



Weed control efficiency and productivity in rice-fish-duck integrated farming system

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ABSTRACT

Rice farming integrated with fish and ducks potentially provides ecological services and supports effective management of weeds which cause rice yield losses due to growth competitiveness with the available resources and productivity. Present study investigated the efficacy of integrating fish and duck in rice farming for controlling weed infestations and their impacts on productivity and economics of the system. Appraisal on diversity of weeds indicated that grassy weeds (*Echinochola colona*, *Echinochola crusgalli*) and sedges (*Cyperus difformis*, *Cyperus iria*, *Fimbristylis miliacea*) were prevalent in rice during tillering stages, while broad leaf weeds (*Ludwigia adscendens*, *Sphenoclea zeylanica*) and aquatic weeds (*Marsilia quadrifolia*, *Otella alismoides*, *Vallisneria spiralis*, *Limnophila indica*, *Ceratophyllum demersum*, *Hydrilla verticillata*) were abundant during active tillering and panicle initiation stages of rice. A significant reduction in weed density and weed biomass was observed in rice-fish (RF), rice-duck (RD) and rice-fish-duck (RFD) integration. However, weed control efficiency (WCE %) was significantly ($p < 0.05$) higher in RFD. The weed biodiversity in terms of species richness (Simpson's index) and species diversity (Shannon-Wiener index) decreased significantly, while Pielou evenness community index increased in RFD, signifying weed community composition was highly diversified with reduction of formerly dominant weed species. Rice agronomic characteristics, productivity and economic returns were higher in integrated system indicating over all improvements in ecology and productivity. Better growth of fishes accrued with RFD integrated system, possibly, due to the better nutrient availability. Thus, fish and duck can be used as biocontrol agents for weed management in rice farming for enhancing productivity in areas where application of chemical herbicides may be partially or totally eliminated in transplanted lowland system.

Keywords: Biocontrol of rice weeds, Rice-fish-duck integrated farming system, Weed biodiversity, Weed control efficiency

Introduction

Rice (*Oryza sativa* Linn.), forms principal food commodity for millions of people in the world. Globally, rice cultivation occupies 158 million ha area with global production of 744.9 million t (FAO, 2014). Rice is cultivated in widely divergent ecosystems (irrigated/rainfed lowlands and uplands) where productivity is subjected to varied biotic and abiotic stresses (Choudhary and Suri, 2014; Kaur *et al.*, 2015). Among the various biotic stresses, weeds are considered as one of the major stresses that affect rice yields (Dass *et al.*, 2017). Weed competitiveness reportedly caused severe losses of rice yields to the extent of 40-60% in transplanted rice and 70-80% in direct seeded rice (Chauhan and Johnson, 2011; Dass *et al.*, 2017). Thus, weed management is considered to be crucial in rice production owing to resource competitiveness with respect to light, space, nutrition and other inputs, leading to reduction of rice yields. Maintaining continuous flooding in the rice ecologies

helps to eliminate many prevalent weed species, but not all; and hence manual or mechanical removal or herbicidal application is practiced for controlling remaining weed species. In the present context, rapid development and expansion of industrial agriculture with intensified applications of agrochemicals leads to environmental degradations and therefore rice-fish-duck integration might provide ecological and environmental security (Nayak *et al.*, 2018b; 2020). Since, manual weeding is labour intensive and to a large extent uneconomical, small holder farmers are gradually shifting and preferring herbicidal application for weed control, which causes ecological imbalances with potential environmental risks *i.e.*, weed shift, herbicidal resistance and phyto-toxicity in crops (Gnanavel *et al.*, 2014; Dass *et al.*, 2017; Ramesh *et al.*, 2017). The aquatic environment is most vulnerable to herbicidal applications with consequences of reduction in dissolved oxygen, pH levels and increase in biological oxygen demand of water, which directly or indirectly impacted or translated the deleterious effects on various

beneficial organisms especially microorganisms (bacteria, fungi and protozoa), thereby upsetting the environmental balancing mechanism of pathogens, beneficial organisms and their ensuing biodiversity (Kalia and Gupta, 2004).

Rice-fish integration is a traditional system in south-east Asian region. Rice ecology provides excellent environments for raising fish and duck/aquatic animals where the components are mutually beneficial to each other (Hu *et al.*, 2016). About 20 million ha area out of the total 43 million ha of rice cultivated in India, are suitable for adoption of rice-fish integrated farming system (Rao and Singh, 1998; Mohanty *et al.*, 2010). Additionally, rice integration with fish and ducks have beneficial effects such as utilisation of lower energy inputs, waste recycling and better provisioning of ecosystem services, leading to achieving production sustainability (Nayak *et al.*, 2018a; 2018b; 2020). Consequently, rice-fish-duck integration can maintain rice productivity at par or at improved levels than conventional farming, potentially involving higher cost in respect to labour and agrochemicals. As a divergence, integration with fish or ducks may enable reduced use of agrochemicals while improving rice ecosystem and crop quality (Zhang *et al.*, 2009; Suh *et al.*, 2014; Nayak *et al.*, 2020). Additionally, rice-fish and rice-duck farming has potential to mitigate global warming through reduction of methane emissions (Xu *et al.*, 2017; Zhao *et al.*, 2019; Nayak *et al.*, 2020) and potentially control the infestation of golden apple snail *Pomacea canaliculata* (Liang *et al.*, 2014). Evidential supports also indicated that use of fish, duck, poultry components has been beneficial in controlling weeds besides enhancement of rice productivity (Kathiresan, 2007; Sinhababu *et al.*, 2009; Long *et al.*, 2013; Sinhababu *et al.*, 2013; Mofidian and Sadeghi, 2015; Wei *et al.*, 2019). Therefore, integrated rice-fish and rice-duck farming have been widely acknowledged as sustainable agroecological practices worldwide (Hu *et al.*, 2016; Wei *et al.*, 2019; Nayak *et al.*, 2020).

Considering the environmental safety in the rice ecosystem in general, development of eco-efficient agricultural approaches of weed management is of paramount necessity, where weed-competitive cultivars, seed rates and planting pattern alterations might be helpful towards weed menace reductions (Dass *et al.*, 2017). However, fish and ducks in integrated farming may provide holistic eco-friendly weed management and enhanced productivity approaches which are helpful in provisioning of poverty eradication, livelihood and nutritional security for the resource poor small holder farming communities. The comprehensive information regarding biological weed control mechanisms and its efficacy on enhancing productivity in rainfed lowland

ecosystems are scanty, especially in co-culture practices of rice-fish-duck integration. Hence, a study on comparative effectiveness of rice-fish and duck integration on reduction of weed population, their system productivity and economics was undertaken. The objectives of the study were to investigate the prevalence of weed species in lowland transplanted rice fields; to assess the efficacy of fish and duck in controlling weed population; to evaluate the effects of fish and duck in rice yield as well as rice attributes and to study the efficiency, productivity and economics of the integrated system.

Materials and methods

Site characteristics

Experiment was conducted during Kharif season (July to December) of three consecutive years (2013-2015) at ICAR-National Rice Research Institute (ICAR-NRRI), Cuttack, (20°25'N; 85°55'E, 24 m above mean sea level), Odisha, India. The characteristics of soil was clayey in texture having 36.6, 19.1 and 44.4% of sand, silt and clay, respectively with neutral pH (6.4-7.2).

Field preparation and treatments

Twelve plots of 500 m² each (25 × 20 m) were selected for experimentation from a shallow lowland rice field. Each plot was separated from the others with raised dykes and surrounded with plastic net to prevent escape of fish and duck from the treated plots as well as to prevent entry of other predators from outside rice fields. A fish refuge (10 m long, 7.5 m wide and 0.75 m deep) was constructed by digging soil at one end of the field covering 15% of the field area. Four treatments *i.e.* Rice (R); Rice and fish (RF); Rice and duck (RD) and Rice, fish and duck (RFD) were executed in these plots, each with 3 replications. The promising lowland rice cultivar, *cv. Varshadhan* (21 days old seedlings) was transplanted during 1st week of July. The crop was fertilised with 60:30:30 kg of NPK ha⁻¹. Full dose of phosphorus and potassium and half dose of nitrogen fertiliser were applied as basal and rest of the N fertiliser was applied in two equal splits during tillering and panicle initiation stages. Fish fingerlings of *Cyprinus carpio* (10-15 g size) @ 5000 nos. ha⁻¹ and duckling of *Khaki campbell* (30 days old with average body weight of 55 g) @ 300 nos. ha⁻¹ were released to the system after 20 days of rice transplanting. The ducks were continuously allowed to forage during day time in rice fields except during the period of rice flowering to harvesting. In addition to duck foraging in the rice fields, supplementary feeds comprising of vegetables and fruit wastes, chaff rice and broken rice grains, rice bran and chalk were also provided. The experiments were concluded on 30th of December after the harvest of rice, fish and duck.

Weed sampling

Characteristics of the prevalent weeds in the rice fields were studied after collecting fresh weed samples from the rice fields. Weed samples from each plot were collected by randomly placing a rectangular iron frames (1 m²) in five places at tillering stages, 60 days after transplanting (DAT) and active tillering or booting stages of rice *i.e.* 100 DAT. After removing the roots, weeds were washed and oven dried (60°C for 48 h) and dry matter weight of weeds were recorded. Weed control efficiency (WCE%) was calculated using the formula:

$$\text{Weed control efficiency (WCE\%)} = (\text{DMC} - \text{DMT}) / \text{DMC} \times 100$$

where, DMC = Dry matter of weeds in control field (rice alone) and DMT = Dry matter of weeds in experimental fields. Biodiversity indices of the weeds *i.e.* species richness (Simpson's index), the species diversity (Shannon-Wiener index), evenness of species (Pielou index) and Bray-Curtis index were calculated (Purvis and Hector, 2000).

Physico-chemical conditions of water in rice fields

Physico-chemical conditions of water in the rice fields were analysed using a water quality meter (Horiba Model U53). The concentrations of nitrate and ammonia were also determined (Bremner, 1965; Kempers, 1974).

Growth increments, yield and economic indices

The percentage of spikelet fertility per panicle were determined. The height of rice plants, panicles (nos. m⁻²), total grains/panicles and 1000 grain weight were measured. The harvested grain was sun dried upto 14% moisture content, weighed and grain yields ha⁻¹ was

calculated. Rice equivalent yield (REY) was computed after taking into consideration of proportionate area and component-wise productions. The farm gate selling prices were ₹15/- per kg of rice and ₹100/- per kg of both fish and duck meat. Fish and ducks were reared for 155 days in the rice fields and their growth performance and survival was evaluated. The total yields (fish and ducks), growth and specific growth rate (SGR) of fish and ducks were calculated:

$$\text{SGR} = \ln W_f - \ln W_i \times 100/t$$

where, W_f - Final weight of fishes, W_i - Initial weight of fishes and t - Period of culture (days).

An economic index of farm productivity was estimated by dividing the output value with cost of cultivation (OV-CC). During OV-CC estimation, variable cost of the inputs used for field operations were taken into consideration for the cost and profit analysis of the integrated farming system.

Statistical analysis

Individual character data sets were statistically analysed using t - test, analysis of variances (ANOVA) and Duncan's multiple range test followed by least significant difference (LSD, p<0.05) (Gomez and Gomez, 1984).

Results

Environmental parameters

The changes in maximum and minimum temperature prevailing during the year of the experiment are shown in Fig. 1. Rainfall was higher in the month of July (469.7 mm) followed by August (356.1 mm), September (349.3 mm) and October (144.4 mm) (Fig.1).

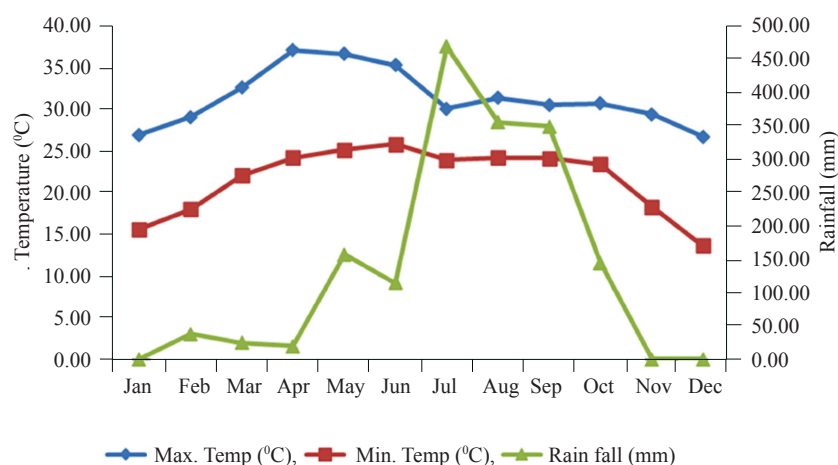


Fig. 1. Prevailing average environmental temperature (minimum and maximum temperature) and rainfall at the experimental site

Physico-chemical conditions of water

Temperature and water pH significantly varied in RF as compared to R. The dissolved oxygen (DO), oxidation reduction potential (ORP) and total dissolved salts (TDS) concentration increased significantly ($p < 0.05$) in integrated system compared to monocropping of rice. The DO concentration increased by 3.2, 19.6 and 11.8%; ORP increased by 15.4, 26.2 and 38.3%; TDS increased by 17.6, 21.1 and 30.2% in RF, RD and RFD system, respectively, over rice monoculture. The nitrate and ammonium concentrations in water also increased significantly ($p < 0.05$) in integrated systems (Table 1).

Types of weeds prevalent in experimental fields

A total of 13 weed species belonging to nine families were observed in different systems. The grass weeds viz. *Echinochola colona*, *E. crusgalli* and sedges viz. *Cyperus difformis*, *C. iria* and *Fimbristylis miliacea* were prevalent in rice during tillering stages, whereas, broad leaf weeds viz. *Ludwigia adscendens* and *Sphenoclea zeylanica* and aquatic weeds viz. *Marsilia quadrifolia*, *Otella alismoides*, *Vallisneria spiralis*, *Limnophila indica*, *Ceratophyllum*

demersum and *Hydrilla verticillata* were abundant during active tillering and panicle initiation stages of rice (Table 2).

Fish and duck stocking density

The stocking density of fish and ducks was standardised for optimal weed control at 60 DAT using fish fingerlings, *C. carpio* @ 4000, 5000 and 6000 nos. ha⁻¹ and ducks *Khaki campbell* @ 250, 300 and 500 nos. ha⁻¹ before conducting the comparative study of the systems. Significantly higher weed control efficiency was recorded with the stocking density of fishes @ 5000 nos. ha⁻¹ and ducks @ 300 nos. ha⁻¹, thus were selected and used for system experimentation (Table 3).

Weed density, biomass and weed control efficiency

Integration of fish and ducks in rice-based system significantly ($p < 0.05$) reduced the weed density and lowest was observed in RFD during both sampling days (60 DAT and 100 DAT) (Fig. 2).

The weed biomass was significantly reduced in integrated system and lowest was recorded in RFD system

Table 1. Water quality parameters in rice-fish-duck integrated farming system

Parameters	R	RF	RD	RFD	LSD ($p=0.05$)
Temperature (°C)	32.4 ± 1.5	31.1 ± 1.2	29.5 ± 1.5	30.3 ± 1.4	NS
pH	6.9 ± 0.5	7.2 ± 0.6	6.75 ± 0.8	6.5 ± 0.6	0.28
EC (dS ml ⁻¹)	0.24 ± 0.03	0.37 ± 0.04	0.35 ± 0.06	0.39 ± 0.06	NS
DO (mg l ⁻¹)	5.81 ± 0.6	6.0 ± 0.8	6.95 ± 0.7	6.5 ± 0.9	0.65
ORP (mV)	115.4 ± 2.1	133.2 ± 5.1	145.7 ± 4.1	159.6 ± 5.5	4.52
TDS (g l ⁻¹)	0.142 ± 2.1	0.167 ± 0.02	0.172 ± 0.03	0.185 ± 0.03	0.024
Nitrate (mg l ⁻¹)	23.15 ± 2.6	31.32 ± 3.5	40.6 ± 4.2	45.21 ± 4.3	1.24
Ammonium (mg l ⁻¹)	8.0 ± 0.7	13.4 ± 1.3	15.12 ± 0.02	21.5 ± 2.1	0.88

R - Rice mono-cropping; RF - Rice-fish; RD - Rice-duck; RFD - Rice-fish-duck system; EC - Electrical conductivity; DO - Dissolved oxygen; ORP - Oxidation and reduction potentials; TDS - Total dissolved salts

Table 2. Categories of weeds prevalent during rice tillering (60 DAT) and panicle initiation stages (100 DAT) in rice based integrated farming systems

Weed species	Family	Life form	Category	Prevalent weeds in 60 DAT	Prevalent weeds in 100 DAT
<i>E. colona</i>	Poaceae	Annual	Grassy weed	AAAA	A
<i>E. crusgalli</i>	Poaceae	Annual	Grassy weed	AAAA	NA
<i>C. difformis</i>	Cyperaceae	Annual	Sedges	AAAA	A
<i>C. iria</i>	Cyperaceae	Annual	Sedges	AAA	A
<i>F. miliacea</i>	Cyperaceae	Annual	Sedges	AA	A
<i>L. adscendens</i>	Onagraceae	Perennial	Broad leaf weed	NA	AAAA
<i>S. zeylanica</i>	Sphenocleaceae	Annual	Broad leaf weed	NA	AAA
<i>M. quadrifolia</i>	Marsileaceae	Annual	Aquatic weeds	A	AAAA
<i>O. alismoides</i>	Hydrocharitaceae	Annual	Aquatic weeds	NA	AAAA
<i>V. spiralis</i>	Hydrocharitaceae	Perennial	Aquatic weeds	A	AAAA
<i>L. indica</i>	Scrophulariaceae	Annual	Aquatic weeds	A	AAA
<i>C. demersum</i>	Ceratophyllaceae	Annual	Aquatic weeds	NA	AA
<i>H. verticillata</i>	Hydrocharitaceae	Annual	Aquatic weeds	NA	AAAA

Note: AAAA- Indicative of prevalence of weeds in higher density; A or NA - Indicate lower density or not observed at the time of sampling

Table 3. Effects of stocking density of fish and ducks on weed biomass and weed control efficiency (WCE) of transplanted lowland rice

Treatments	Stocking density (nos. ha ⁻¹)	Weed biomass (g m ⁻²) 60 DAT	WCE (%) 60 DAT
Rice		0.65	
Fish (<i>Cyprinus carpio</i>)	4000	0.31	52.3
	5000	0.22	66.15
	6000	0.19	68.42
Duck (<i>Khaki campbell</i>)	200	0.25	61.53
	300	0.16	75.38
	500	0.11	83.07

(Fig. 3). WCE was significantly higher in integrated system at both 60 DAT (54.7, 72.0 and 85.3%) and 100 DAT (48.6, 75.5 and 93.3%) in RF, RD and RFD system, respectively (Fig. 4).

Weed species diversity and evenness index

The weed species richness (Simpson's index D) decreased significantly in RFD both at 60 DAT and 100 DAT. The weed diversity (Shannon-Wiener diversity index H') decreased in RD and RFD system during both samplings (60 DAT and 100 DAT) in comparison to rice monoculture. However, the Pielou community evenness species index (E) increased significantly in RD and RFD at 60 DAT and only RFD at 100 DAT (Table 4). This indicated that weed community composition was improved along with reduction of former dominant weeds. The Bray-Curtis index was higher (0.730, $p < 0.05$) in RFD at 60 DAT, while higher indices were observed in both RD (0.56, $p < 0.05$) and RFD (0.75, $p < 0.001$) at 100 DAT (Table 4).

Yield and yield attributes of rice

The yield attributes of rice *i.e.* panicle numbers and spikelet fertility increased significantly after integration

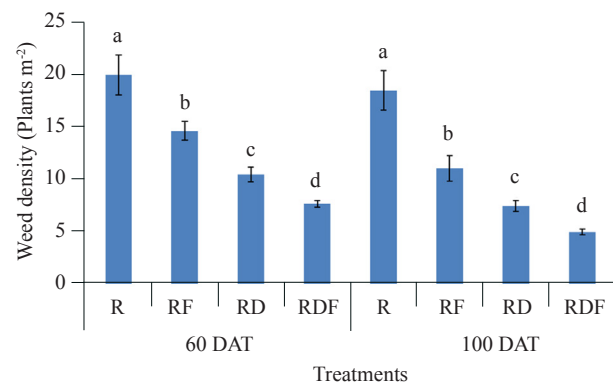


Fig. 2. Weed density per m² area in rice mono-cropping (R) and integrated system (RF, RD and RFD) at 60 DAT and 100 DAT. Values are expressed as Mean±SE. Alphabets above the bar indicate statistical significance ($p < 0.05$) between treatments, however, treatments bearing same alphabets are not significant among the treatments

of fish and duck with rice cultivation (RD and RFD). All the integrated systems registered higher grain yield compared to rice monoculture. The highest rice grain yield was recorded in RFD and significantly higher compared to rice monoculture as well as other integrated systems (Table 5).

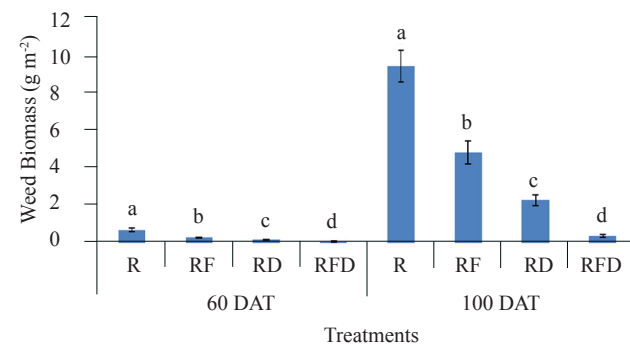


Fig. 3. Weed biomass (g m²) area in rice mono-cropping (R) and integrated system (RF, RD and RFD) at 60 DAT and 100 DAT. Values expressed as Mean±SE. Alphabets above the bars indicate statistical significance ($p < 0.05$) between treatments, however, treatments bearing same alphabets are not significant among the treatments

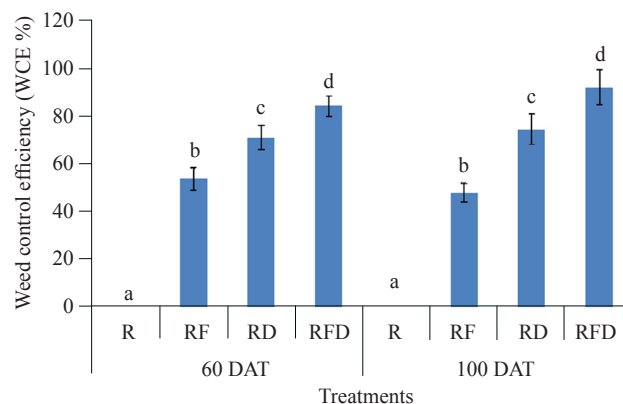


Fig. 4. Weed control efficiency (WCE%) percentage in rice mono-cropping (R) and integrated system (RF, RD and RFD) at 60 DAT and 100 DAT. Values expressed as Mean±SE. Alphabets above the bars indicate statistical significance ($p < 0.05$) between treatments, however, treatments bearing same alphabets are not significant among the treatments

Productivity and economics of the system

The system productivity and economic index improved with integration of fish and duck in rice cultivation. Significantly higher REY was recorded in RFD (7.74 t ha⁻¹, $p < 0.001$) followed by RD (5.48 t ha⁻¹, $p < 0.005$) and RF (5.34 t ha⁻¹, $p < 0.005$) as compared to rice alone, (R) (3.81 t ha⁻¹). The REY of RFD was almost double while RD and RF was 1.43 and 1.40 times higher compared to rice monoculture. The highest OV-CC ratio was observed in RFD system (3.01) followed by RD (2.65) and RF (2.61) as compared to the rice monoculture (Table 6).

Growth, survival and yield of fish and duck

The growth of *C. carpio* after 155 days of rearing in rice field was significantly higher in RFD (112.5±7.25 g, $p < 0.05$) compared to RF (90.4±6.85 g). However, the

growth of duck *Khaki campbell* did not increase with integration of fish in rice field (RD, 1320.8±30.5 g and RFD 1282.6±32.1 g). Survival percentage of the integrated animals did not register any significant differences among the systems. The specific growth rate (SGR) of fish *C. carpio* was significantly higher in RFD (1.52%, $p < 0.05$) in comparison to RF (1.39%) however no such differences were observed with respect to ducks in integrated system. Significantly higher ($p < 0.05$) fish yield was recorded in RFD system; however, the weight of duck did not differ significantly (Table 7).

Discussion

Rice productivity is severely affected unless weed population are suitably controlled. Manual weeding operations in rice is mostly constrained with non-availability of labour force timely as well as increased cost

Table 4. Influence of rice-fish-duck integration on the weed diversities and compositions in paddy fields

Days of sampling	Treatments	Diversity index			
		Simpson's (D)	Shannon- Weiner (H')	Evenness of species (E)	Bray- Curtis (B)
60 DAT	R	0.916	0.936	1.029	0
	RF	0.905	0.935	1.093	0.37
	RD	0.912	0.829*	1.412*	0.71
	RDF	0.878*	0.759*	1.462*	0.730*
100 DAT	R	0.895	0.881	1.074	0
	RF	0.855	0.768	1.134	0.38
	RD	0.889	0.687*	1.199	0.56*
	RDF	0.767*	0.477**	2.318*	0.75**

* $p < 0.05$; ** $p < 0.005$

Table 5. Rice yield attributes in rice alone and rice, fish and duck integrated farming systems

Treatments	Plant height (cm)	Panicle (nos. m ⁻²)	Grain nos. per panicle	1000 grain wt. (g)	Filled grain per panicle (%)	Grain yield (t ha ⁻²)	Straw yield (t ha ⁻²)
R	176.22	159.23 a	121.3	25.43	82.56 a	3.81 a	5.11a
RF	178.53	172.82 a	124.1	25.89	88.47 a	4.19 b	5.49a
RD	179.14	178.58 b	124.8	27.36	94.16 b	4.37 c	5.62b
RDF	181.45	189.64 c	131.3	29.78	98.85 c	4.58 d	5.91c

In each column, the mean values (five replicated observations) followed by a common alphanumer are not significantly different ($p > 0.05$) between treatments

Table 6. The average production of rice, fish, duck, rice equivalent ratio (REY) and ratio of output value to the cost of cultivation (OV-CC) in rice-fish-duck IFS system

Treatments	Rice yield (t ha ⁻¹)	Fish yield (t ha ⁻¹)	Duck yield (t ha ⁻¹)	REY (t ha ⁻¹)	OV-CC ratio
R	3.81			3.81	1.90
RF	4.19	0.268		5.34	2.61
RD	4.37		0.331	5.48	2.65
RDF	4.57	0.314	0.329	7.74	3.01

REY calculated with prevailing market price (Rice = ₹15/- per kg, Fish = ₹100/- per kg, Duck = ₹ 80/- per kg meat). The OV-CC ratio calculated with the cultivation cost (Rice = ₹30,000/- per ha; procurement of fish fingerlings = ₹1/- per fingerling, ducklings = ₹ 25/- per duckling, along with cost of feed components and labour requirements) in the rice-fish-duck integrated farming systems

Table 7. Survival, growth and specific growth rate of fish and duck in rice-fish-duck integrated farming system

Components/Species	Treatments	Initial weight (g)	Final weight (g)	SGR (% per day)	% Survival	Total production (t ha ⁻¹)
Fish (<i>Cyprinus carpio</i>)	RF	10.5 ± 2.1	90.4 ± 6.85	1.389	59.4	0.268
	RDF	10.7 ± 2.3	112.5 ± 7.25*	1.517*	55.8	0.314*
Duck (<i>Khaki campbell</i>)	RD	55.6 ± 8.4	1320.8 ± 30.5	2.043	83.4	0.331
	RDF	54.6 ± 9.2	1282.6 ± 32.1	2.032	85.6	0.329

The period of culture was restricted to the release of fish and duck in to rice based integrated farming system *i.e.* Kharif season only (27 July - 30 December of the year (*i.e.* 155 days). *Indicate significant difference ($p < 0.05$) among similar group

of hiring human labour. This compelled rice farmers to shift their weed control strategies to chemical herbicidal methods subsequently leading to environmental degradation. Rice-fish-duck integration decreased weed density, weed biomass in rice ecologies. In the present study, presence of fish *C. carpio* significantly reduced the weed density, their biomass and enhanced WCE (54.66±4.8% at 60 DAT and 48.59±3.9% at 100 DAT) in waterlogged rice fields (Fig. 1, 2, 3). The common carp, *C. carpio* is a voracious omnivorous bottom feeder, which directly consume small weeds, helps in uprooting the weeds in the initial stages during bottom feeding and disturbing the weed germination through continuous movements thereby suppressing weed infestation in the rice fields. Our results are in conformity with the previous reports on effectiveness of common carp on weed control in rice fields (Rothuis *et al.*, 1999; Kathiresan *et al.*, 2007; Sinhababu *et al.*, 2013). It is noted that 82-86% WCE was achieved using *C. carpio* and *O. niloticus* (Frei *et al.*, 2007) whereas 46.89% (at 60 DAT) using *C. carpio* (Sinhababu *et al.*, 2013). Presence of ducks significantly reduced the weed infestation in the rice fields (Fig. 1, 2). RDF system resulted in higher ($p < 0.05$) WCE than in other groups (Fig. 3). Duck integration appears to be most efficient system in controlling the weed population in transplanted rice. Fish (*C. carpio*) and ducks in rice fields mainly control weeds through foraging where they directly consume varieties of weeds, pecking and consuming weed seeds from weed plants and weed seed originally buried under soil surfaces and their activities within the rice ecosystems which caused uprooting small weeds. At the same times, continuous movements and activities (scooping, stirring, churning and trampling) of fish and duck stir up the soil and water leading to muddy water which indirectly suppresses the germination and normal growth of weeds. Additionally, continuous addition of duck droppings and loosening of upper soil layers might be helpful in stimulating rice plant growth through higher nutrient availability that indirectly contributed in suppressing the weed growth in rice field. During the 3 years of study in weed density and weed biomass drastically reduced along with significant changes in weed compositions in the integrated system (RF, RD and RFD). Present study

is in conformity with the previous findings on reductions of weed density associated with fish and ducks integrated systems (de Sousa *et al.*, 2011; Long *et al.*, 2013; Teng *et al.*, 2016). Duck activities adversely affected the growth of weeds (Zhang *et al.*, 2009) and the weed seed bank compositions of the rice fields (Li *et al.*, 2012). Combined integration of fish and ducks most effectively control the weed community composition, hence, can be used as an effective tool for controlling weeds in transplanted rice or in organic farming where reduction and elimination of herbicide applications are mostly emphasised.

Evaluation of diversity of weeds indicated that population of grasses and sedges was higher during tillering stage, whereas, broad leaf and aquatic weeds were higher during reproductive stage of rice (panicle initiation and booting stage). Increase of Pielou evenness indices indicates a change in weed community composition favouring reduction in former by dominant species. Ducks preferentially consumed broad leaved weeds first, followed by the sedges and grassy weeds later on (Long *et al.*, 2013). Our observation indicated that even though grassy weeds are not preferred by ducks in the presence of broad leaf weeds, grassy weeds mostly got damaged, pressed and sometimes uprooted with duck's movements and activities, thereby, promoting suppression of weed population leading to better rice growth.

The water quality in integrated rice-fish and duck system was slightly acidic in nature, possibly due to continuous accumulation of duck droppings. The observed higher range of DO, ORP, TDS, nitrate and ammonia concentrations in integrated systems were assigned to the constant disturbances of soil and water, accumulation of faecal matter with consequential enhancements of release of nutrients into the system. Additionally, fish (*C. carpio*) and ducks integration lead to reduction in greenhouse gas emissions from rice ecosystem (Xu *et al.*, 2017; Zhao *et al.*, 2019; Nayak *et al.*, 2020). The methane emission from paddy fields drastically reduced due to the enhancement of dissolve oxygen in water, and loosening of rice field surface layer of soil ultimately leading to better soil aerations in the rice fields. The process accelerates the methane oxidative processes resulting in

lowering of methane fluxes as well as inhibition of activity of methanogen bacteria which decreases further emissions of CH₄.

In the present study, fish and duck integration caused increase in panicle numbers and spikelet fertility which is attributed to the enhancement of rice yields, which reflected through increment in numbers of rice plant tillering and enhanced grain filling, possibly due to the higher nutrient availability. Our observation is in agreement with previous workers' findings *i.e.* yield improvement in rice through integration of fishes and ducks (Wang *et al.*, 2004; Hossain *et al.*, 2005; Sasmal *et al.*, 2010; Teng *et al.*, 2016; Sheng *et al.*, 2018; Nayak *et al.*, 2018b). The absorption of water and nutrients (especially in lowland rice) by plant roots are mediated through endodermis and casparian strips which undergoes secondary differentiation to hydrophobic suberin coating, that presumably changes the active absorbing epithelium to a protective barrier towards the nutrient flows (Barberon *et al.*, 2016). Possibly, the fish and ducks scooping and stirring activities disturbed the older rice roots which is subsequently helpful in regeneration of the new rice plant rooting system and better nutrient absorption capabilities leading to better rice plant growth and productions in the integrated system. This has been reflected in improvement in agronomic attributes of rice in terms of numbers of panicles, filled grain per panicle, straw and grain yields.

The total system productivity (REY) and economics (OV-CC ratio) were higher in integrated system. The higher growth of fish and SGR (Table 7) resulted in higher production of fishes in RFD as compared to RF, suggesting better fish growth accrued in the presence of ducks in the rice fields, possibly, better availability of nutrients which increased growth of fish food organisms (phyto and zooplankton as well as micro and macro-benthos) and their availability within the system. Organic manure application enhanced growth of fish (*C. carpio*) and rice yields in rice-fish integrated farming (Nayak and Mandal, 1990). Integration of rice with fish or ducks increases rice biomass and yields (Mohanty *et al.*, 2010; Zhang *et al.*, 2011; Suh, 2014; Mofidian and Sadeghi, 2015; Nayak *et al.*, 2018b). Rice-fish integration especially bottom feeder fishes through their soil scooping activities enhances the release of phosphorous from soil sediment layers, which stimulates the growth of phytoplankton and increases the chlorophyll-*a* concentration in rice fields (Frei and Becker, 2005) and fish food organisms including soil micro benthos (Nayak *et al.*, 2018b), justifying our contention of existence of beneficial mutualism in the integrated system.

The rice ecosystem function does not only restrict to rice grain production, but also preferring a coordinating

function on maintenance of ecological environment. Although intensification of rice production with application of massive agrochemicals enhanced the rice productivity, however led to serious problems of ecological health and security as well as food safety. In the recent years, concerned over the environmental safety, development of eco-efficient and environment-friendly approaches are emphasised in agriculture and in this context rice-fish-duck integration has become a popular intervention in the Asia and Pacific region. Practicing rice-fish-duck integration might do an important function of reducing deleterious impacts of conventional rice farming on environment as well as lessening the ecological cost of rice production. Fish and duck integration with rice cultivation impacted on weed control through their grazing and foraging activity which lower the weed densities and availability of weed seeds in rice soil resulting in suppression of weed infestation in the subsequent season. Present study emphasised that, fish and ducks integration with rice helps in weed control mechanisms and their droppings are utilised for growth of rice plants which indirectly suppresses the degree of infestation of weeds in paddy fields. Possibly, fish and ducks encourage new root growth and nutrient absorption capabilities of rice plants and their activities (constant churning, trampling and muddying activities) lead to higher nutrient release and availability, thereby promoting rice biomass growth and yields in the integrated system.

Transplanted rice integrated with fish and ducks control the weed infestation to a great extent. Fish and duck integration changed the weed community composition (weed density and biomass, weed species diversity and evenness) and diversity in the rice ecosystem. The constant movement and after effects on the soil and water of the rice fields reduced weed infestation in the subsequent seasons. The integrated system enhanced the productivity and better economic returns in addition to the provisioning of safe environment to a large extent and could be helpful to the small and marginal farmers. Integrated farming (rice-fish-duck) could effectively control the infestation of weeds in rice fields along with potential of labour cost reduction as well as lessening the magnitude of herbicidal use. The rice-fish-duck integrated system could be an alternative for transforming conventional system to organic farming with reduction in environmental degradation and can be a way forward for developing eco-efficient sustainable agricultural practices.

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