited increased plant height (131.52 cm), LAI (5.85), tillers (548 m^{-2}) and dry matter (1470 g m^{-2}). Similarly, T_{11} resulted in higher SPAD (42.60), leaf area (41.96 cm^2), leaf area ratio (255.65cm^2 g^{-1}), leaf weight ratio (0.455 g g^{-1}), specific leaf ratio (154.28 cm^2 g^{-1}) and specific leaf weight (0.130 g cm^{-2}). However, conventional (RDF) (T_1) had lower values on rice growth and physiological parameters (Table 2).

The combined use of green manure, *Azolla*, fish, ducks, liquid biofertilizer and nano urea resulted in an extended availability of nutrients in an absorbable form, facilitating enhanced growth and physiological parameters in the rice crop. *Azolla*, an aquatic fern with nitrogen-fixing capabilities, helps enrich the soil by supplying essential nutrients. *Azolla* can increase nitrogen availability by 30 to 60 kg ha^{-1}, leading to increased plant height, a greater number of tillers and ultimately, higher grain output (33). The results align with previous findings, which demonstrated that the decomposition of Azolla enhances nutrient availability, particularly in nitrogen-deficient soils (34). This diminished reliance on chemical fertilizers renders it a cost-effective and sustainable option for rice growing. Incorporating Azolla as green manure in rice fields has been shown to effectively enhance the leaf area index (LAI), a crucial factor in determining crop productivity (35). An increased LAI means that rice plants can capture more sunlight, resulting in improved photosynthetic efficiency. This improvement in light interception enables better energy conversion, promoting faster growth and ultimately leading to higher yields. Similarly, (36) also reported that the provision of *Azolla* and organic manure had increased the growth and physiological parameters of rice by increasing nutrient availability. These findings are consistent with similar results observed in rice (37).

The continuous movement of ducks and fish in the rice field enhances nutrient availability, resulting in enhanced plant development and improved physiological traits in rice. The obtained results align with the outcomes of the experiment by Wang *et al.* (38), who reported that rearing of fish and ducks in rice fields contribute to nutrient cycling by enhancing soil fertility, which in turn promotes better rice plant growth, leaf area index and leaf area and leads to increased productivity. Incorporating ducks and fish into rice cultivation systems has been shown to enhance physiological traits such as internodal length and overall biomass in rice plants (39). The presence of these animals promotes nutrient cycling and improves soil aeration due to their constant movement and natural behavior in the fields. This integration ultimately creates a more supportive environment for rice growth, resulting in healthier plants with improved growth characteristics. Similarly, the droppings of ducks and fish, in the presence of Azolla, have been shown to significantly enhance the growth and physiological parameters of rice (40). These findings are consistent with results observed in rice (41,42).

Additionally, the application of liquid biofertilizer in seed treatment and seedling dipping accelerates internodal length, which increases crop growth by promoting cell division and enlargement. The obtained results align with findings from experiments showing that treating seeds with liquid biofertilizers significantly boosts plant height and internodal length in various crops (43). These improvements are attributed to enhanced nutrient availability and increased microbial activity within the rhizosphere, which supports plant growth by improving nutrient uptake and soil health. Similarly, treating seeds with liquid biofertilizers has been shown to boost seedling vigor and promote more robust root development (44). This enhanced root system supports increased internodal length and leads to overall improved crop performance, likely due to better nutrient absorption and root-zone microbial activity. These findings are consistent with similar results observed in rice (45).

The application of foliar spray effectively induced the photosynthetic activity and nutrient uptake, which promoted

Table2: Effect of integrated rice-based farming system approaches on growth and physiological parameters of rice (Mean of 2022 and 2023)

Treatments	Growth parameters				Physiological parameters					
	Plant height (cm)	LAI	No. of tillers m^{-2}	DMP (g m^{-2})	SPAD	LA (cm^2)	LAR (cm^2 g^{-1})	LWR (g g^{-1})	SLA (cm^2 g^{-1})	SLW (g cm^{-2})
T_1	115.53	3.54	341	1037	29.06	36.18	233.56	0.285	149.94	0.064
T_2	118.01	3.95	369	1109	30.68	36.82	236.23	0.306	150.42	0.071
T_3	119.39	4.02	378	1119	31.96	37.36	237.28	0.320	150.71	0.073
T_4	121.72	4.42	403	1197	33.53	38.05	240.09	0.342	151.30	0.084
T_5	122.40	4.49	415	1209	34.86	38.51	241.82	0.355	151.60	0.086
T_6	124.98	4.89	454	1281	36.42	39.15	244.55	0.376	152.18	0.097
T_7	125.60	4.94	469	1295	37.68	39.67	246.14	0.390	152.57	0.102
T_8	127.95	5.35	492	1364	39.27	40.34	248.88	0.410	153.09	0.110
T_9	128.31	5.40	504	1381	40.13	40.86	250.71	0.425	153.42	0.115
T_{10}	130.64	5.80	530	1450	41.77	41.52	253.42	0.446	153.96	0.126
T_{11}	131.52	5.85	548	1470	42.60	41.96	255.65	0.455	154.28	0.130
SE.d	**1.11**	**0.185**	**9.97**	**1.11**	**0.74**	**0.292**	**1.264**	**0.009**	**0.228**	**0.0034**
CD (p=0.05)	**2.31**	**0.386**	**20.80**	**2.31**	**1.55**	**0.612**	**2.636**	**0.018**	**0.476**	**0.0070**

LAI = Leaf area index; DMP= Dry matter production; SPAD = Soil plant analysis development; LA = Leaf area; LAR = Leaf area ratio; LWR = Leaf weight ratio; SLA = Specific leaf area; SLW = Specific leaf weight rice growth by enhancing nutrient availability during critical growth stages. Optimized utilization of nano urea through foliar spray has been shown to significantly enhance rice growth characteristics (46). Similarly, nano urea foliar application has been suggested to enhance growth parameters in rice, possibly due to excess nitrogen promoting cell elongation and increasing the photosynthetic rate (47). These findings are consistent with similar results observed in rice (48).

Effect of integrated rice-based farming system approaches on yield attributes, yield and economics of rice

The practices of GM- Rice (PSB + KSB + ZSB) + fish+ *Azolla*+ duck along with nano urea foliar spray at 0.4 % (T_{11}) in rice cultivation was recorded higher number of panicles m^{-2} (457 m^{-2}), panicle length (31.26 cm), panicle weight (3.94 g) and filled grains (331.5 $panicle^{-1}$). Lower yield traits were observed in conventional rice (RDF) (Table 3). The significantly positive effects on yield parameters were achieved from the inclusion of farming system components like *Azolla*, fish and duck and nutrient sources like liquid biofertilizer and nano urea, leading to increased tiller production, panicle characteristics and overall grain yield of rice. These findings are consistent with similar results observed in rice as reported by (49).

The superior performance of rice is primarily attributed to the surplus nitrogen obtained from *Azolla* incorporation, nutrients derived from fish and duck excreta, as well as those acquired from liquid biofertilizer and nano urea, which enhanced nutrient uptake and improved nutrient use efficiency. Enhanced production has also been observed with the implementation of long-term organic fertilization in rice cultivation (50). This may result from improved nutrient uptake and interaction with the soil microbial community. The increased availability and absorption of nutrients from several sources, including green manure, *Azolla*, fish, ducks, liquid biofertilizers and nano urea, have improved efficiency and elevated yield parameters in rice. This may result from the regular distribution of nutrients via *Azolla* incorporation and the movement of fish and ducks over the field, which enhances the soil rhizosphere zone and promotes the efficient transfer of nutrients to the crops. This combined effect enhances crop growth parameters and yield of rice, aligning with previous studies by Zhen *et al.* (51).

The rice-based integrated farming technique greatly impacted the grain and straw production of rice (Table 3). The highest grain yield of 6063 kg ha^{-1} was recorded in GM- Rice (PSB + KSB + ZSB) + fish + *Azolla* + duck along with nano urea foliar spray at 0.4 %, which was at par with GM- Rice (PSB + KSB + ZSB) + fish + *Azolla* + duck. The comprehensive integration of agricultural elements such as *Azolla*, fish and ducks, together with nutrient sources including green manure and liquid biofertilizer, has markedly impacted growth and production parameters, greatly augmenting rice grain yield. The obtained results align with the outcomes of the experiment by Islam *et al.* (52), who demonstrated that the integration of *Azolla*, fish and duck in rice cultivation potentially increased rice yield more than rice monoculture. The excreta of fish and ducks have been shown to contribute nutrients and organic carbon to the soil, thereby improving the duration of nitrogen availability throughout the growth cycle of rice crops, significantly impacting growth and yield parameters and resulting in increased grain yield (53). These findings are consistent with similar results observed in previous studies (54). Similarly, a higher straw yield has been recorded in the rice-fish-Azolla-duck system (55). The presence of macronutrients in duck and fish excreta may enhance crop development and increase photosynthate, greatly affecting growth parameters and resulting in a greater straw yield in rice. These findings are consistent with similar results reported in previous studies (56).

In economics, the result indicated that higher gross return (458879 ₹ ha^{-1}) and net return (321777 ₹ ha^{-1}) were also highest in T_{11}. The cost of input and treatment maintenance costs are described in (Annexures I and II). The highest benefit-cost ratio (BCR) (3.37) was obtained in T_{10}. The results of the present study were in line with earlier findings of Che *et al.* (57). The adoption of fish and ducks into rice fields provides farmers with additional income sources beyond rice production. Sales of fish, ducks and duck eggs create a more diversified and dependable revenue stream for farmers. These findings underscore the financial advantages of integrated rice-fish

Table 3. Effect of integrated rice-based farming system approaches on yield attributes, yield and economics in rice (Mean of 2022 and 2023)

Treatments	Yield attributes				Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Economics			
	Panicle m^{-2}	Panicle weight (g)	Panicle length (cm)	Filled grains $panicle^{-1}$			Cost of cultivation (₹ ha^{-1})	Gross returns (₹ ha^{-1})	Net returns (₹ ha^{-1})	B:C ratio
T_1	284	2.90	23.62	266.6	4175	5421	37942	88911	50969	2.34
T_2	305	3.08	24.86	275.3	4537	5931	33703	96661	62959	2.87
T_3	311	3.11	25.02	278.7	4643	6053	35503	98903	63400	2.79
T_4	330	3.30	26.27	288.9	4505	5871	92533	242867	150334	2.62
T_5	346	3.33	26.51	293.2	4617	5999	94333	245225	150893	2.60
T_6	365	3.48	28.03	301.5	4975	6504	94633	252900	158267	2.67
T_7	379	3.51	28.38	305.8	5101	6654	96433	255560	159127	2.65
T_8	403	3.66	29.60	315.0	5436	7054	133203	445580	312378	3.35
T_9	418	3.69	29.87	319.3	5578	7223	135003	448579	313577	3.32
T_{10}	440	3.88	31.09	327.3	5908	7625	135303	455581	320279	3.37
T_{11}	457	3.94	31.26	331.5	6063	7813	137103	458879	321777	3.35
SE.d	**8.52**	**0.062**	**0.554**	**2.12**	**156.8**	**212.9**	**-**	**-**	**-**	**-**
CD (p=0.05)	**17.77**	**0.130**	**1.157**	**4.43**	**327.1**	**446.4**	**-**	**-**	**-**	**-**

* Economics was not statistically calculated

Annexure I: Cost of input used on experiments

S.No.	Cost	Unit	Cost (₹)
1.	Dhaincha seed	kg	₹ 65
2.	Hitachi (fish trench digging)	Per hour	₹ 1050
3.	Tractor	Per hour	₹ 550
4.	Rice seed	kg	₹ 37
5.	Urea	kg	₹ 5.93
6.	SSP	kg	₹ 8.80
7.	MOP	kg	₹ 19
8.	$ZnSo_4$	kg	₹ 35
9.	Liquid biofertilizer	Per litre	₹ 350
10.	*Azolla*	kg	₹ 10
11.	Fish	Per fingerlings	₹ 3
12.	Duck	Per ducklings	₹ 125
13.	Rice bran	kg	₹ 1
14.	Groundnut oil cake	kg	₹ 20
15.	Nano urea liquid	Per litre	₹ 480
16.	Carbendazim	kg	₹ 500
17.	Eros	kg	₹ 237.5
18.	Flubendiamide	Per litre	₹ 750
19.	Propiconazole	Per litre	₹ 620
20.	Beauveria bassiana	kg	₹ 135
21.	Bacillus subtilis	kg	₹ 135

systems over conventional monoculture approaches, suggesting a promising alternative for enhancing farm income stability. Practicing rice-fish culture has been shown to result in over a 50% increase in net income compared to traditional rice monoculture (58). The lower grain and straw yield obtained with the application of RDF alone was the reason for the lesser net return and BCR. Without supplementary inputs or complementary practices, the nutrient supply may fall short of what is needed for optimal crop growth, thereby restricting overall productivity and profitability. These findings are consistent with similar results observed by Singh S, Singh (59). When additional inputs or complementary practices are not employed, the nutrient availability may fall short of what is required for optimal crop growth.

Effect of integrated rice-based farming system approaches on farming system indicators of rice

The different rice-based integrated farming system approaches caused significant variations in the farming system indicator of rice (Table 4). Among the various rice-based integrated farming system approaches, the highest REY (22.5 t ha^{-1}), system productivity (61.79 kg ha^{-1} day^{-1}), system profitability (881.58 ₹ $ha^{-1}day^{-1}$), sustainable yield index (0.881), sustainable value index (0.658), relative production efficiency (440.3 %), relative economic efficiency (411.1 %), employment generation (171 man days yr^{-1}) and resource use efficiency of labour (7.93 kg hr^{-1}) was recorded in T_{11}. The fertilizer use efficiency was recorded as higher in control (T_1). The inclusion of *Azolla*, fish and duck in rice cultivation effectively increased the system indices, sustainability performance, relative efficiency and diversified income than conventional. The results obtained are consistent with experiments showing that the application of farming system components in rice cultivation markedly enhances rice grain production, system profitability, return on income and resource usage efficiency compared to conventional methods (60). This approach also improves the yield of fish, ducks and duck eggs compared to the normal integrated farming system (60). These findings align with similar results reported in previous studies (61).

Annexure II: Cost of maintenance (only for nutrient management approaches in treatment wise)

Treatments	Organic components		Farming system components			Inorganic components		Total
	Green manure	Liquid bio fertilizer	Fish	Azolla	Duck	Nano urea	Fertilizer	
T_1	-	-	-	-	-	-	8342	8342
T_2	3318	2738	-	-	-	-	-	6056
T_3	3318	2738	-	-	-	1800	-	7856
T_4	3318	2738	53580	-	-	-	-	59636
T_5	3318	2738	53580	-	-	1800	-	61436
T_6	3318	2738	53580	2100	-	-	-	61736
T_7	3318	2738	53580	2100	-	1800	-	63536
T_8	3318	2738	53580	-	40670	-	-	100306
T_9	3318	2738	53580	-	40670	1800	-	102106
T_{10}	3318	2738	53580	2100	40670	-	-	102406
T_{11}	3318	2738	53580	2100	40670	1800	-	104206

Table 4: Effect of integrated rice-based farming system approaches on farming system indicators of rice (Mean of 2022 and 2023)

Treatments	REY (t ha^{-1})	System indices		Sustainability Performance		Relative efficiency		EG (man-days yr^{-1})	Resource use efficiency	
		System productivity (kg $ha^{-1}day^{-1}$)	System profitability (₹ $ha^{-1}day^{-1}$)	SYI	SVI	RPE (%)	REE (%)		LRUE (kg hr^{-1})	FRUE (kg kg^{-1})
T_1	4.17	11.44	139.64	0.838	-0.184	0.0	0.0	87	6.00	12.85
T_2	4.54	12.43	172.49	0.849	-0.146	8.7	23.5	84	6.75	1.55
T_3	4.64	12.72	173.70	0.853	-0.145	11.2	24.4	86	6.75	1.58
T_4	11.85	32.47	411.87	0.848	0.125	183.9	138.8	132	7.62	1.36
T_5	11.96	32.77	413.40	0.851	0.127	186.5	139.7	134	7.61	1.39
T_6	12.32	33.75	433.61	0.860	0.150	195.1	151.4	139	7.67	1.29
T_7	12.45	34.10	435.96	0.863	0.153	198.1	152.7	141	7.67	1.32
T_8	21.93	60.07	855.83	0.871	0.629	425.2	396.2	162	7.87	1.44
T_9	22.07	60.46	859.11	0.873	0.633	428.6	398.1	164	7.88	1.47
T_{10}	22.40	61.36	877.48	0.879	0.653	436.5	408.7	169	7.90	1.36
T_{11}	22.55	61.79	881.58	0.881	0.658	440.3	411.1	171	7.93	1.39

REY = Rice equivalent yield; SYI = System yield index; SVI = System value index; RPE = Relative production efficiency; REE = Relative economic efficiency; EG = Employment generation; LRUE = Labour resource use efficiency; FURE = fertilizer resource use efficiency

Effect of integrated rice-based farming system approaches on insect-pest and predator population, richness, diversity and evenness indices of rice

The different rice-based integrated farming system approaches caused significant variations in the pest population, richness, diversity and evenness indices of rice. The practices of GM- Rice (PSB + KSB + ZSB) + fish + *Azolla* + duck along with nano urea foliar spray at 0.4 % recorded the lowest value of rice pest population and highest value of predators (Fig.2) and noticed a higher value of insect pest control efficiency (52.24 %) (Table.5). The simultaneous rearing of fish and ducks in rice cultivation effectively diminished hazardous insect-pest populations, which is closely connected with pest incidences. Ducks contribute to pest management in rice paddies by foraging on insects and weeds, effectively reducing the population of damaging species such as the brown planthopper and green leafhopper (62). This natural method of pest control helps to limit the need for chemical pesticides, supporting a more sustainable and balanced ecosystem within the rice field. Their foraging behavior effectively suppresses both pests and weeds, promoting healthier rice plants and an eco-friendlier farming approach. Similarly, Teng *et al.* (63) also demonstrated that rearing ducks in rice fields can effectively reduce pest incidence. These findings are consistent with similar results observed by Li *et al.* (64).

Similarly, the highest value of richness indices *viz.,* Margalef index (6.542), Menhinick index (4.425) and diversity indices *viz.,* Brillouin index (3.613), Simpson's index (1.369) were also recorded in T_{11}. Some other diversity indices like the Shannon-Weiner index (1.858) and evenness indices *viz.,* Pielou index (0.893) and Smiths index (4.947) were recorded higher in T_7 (Table.5). The adoption of fish, duck and *Azolla* are predominantly affected the pest ecosystem and their survival mechanism. Consequently, an increased predator population and a diminished insect population resulted in the highest indices of richness, diversity and evenness in rice farming. These findings are consistent with similar results observed by Liu *et al.* (65).

Correlation of growth, physiological and yield attributes with grain yield of rice

The correlation matrix plot (Fig.3) shows the pairwise correlations between different agronomic traits (variables) related to crop yield and growth characteristics. This correlation matrix indicates a high degree of association among the agronomic traits studied, with most variables showing strong positive correlations with grain yield. Key yield contributors appear to be panicle density, biomass production, filled grain count, panicle weight and chlorophyll content. Notably, the panicle length of rice exhibited strong positive correlations but orderwise lower contributes to yield. This suggests potential associations between growth, physiological and yield attributes and their predominant contributions to observed yield across the farming system components practiced treatments.

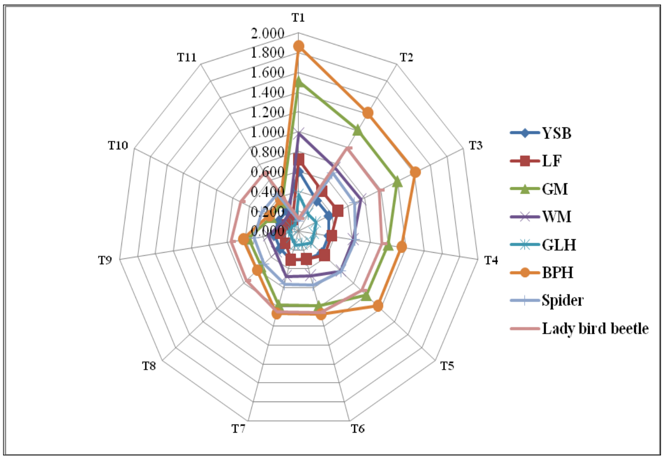

Fig 2. Insect-pest and predators population of rice (mean of 2022 and 2023)

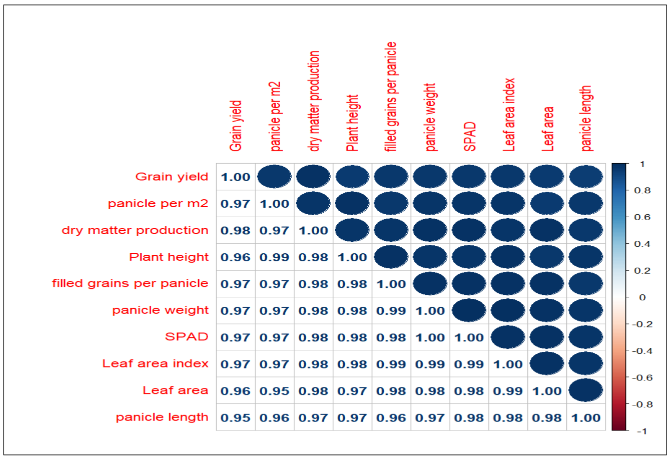

Fig 3. Correlation of growth, physiological and yield attributes with grain yield of rice (mean of 2022 and 2023)

Table 5: Effect of integrated rice-based farming system approaches on richness, diversity and evenness indices of rice pest and predator (Mean of 2022 and 2023)

Treatments	IPCE (%)	Richness indices		Diversity indices			Evenness indices	
		D_{Mg}	D_{Mn}	H_B	H'	D_{sim}	J	SE
T_1	0.00	3.274	2.800	0.945	1.617	0.914	0.778	3.360
T_2	15.77	3.322	2.837	0.586	1.840	0.989	0.885	4.317
T_3	15.39	3.320	2.835	0.584	1.840	0.988	0.885	4.292
T_4	23.30	3.641	3.071	0.862	1.846	1.026	0.888	4.519
T_5	22.82	3.636	3.067	0.856	1.846	1.025	0.888	4.491
T_6	31.40	4.106	3.371	1.286	1.854	1.083	0.892	4.900
T_7	31.06	4.111	3.374	1.284	1.858	1.084	0.893	4.947
T_8	41.84	4.978	3.831	2.132	1.851	1.187	0.890	4.335
T_9	41.05	4.943	3.815	2.093	1.854	1.183	0.892	4.429
T_{10}	52.23	6.520	4.418	3.595	1.821	1.364	0.876	3.535
T_{11}	52.24	6.542	4.425	3.613	1.823	1.369	0.877	3.574

IPCE = insect pest control efficiency; D_{Mg} = Margalef richness index; D_{Mn} = Menhinick index; HB= Brillouin index; H'= Shannon-Weiner index; D_{sim} = Simpson's index; J = Pielou index; SE = Smiths evenness index

Principal component analysis of the pest and predator population of rice under different integrated farming system approaches

The principal component biplot representation is displayed in (Fig.4). The first (PC_1) and second (PC_2) principal components explained 61.8 % and 38.2 % of the total variance, respectively. It can be used to explore the relationships of control and organic system treatments associated with pests and predators. The control treatment is positioned far left, aligning somewhat with the "pest" vector. This may imply that the control treatment has a stronger association with higher pest populations or conditions favorable for pests. The organic treatments (organic and farming components) are clustered around the center and on the right side, closer to the "predator" vector. This suggests that these organic treatments may support conditions that favor predators or have a lower association with pests. Different organic treatments are distributed differently, with some (e.g., ORGFA+N, ORGFAD) appearing further from the origin. This variation indicates that these specific treatments might have different effects on pest and predator populations. Overall, the graphical representation revealed significant differences in the farming system adopted treatments, providing insights into the impacts of adaptation of fish, *Azolla* and duck on pest and predator populations of the observed traits. These findings are consistent with similar results reported in previous studies (66).

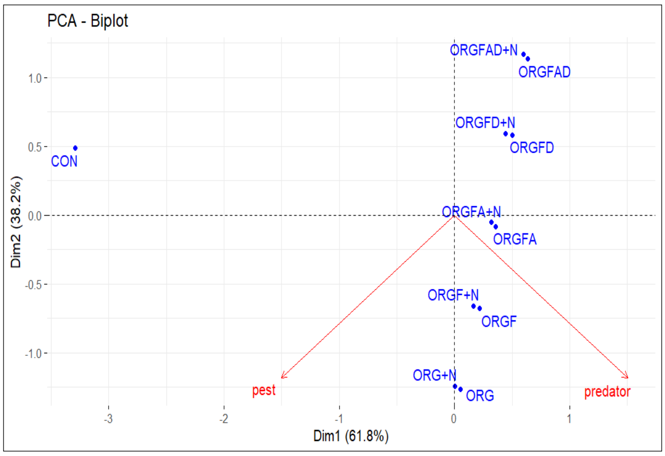

Fig 4. Principal component analysis of the pest and predator population of rice under different integrated farming system approaches (mean of 2022 and 2023).

CON denotes conventional; ORG designates organic; ORGF indicates organic with fish; ORGFA represents organic with fish and *Azolla*; ORGFD designates organic with fish and duck; ORGFAD indicates organic with fish, *Azolla* and duck; N denotes foliar spray of nitrogen.

Conclusion

From the two-year field investigation, results confirmed that integrating fish, *Azolla* and duck with rice crops significantly increased the growth, physiological and yield parameters and grain and straw yield as well in RFAD system. In addition, the highest farming system indicators, richness index, diversity index and evenness index were also observed in rice integration with fish, *Azolla* and duck systems than in rice monoculture. Hence, the adoption of rice-based integrated farming system with enterprises of fish, *Azolla* and duck system can be recommended to obtain higher productivity and profitability in the Cauvery Delta Zone of Tamil Nadu. The rice-fish-*Azolla*-duck farming system not only enhances productivity and income in the Cauvery Delta Zone, but also presents a viable model for the Northeastern Zone, Southern Zone and High Rainfall Zone in Tamil Nadu. By leveraging local resources and adapting practices to agro-climatic conditions, farmers across that above-mentioned zone could benefit from this innovative approach to agriculture. In further, integrating mushrooms, cover crops, fruit crops, flower crops, vegetable crops and agroforestry into the rice-fish-*Azolla*-duck farming system can significantly enhance its productivity and sustainability based on agro-climatic conditions. This approach fosters a more diverse ecosystem that leverages natural processes for pest control, nutrient cycling and soil health improvement, enabling farmers to achieve greater resilience against environmental challenges while increasing their economic viability.

Acknowledgements

We would like to express gratitude to the Tamil Nadu Rice Research Institute for funding this research work and the Department of Agronomy, TNAU, Coimbatore. Special thanks are extended to the Chairman-Director (TRRI) and advisory members for their valuable feedback and constructive suggestions on the manuscript.

Authors' contributions

RR carried out the experiment, recorded observations, analyzed the data and prepared the original draft. KS contributed to the conceptualization of the study, supervised the work, secured funding and participated in writing, review and editing. SE, RM, KM and TS assisted in summarizing and revising the manuscript.

Compliance with ethical standards

Conflict of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical issues: None

References

1. IndiaStat. Selected state/season-wise area, production and productivity of rice in India (2023-2024). 2023 [cited 2024 Nov 15]. https://www.indiastat.com/table/agriculture/ selected-state-season-wise-area-production product/1456796
2. Rakholia R, Tailor J, Prajapati M, Shah M, Saini JR. Emerging technology adoption for sustainable agriculture in India-A pilot study. J Agric Food Res. 2024:101238. https://doi.org/10.1016/ j.jafr.2024.101238
3. Bashir MA, Liu J, Geng Y, Wang H, et al. Co-culture of rice and aquatic animals: An integrated system to achieve production and environmental sustainability. J Clean Prod. 2020; 249:119310. https://doi.org/10.1016/j.jclepro.2019.119310
4. Ibrahim LA, Shaghaleh H, Abu-Hashim M, Elsadek EA, Hamoud YA. Exploring the integration of rice and aquatic species: Insights from global and national experiences. Water. 2023;15 (15): 2750. https://doi.org/10.3390/w15152750
5. Shanmugam PM, Sangeetha SP, Prabu PC, Varshini SV, et al.

Crop–livestock-integrated farming system: A strategy to achieve synergy between agricultural production, nutritional security and environmental sustainability. Front Sustain Food Syst. 2024;8:1338299. https://doi.org/10.3389/fsufs.2024.1338299

6. Wawire AW, Csorba Á, Tóth JA, Michéli E, et al. Soil fertility management among smallholder farmers in Mount Kenya East region. Heliyon. 2021;7(3):e06488 https://doi.org/10.1016/j.heliyon.2021.e06488

7. Thakuria D, Talukdar NC, Goswami C, Hazarika S, et al. Evaluation of rice-legume-rice cropping system on grain yield, nutrient uptake, nitrogen fixation, and chemical, physical and biological properties of soil. Biol Fertil. Soils. 2009;45: 237-51.

8. Zhu Z, Ge T, Liu S, Hu Y, et al. Rice rhizodeposits affect organic matter priming in paddy soil: the role of N fertilization and plant growth for enzyme activities, CO2 and CH4 emissions. Soil Biol. Biochem. 2018;116:369-77. https://doi.org/10.1016/j.soilbio.2017.11.001

9. Wang J, Zhao Y, Zhang J, Zhao W, et al. Nitrification is the key process determining N use efficiency in paddy soils. J Plant Nutr Soil Sci. 2017;180(6):648-58.

10. Dabin Z, Pengwei Y, Na Z, Changwei Y, et al. Contribution of green manure legumes to nitrogen dynamics in traditional winter wheat cropping system in the Loess Plateau of China. Eur J Agron. 2016;72:47-55. https://doi.org/10.1016/j.eja.2015.09.012

11. Borah A, Das H. Liquid bio-fertilizers: a replacement tool for chemical fertilizer. Just Agriculture. 2023;3(12):230-31.

12. Bouizgarne B, Bakki M, Boutasknit A, Banane B, et al. Phosphate and potash solubilizing bacteria from Moroccan phosphate mine showing antagonism to bacterial canker agent and inducing effective tomato growth promotion. Front Plant Sci. 2023;14: 970382. https://doi.org/10.3389/fpls.2023.970382

13. Bhagat R, Walia SS, Sharma K, Singh R, et al. The integrated farming system is an environmentally friendly and cost-effective approach to the sustainability of agri-food systems in the modern era of the changing climate: A comprehensive review. Food Energy Secur. 2024;13(1): 534.

14. Hu L, Zhang J, Ren W, Guo L, et al. Can the co-cultivation of rice and fish help sustain rice production?. Sci Rep. 2016;6(1):28728. https://doi.org/10.1038/srep28728

15. Wang C, Yang Q, Zhang C, Li X, et al. Rice-fish-duck system regulation of soil phosphorus fraction conversion and availability through organic carbon and phosphatase activity. Front Environ Sci. 2022;10:979234. https://doi.org/10.3389/fenvs.2022.979234

16. Meng S, Hu G, Li D, Qiu L, et al. Research progress of rice-fish integrated farming. Agric Biotechnol. 2018;7(4):129-35.

17. Adhikari K, Bhandari S, Acharya S. An overview of azolla in rice production: a review. Reviews in Food and Agriculture. 2020;2 (1):04-8. http://doi.org/10.26480/rfna.01.2021.04.08

18. Kumar A, Saharan BS, Parshad J, Gera R, et al. Revolutionizing Indian agriculture: the imperative of advanced biofertilizer technologies for sustainability. Discov Agric. 2024; 2(1): 24.

19. Yao Y, Zhang M, Tian Y, Zhao M, et al. Azolla biofertilizer for improving low nitrogen use efficiency in an intensive rice cropping system. Field Crops Res. 2018;216:158-64. https://doi.org/10.1016/j.fcr.2017.11.020

20. Mofidian S, Sadeghi SM. Evaluation of integrated farming of rice and duck on rice grain yield in gilan, Iran. Acta Univ Agric Silvic Mendelianae Brun. 2015;63(4):1161-168.

21. Mishra A, Mohanty RK. Productivity enhancement through rice-fish farming using a two-stage rainwater conservation technique. Agric Water Manag. 2004;67(2):119-31. https://doi.org/10.1016/j.agwat.2004.02.003

22. Jadon P, Selladurai R, Yadav SS, Coumar MV, et al. Volatilization and leaching losses of nitrogen from different coated urea fertilizers. J Soil Sci Plant Nutr. 2018;18(4):1036-47.

23. Ravi MV, Rao KN, Vishwanath J, Umesh MR. Effect of nano nitrogen and nano zinc on growth and yield of paddy in paddy-paddy cropping system. International Int J Environ Clim Chang. 2023;13(6):244-58. https://doi.org/10.9734/ijecc/2023/v13i61820

24. Prasad R, Bhattacharyya A, Nguyen QD. Nanotechnology in sustainable agriculture: recent developments, challenges and perspectives. Front Microbiol. 2017;8:1014. https://doi.org/10.3389/fmicb.2017.01014

25. Munyuli MB, Luther GC, Kyamanywa S. Effects of cowpea cropping systems and insecticides on arthropod predators in Uganda and Democratic Republic of the Congo. Crop Prot. 2007;26(2):114-26.

26. Xu F. Study on the economic and ecological benefits of rice-fish-duck production mode. Poultry Ind. 2010;21:45-6.

27. Widyaningrum I. Pest and weed suppressive mechanisms in complex rice system at Malang, East Java, Indonesia. PhD dissertation: Wageningen University.

28. Singh JP, Salaria A, Singh K, Gangwar B. Diversification of rice-wheat cropping system through inclusion of basmati rice, potato and sunflower in Trans-Gangatic plains. Journal Farming Systems Research and Development. 2005; 11(1):12-8.

29. Kumari A, Kumar R, Sinha T, Kumari S, Kumar R. Effect of diversification on system productivity and profitability under north Bihar condition. Int J Environ Clim Chang. 2023; 13 (10): 3928-32. https://doi.org/10.9734/ijecc/2023/v13i103067

30. Mukherjee P, Khan MM. Influence of rice growth stages and neighboring plants on relative abundance and diversity indices of arthropod insect pests and natural enemies in rice ecosystem. Bangladesh J Entomol. 2014;24(1):75-89.

31. Khan MM. Abundance and diversity of insect pests and natural enemies in coastal rice habitat. Bangladesh J Entomol. 2013;23 (1):89-104.

32. Gomez KA. Statistical procedures for agricultural research. John New York: Wiley and Sons. 1984.

33. Da Silva ME, Mathe LO, Van Rooyen IL, Brink HG, et al. Optimal growth conditions for Azolla pinnata R. brown: impacts of light intensity, nitrogen addition, pH control and humidity. Plants. 2022;11(8):1048. https://doi.org/10.3390/plants11081048

34. Marzouk SH, Semoka JM, Amuri NA, Tindwa HJ. Rice straw incorporation and Azolla application improves agronomic nitrogen-use-efficiency and rice grain yields in paddy fields. Front Soil Sci. 2024;4:1378065. https://doi.org/10.3389/fsoil.2024.1378065

35. Brouwer P, Schluepmann H, Nierop KG, Elderson J, Bijl PK, et al. Growing Azolla to produce sustainable protein feed: the effect of differing species and CO_2 concentrations on biomass productivity and chemical composition. J Sci Food Agric. 2018;98(12):4759-68. https://doi.org/10.1002/jsfa.9016

36. Seleiman MF, Elshayb OM, Nada AM, El-leithy SA, et al. Azolla compost as an approach for enhancing growth, productivity and nutrient uptake of *Oryza sativa* L. Agronomy. 2022;12 (2):416. https://doi.org/10.3390/agronomy12020416

37. Darthiya M, Mude A, Kommireddy P. Super plants (Azolla) for sustainable rice production. Just Agriculture. 2021;1(8):1-5.

38. Wang C, Yang Q, Zhang C, Li X, et al. Rice-fish-duck system regulation of soil phosphorus fraction conversion and availability through organic carbon and phosphatase activity. Front Environ Sci. 2022;10:979234. https://doi.org/10.3389/fenvs.2022.979234

39. Geetha Jebarathnam Kuttibai T. A holistic climate resilient approach with rice-fish-duck-azolla systems. Journal of

Emerging Technologies and Innovative Research. 2023;10 (10):595.

40. Baigi MG, Pirdashti H, Abbasian A, Mazandarani GA. Combined effect of duck and Azolla on dry matter partitioning of rice (*Oryza sativa* L.) in the integrated rice-duck farming. International Journal of Farming and Allied Sciences. 2013;2 (22):1023-8.
41. Xu Q, Zhang M, Wang C. Effects of integrated rice-fish farming on nutrient cycling and soil fertility in rice paddies. Agric Syst. 2017; 155: 1-7.
42. Long P, Huang H, Liao X, Fu Z, et al. Mechanism and capacities of reducing ecological cost through rice-duck cultivation. J Sci Food Agric. 2013;93(12):2881-91. https://doi.org/10.1002/jsfa.6223
43. Yadav S, Kumar S, Singh R. Effect of liquid biofertilizer on growth parameters of rice seedlings. Int J Curr Microbiol App Sci. 2021;10(5):1234-240.
44. Sharma P, Gupta R, Verma S. Role of biofertilizers in enhancing crop growth: A review. Agric Sci. 2020;11(3):145-54.
45. Chaudhary P, Singh S, Chaudhary A, Sharma A, Kumar G. Overview of biofertilizers in crop production and stress management for sustainable agriculture. Front Plant Sci. 2022;13:930340. https://doi.org/10.3389/fpls.2022.930340
46. Bhargavi G, Sundari A. Effect of nano urea on the growth and yield of rice (Oryza sativa) under SRI in the Cauvery delta zone of Tamil Nadu. Crop Research. 2023; 58(1&2):12-7.
47. Velmurugan A, Subramanil T, Bommayasamy N, Ramakrishna MK, Swaranam TP. The effect of foliar application of nano urea (liquid) on rice (*Oryza sativa* L.). J. Andaman Sci. Assoc. 2021;26:76-81.
48. Dhawne MN, Shamkuwar GR, Shamkuwar SG, Landge NH, et al. Influence of foliar applications of Nano urea on morpho-physiological and yield parameters in rice (*Oryza sativa* L.). Biol Forum. 2023;15(11):548-53.
49. Safriyani E, Hasmeda M, Munandar, Sulaiman F, Holidi. Increasing the growth and production of irrigated rice through the integrated application of Rice–Duck–Azolla. Acta Agrobot. 2020;73(2). https://doi.org/10.5586/aa.7322
50. Liu J, Shu A, Song W, Shi W, et al. Long-term organic fertilizer substitution increases rice yield by improving soil properties and regulating soil bacteria. Geoderma. 2021;404:115287. https://doi.org/10.1016/j.geoderma.2021.115287
51. Zhen RH, wang QS, deng JP, du YL, et al. Main ecological effects of rice-duck-azolla integrated compound system. J Ecol Rural Environ. 2006;22(3):11-4.
52. Islam SS, Azam MG, Adhikary SK, Wickramarachchi KS. Efficiency of integrated rice, fish and duck polyculture as compared to rice and fish culture in a selective area of Khulna District, Bangladesh. Pak J Biol Sci. 2004;7(4):468-71.
53. Li M, Li R, Zhang J, Wu T, et al. Effects of the integration of mixed -cropping and rice–duck co-culture on rice yield and soil nutrients in southern China. J Sci Food Agric. 2020;100(1):277-86.
54. Mian MH. Azobiofer: a technology of production and use of Azolla as biofertiliser for irrigated rice and fish cultivation. Biofertilisers in action. Rural Industries Research and Development Corporation, Canberra. 2002:45-54.
55. Susanti WI, Cholidah SN, Agus F. Agro ecological Nutrient Management Strategy for Attaining Sustainable Rice Self-Sufficiency in Indonesia. Sustainability. 2024;16(2):845. https://doi.org/10.3390/su16020845
56. Adhikari K, Bhandari S, Acharya S. An overview of azolla in rice production: a review. Reviews in Food and Agriculture. 2020;2 (1):04-8. http://doi.org/10.26480/rfna.01.2021.04.08
57. Che, Z.; Zhu Ch Li, C.; Pu, W.; Lv, J. Benefit analysis of rice-duck-fish symbiosis model in Yuanyang county. Yunnan Agric Sci Technol. 2019;3:34-36.
58. Xie J, Hu L, Tang J, Wu X, Li N, et al. Ecological mechanisms underlying the sustainability of the agricultural heritage rice-fish co-culture system. Proc Natl Acad Sci. 2011;108(50):1381-7. https://doi.org/10.1073/pnas.1111043108
59. Singh S, Singh M. Economic evaluation of integrated farming systems in eastern Uttar Pradesh. Indian J Agric Econ. 2002;57 (1):75-87.
60. Nayak PK, Nayak AK, Panda BB, Lal B, et al. Ecological mechanism and diversity in rice based integrated farming system. Ecol Indic. 2018;91:359-75. https://doi.org/10.1016/j.ecolind.2018.04.025
61. Nayak PK, Nayak AK, Panda BB, Senapati A, et al. Rice-based integrated farming system improves the soil quality, bacterial community structure and system productivity under sub-humid tropical condition. Environ Geochem Health. 2024; 46(2):65. https://doi.org/10.1007/s10653-024-01863-1
62. Zhang Y, Guan C, Li Z, Luo J, et al. Review of rice-fish-duck symbiosis system in China-One of the globally important ingenious agricultural heritage systems (GIAHS). Sustainability. 2023;15(3):1910. https://doi.org/10.3390/su15031910
63. Teng Q, Hu XF, Cheng C, Luo Z, Luo F, et al. Ecological effects of rice-duck integrated farming on soil fertility and weed and pest control. J Soils Sediments. 2016;16:2395-407. https://doi.org/10.1007/s11368-016-1455-9
64. Li M, Li R, Zhang J, Liu S, et al. A combination of rice cultivar mixed-cropping and duck co-culture suppressed weeds and pests in paddy fields. Basic Appl Ecol. 2019;40:67-77. https://doi.org/10.1016/j.baae.2019.09.003
65. Liu Q, Zhang L, Yang Y, Zou J, et al. Ecological performance of an integrated ex-situ rice-fish co-culture system. Aquaculture. 2024;582:740511. https://doi.org/10.1016/j.aquaculture.2023.740511
66. Khumairoh U, Lantinga EA, Handriyadi I, Schulte RP, et al. Agro-ecological mechanisms for weed and pest suppression and nutrient recycling in high yielding complex rice systems. Agric Ecosyst Environ. 2021;313:107385. https://doi.org/10.1016/j.agee.2021.107385