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Assessment of Flood Disaster Vulnerability, Sustaining Agricultural Productivity and Mitigation of CH_4 Emission through Rice-Duck-Fish Mixed Farming Systems across the Dingaputa Haor of Netrokona District, Bangladesh

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Abstract

Dingapota Haor, the low-lying wetland ecosystem in Bangladesh, was found to be mostly vulnerable to natural disasters like flash floods and seasonal floods, which posed severe impacts on agricultural productivity and the economy of the haor community. The flood vulnerability index (FVI) was estimated by incorporating the social, economic, environmental, and physical components. This study highlights a gradual increase in climate-related risks over the past decade, including rising floodwater (VI = 0.63), temperature (VI = 0.76), lightning and thunderstorms (VI = 0.84), hailstorms (VI = 0.58), and rainfall (VI = 0.67), ultimately revealing the total FVI value of 0.95, indicating very high vulnerability of the haor community to flood disaster. The rice-duck-fish mixed farming system trials conducted at different locations in the Dingapota haor revealed the overall superiority of rice-duck and rice-duck-fish farming practices over the traditional rice monoculture system. On average, rice yield was increased by 9.0% - 14.5% and 6.10% - 10.40% under rice-duck-fish and rice-duck mixed farming practices over the rice sole cropping. The mean maximum net return Tk. 308,570/ha, Tk. 198,484/ha, BCR values of 1.8 and 1.7 were obtained from rice-duck-fish and rice-duck mixed farming practices, respectively. The total seasonal CH_4 flux was decreased by 19.5%, 15.4%, and 21.0% under rice-duck, rice-fish, and rice-duck-fish mixed farming, respectively, compared to rice sole cropping. The Rice-Duck and Rice-Fish-Duck mixed farming systems reduced GWPs by 15% - 19% and 16% - 20% compared to the rice sole cropping system (5751 - 6156 kg CO_2 eq. ha^{-1}). Positive correlations were observed between seasonal cumulative CH_4 emissions and floodwater pH, whereas negative correlations were observed with DO, EC, TDS, nitrate, dissolved Fe, Eh, ammonium, and phosphate contents. Conclusively, spirulina-based biofertilizer with half of the conventional inputs application in rice-duck-fish and rice-duck mixed farming systems may be suitable for sustainable agricultural productivity, improving rural economy, and mitigation of GHG emissions as well as GWPs from the haor ecosystem of Bangladesh.

Keywords

Flood Vulnerability, Haor Ecosystem, Rice-Duck-Fish Farming, GWPs, Spirulina

1. Introduction

Rice is a staple food crop for more than half of the global population (FAO, 2012), particularly in Asia, where it is cultivated across vast irrigated and rain-fed areas. The demand for rice is projected to increase 30% by 2050 to accommodate population growth (Yuan et al., 2021; FAO, 2024). Economically, rice production supports the livelihoods of over one billion people globally, with the majority being smallholder farmers in Asia with limited landholdings, often less than one hectare per farm. Bangladesh is extremely vulnerable to climate change because of its geophysical settings. Bangladesh is a low-lying deltaic country, which experiences a mostly subtropical monsoon climate. Haors are large backswamp or bowl-shaped depressions between the natural levees of rivers, subject to monsoon flooding every year, mostly found in the northeastern part of Bangladesh, collectively known as the Haor basin. The Haor basin is a wetland habitat that includes rivers, streams, and irrigation canals, as well as large areas of seasonally flooded cultivated plains. Basically, rice-based agriculture is dominant in the Haor basin, and other crops like potato, groundnut, sweet potato, mustard, and pulses are grown to a small extent in the Rabi season. In Haor districts, mainly Sunamgonj, Sylhet, Maulvi Bazar, Kishoregonj, and Netrokona, more than 80% of the total cropped area is covered by the Boro-Fallow-Fallow cropping pattern, where crops are grown only in the Rabi season (Nov-April) and land remains uncultivated from April to November (Alam et al., 2010). It is worth mentioning that Haor areas contribute with 18% to the national rice production (Huq et al., 2012). Total rice production in Bangladesh was 34.28 million metric tons (milled rice) in FY2008-09 and increased to 36.6 million metric tons in FY2024-25 (USDA FAS, 2025). Bangladesh may require more than 55.0 million tons of rice to meet the food demand of the expanding population

(233.0 million) by the year 2050. Different climatic hazards, such as flash floods and conventional floods during the wet season, may result in partial or complete failure of Boro and T. Aman rice in low-lying areas of the country. Meanwhile, rice paddies have been identified as a major sector utilizing available water resources and a vital source of greenhouse gas emissions (FAO, 2024). The primary concerns for rice growers are increased production costs and changing climatic variables, which may badly affect the agricultural sector. In addition, the vulnerability of agricultural systems and productivity will be greatly threatened by changing climatic conditions and frequent natural calamities.

Dingaputa Haor is a large wetland ecosystem located in the northeastern part of Bangladesh, specifically at Mohonganj Upazila of the Netrokona district. The total area of the Dingapota haor is 8000 ha. Geographically, it is situated between latitudes 24˚43'N to 24˚50'N and longitudes 90˚40'E to 92˚57'E. Notably, the haor covered the three unions of Mohonganj upazila, which are Suair, Tetulia, and Gaglajur union. Farmers in these haor areas are considerably more vulnerable to climate change than those in other parts of the country, probably due to economic constraints, a lack of proper communication and poor infrastructure, a lack of technical support, and a lack of proper adaptation strategies. Therefore, rice cultivation system has to be modified for sustaining productivity as well as ensuring food security and mitigation of GHG emissions. In this regard, co-culture of rice and aquatic animals (e.g., fish, shellfish, crab, shrimps, and ducks) in paddy rice systems, has been suggested as a strategy to improve the utilization of land and water resources for providing both grains and meat to humans, while reducing the risks of natural hazards associated with rice production (Ahmed & Garnett, 2011; Hu et al., 2016).

The rice duck fish mixed farming holds a potentially feasible farming technique to overcome the vulnerability of agricultural productivity, which will provide rice to the resource-poor farmers as the main crop and subsidiary products such as fish, duck meat, and eggs from the same piece of land at the same time (Hossain et. al., 2005). Besides, the droppings from these ducks will provide almost all essential nutrients to rice crops and may effectively control weeds and insects (Choi et al., 1996). In addition, the incorporation of microalgae/Spirulina with Azolla compost may enhance rice production and decrease CH4 emissions (Prasanna et al., 2002; Ali et al., 2014), due to a symbiotic relationship among soil, methanogens, and microalgae (Geetha Thanuja & Karthikeyan, 2020). Furthermore, spirulina-supplemented diets may improve fish growth and develop immune-potentiating functions in fish species such as carp, red tilapia, shrimp, and mollusks (Watanuki et al. 2006; Abdel-Tawwab et al. 2006). It has also been reported that a Chlorella-Spirulina mixture, used as a biofertilizer, reduced chemical nitrogen use by 50% - 75% while increasing rice yields by 7.0% - 20.9% (Dineshkumar et al., 2018). There are no specific research findings available so far regarding rice duck fish mixed farming for sustainable productivity and mitigation of CH_4 gas emissions from the floodwater paddy-ecosystems around the Dingaputa haor areas. Therefore, this research program was undertaken to assess the flood disaster vulnerability for agricultural farming, and the feasibility of rice duck fish farming for enhancing agricultural productivity as well as mitigating CH_4 emissions across the Dingaputa haor of Netrokona district.

2. Materials and Methods

2.1. Flood Vulnerability Assessment

Flood vulnerability is an important factor to consider when assessing flood risk and assessing damage. It's difficult to quantify flood vulnerability because it depends on a variety of factors, including social, economic, environmental, and physical factors. The selection of indicators is the first step in any indicator-based vulnerability assessment. The vulnerability index system has been used to assess flood vulnerability in the Dingapota Haor area. Balica (2012) introduced the most advanced and reliable method, the "Flood Vulnerability Index (FVI)" to quantify the vulnerability of floods for an area. The general formula for FVI is calculated by classifying the component into three groups of indicators: exposure (R), susceptibility (S), and resilience (R). The general formula for FVI is calculated by classifying the component into three groups of indicators: exposure (E), susceptibility (S), and resilience (R), $\text{Vulnerability}\left(\text{V}\right)=\frac{\text{Exposure}\left(\text{E}\right)/\text{times Susceptibility}\left(\text{S}\right)}{\text{Resilience}\left(\text{R}\right)}$ (Balica & Wright, 2010).

With regard to indicators, this equation becomes the following one (Balica, 2012).

$$\text{FVI Dingapota Haor area} = \text{FVI Social} + \text{FVI Economic} + \text{FVI Environmental} + \text{FVI Physical}$$

The total FVI of Dingapota Haor is the sum of these four indicators based on FVI.

This index value indicates the extent of vulnerability. According to Balica (2012), the Flood Vulnerability Index value 0.01 indicates very small vulnerability to floods, 0.01 - 0.25: small vulnerability to floods, 0.25 - 0.50: vulnerable to floods, 0.50 - 0.75: high vulnerability to floods, 0.75 - 1.00: very high vulnerability. The general formula for FVI is calculated by classifying the component into three groups of indicators: exposure (E), susceptibility (S), and resilience (R),

$$FVI=\frac{E*S}{R} \tag{i}$$

With regard to indicators, this equation becomes the following one (Balica, 2012)

$$FVI_{Social}=\frac{P_{FA}*R_{POP}*\%_{disables}*C_{M}}{P_{E}*A/P*C_{PR}*W_{S}*E_{R}} \tag{ii}$$

$$FVI_{Economic}=\frac{L_{U}*U_{A}}{F_{I}*A_{mInv}*S_{C}/V_{year}} \tag{iii}$$

$$FVI_{Environmental}=\frac{R_{ainfall}*D_{A}*U_{G}}{L_{U}*U_{npop}} \tag{iiv}$$

$$FVI_{Physical} = \frac{T}{E_V / R_{ainfall} * S_C / V_{year} * D_L} \quad \text{(v)}$$

$$FVI_{DingapotaHaorarea=}FVI_{Social} + FVI_{Economic} + FVI_{Environmental} + FVI_{Physical} \quad \text{(vi)}$$

The total FVI of Dingapota Haor is the sum of these four indicators based on FVI (Equations (ii) - (vi)).

2.2. Data Collection Method

Primary data were collected from the Gaglajur, Tetulia, and Suair union households. Similarly, secondary data are collected from the Mohonganj Upzilla Parishad; the Local Government Engineering Department, Mohonganj; the Water Development Board, Netrokona; the Local Public Representative of Gaglajur, Tetulia, and Suair Union; and various web portals, and published research papers. 375 respondents/households were selected through a purposive random sampling method from 12,040 households in the study area. A single person was selected from every household (HH). The head of the family and the oldest person were selected for the questionnaire survey. Primary data were collected from the study area mainly by following two ways: (A) Questionnaire Development and Field testing, and (B) Focused Group Discussions (FGD).

A) Questionnaires Developed and Field Survey

A questionnaire was designed by the authors, presented, and administered at the household level to obtain primary data. The survey was conducted with all classes of people, such as farmers, fishermen, day laborers, and the chairmen of the studied union, through face-to-face interviews to collect information.

B) Focused Group Discussions (FGDs)

A focus group discussion was arranged to collect flood-disaster-related data, and flood vulnerability was assessed at the community level. About ten (10) FGDs were conducted at the selected research sites. The data regarding the frequency of floods, loss and damage due to flood, rainfall, size of the population, Dikes/levees of the haor area, storage capacity, and runoff of the river basin were mainly collected by the FGDs.

2.3. Rice Duck Fish Farming System Design

Field experiments were conducted at Showair and Tetulia Unions of Mohanganj Upazila of Netrokona district, near the Dingaputa Haor. The experiment was designed with a Randomized Complete Block Design (RCBD), having four (4) treatments, each replicated 3 times. There were twelve (12) plots, each with an area of 48 m^2. The selected soil amendments, Azolla compost (2 t/ha) and Oystershell powder, were applied in selected field plots one week prior to rice transplanting, and Cyanobacteria (Spirulina) were inoculated (100 ml/plot) in field plots after one week of rice transplanting. The rice cultivar BRRI Dhan-88 is cultivated for the boro season, and BRRI Dhan 39 for the Aman growing season. Composition of azolla compost: Total Carbon 43.6%, T-N 3.10%, C/N 14.06, T-P 0.65, T-K 1.5%. The characteristics of the microalgae are as follows: algal cell density of 8.0 × 106 cells mL^{-1}, chlorophyll content of 4.12 mg L^{-1}, pH value of 7.09, total carbon concentration of 359.70 mg L^{-1}, total nitrogen concentration of 505.55 mg L^{-1}, and total phosphorus concentration of 12.39 mg L^{-1}.

Experimental treatments:

T_1	Rice sole cropping (Farmers' practice, FP), without any amendments
T_2	Rice cropping (FP with Oyster shell and Azolla-Spirulina) with ducklings rearing
T_3	Rice cropping (FP with Oyster shell + Azolla-Spirulina) with fish
T_4	Rice cultivation (FP with Oyster shell + Azolla-Spirulina) with fish and ducklings rearing

28-day-old rice seedlings of cultivar BRRI Dhan-88were transplanted in the field at 25 cm × 25 cm spacing with two seedlings hill^{-1}. Ten days after rice transplanting in the field, ducklings (20-day-old) were released in the plots at the rate of 5 birds/ plot. Ducklings were kept in the plots for 4 hours a day (1st week), then allowed to remain in the plots from morning to evening and removed from the rice fields when the plants reached the flowering stage.

2.4. Rice, Ducklings, and Fish Growth Measurement

Rice plants, Tiller no/hill, Panicles/hill, grain/hill, grain yield/plot, etc., were randomly measured prior to harvesting. The ducklings were reared in the experimental plot, and growth was measured at weekly intervals using a digital weighing balance. Fish reared in the experimental plots were periodically sampled, and their body weights were measured using a digital weighing balance at two-week intervals during the experimental period. At each sampling event, fish were carefully collected using a hand net to minimize stress and injury. After weighing, the fish were immediately released back into their respective plots to continue normal growth. The collected data were used to evaluate growth performance, including weight gain under different treatment conditions. The specific growth rate of fish and ducklings was calculated to assess growth performance during the experimental period. SGR was determined using the natural logarithm of initial and final body weights over a given time interval.

$$SGR = \frac{\ln(w2) - \ln(w1)}{t} \times 100$$

here, $w2$ = the final live body weight (g) at time T2 (day), $w1$ = the initial live body weight (g) at time, t = Time intervals, $T2$ = time duration at the end of the experiment, $T1$ = initial time of the experiment (day).

2.5. Benefit-Cost Ratio (BCR)

The BCR is a relative measure, used to compare benefit per cost unit. The BCR estimated gross returns and gross costs as a ratio. The formula for measuring BCR is shown below:

$$\text{Benefit-cost ratio (BCR)} = \text{Gross benefit} \div \text{Gross cost}$$

2.6. Methane Gas Sampling from Field Plots and Analysis

Gas samples were collected by the modified closed-chamber method (Rolston, 1986; Ali et al., 2008) during rice cultivation. Gas samples were collected once a week, starting from 21 DAT until rice harvesting, to get the average CH_4 emissions during the cropping season. During gas sampling, a glass chamber was placed over the rice plants in the middle of the field plot. Gas samples were collected by a 50 ml air-tight syringe at 0 min, 15 min, and 30 min intervals after chamber placement over the rice-planted plot. The samples were analyzed to determine the concentration of CH_4 gas by Gas Chromatograph (Shimadzu/GC 2014, Japan) equipped with a Flame Ionization Detector (FID). The analysis column was a stainless-steel column packed with Porapak NQ (Q 80 - 100 mesh). The temperatures of the column, injector, and detector were set to 100˚C, 200˚C, and 200˚C.

2.7. Estimation of CH_4 Flux and Global Warming Potentials (GWPs)

CH_4 emission from an irrigated rice field was calculated from the increase in CH_4 concentrations per unit surface area of the chamber for a specific time interval. A closed chamber equation (Rolston, 1986; Ali et al., 2008) was used to estimate CH_4 fluxes from each treatment.

$$F = \rho.V/A.\Delta c/\Delta t.273/T$$

where, F= CH_4 flux (mg CH_4 m^2 hr^{-1}), ρ = gas density (0.714 mg cm^{-3}), V = volume of chamber (m^3), A = surface area of chamber (m^2), H = height of the chamber (m), $\Delta c/\Delta t$ = rate of increase of CH_4 gas concentration in the Chamber (mg m^{-3} hr^{-1}), T (absolute temperature) = 273 + mean temperature in chamber (˚C).

The CH_4 emissions data were correlated with and interpreted in relation to plant growth, yield, soil properties, and environmental factors. The seasonal cumulative CH_4 flux for the entire cropping period was computed as reported by Singh et al. (1999): Seasonal CH_4 flux = $\sum n_i = (R_i \times D_i)$.

Estimation of Global Warming Potentials (GWPs)

In this study, we used the IPCC factors to calculate the combined GWP for 100 years, GWP = 27 × CH_4 (kg CO_2-equivalents ha^{-1}) + 273 × N_2O (kg CO_2-equivalents ha^{-1}) (IPCC, 2021). In addition, the greenhouse gas intensity (GHGI) was calculated by dividing GWP by rice grain yield (Mosier et al., 2006).

2.8. Investigation of Flooded Water and Soil Properties

Water Samples were collected from each experimental plot under the four treatments at regular intervals throughout the study period. Water samples were collected from 10 cm below the surface using clean, labeled plastic bottles. Soil redox potential (Eh), flood water pH, EC, TDS, total dissolved Fe (iron) conc. and DO conc. were measured at every week interval during rice cultivation. Nitrate NO_3^- concentration in water samples was determined at 410 nm using a UV spectrophotometer (Brucine-sulfanilic acid method). Ammonium (NH_4^+) concentration in water samples was determined by the Indophenol blue method. Dissolved iron concentration was measured by the 1, 10 Phenanthroline method.

After rice harvesting, soil organic carbon (Walkley and Black method; Allison 1965), total N (Micro-Kjeldahl method), available P (Colorimetric method, Olsen et al., 1954), and available S (by the calcium chloride (0.15%) extraction method) were determined following standard methods. Exchangeable calcium (Ca), sodium (Na), and potassium (K) were extracted from soil using 1 M CH_3COONH_4 solution, and their concentrations in the extract were directly determined by Flame Photometer (Model: FP 902 PG Instrument).

2.9. Statistical Analysis

Statistical analyses were performed with both MS Excel and IBM SPSS. ANOVA and DMRT analyses were computed with SPSS. The figures were generated using SigmaPlot 16.0. ArcGIS 10.8 software was used to prepare the study area map.

3. Results and Discussion

3.1. Flood Vulnerability Assessment Results

Flood vulnerability is an important factor for assessing flood risk and associated damage. Flood vulnerability depends on social, economic, environmental, and physical components.

The FVI (social), FVI (economic), FVI (environmental), and FVI (physical) were calculated through the equation for assessing the flood vulnerability Index. The social value was 0.22, the economic value was 0.04, the Environmental value was 0.68, and the Physical value was 0.01 (**Table 1**). The sum of the four components revealed an FVI of 0.95, indicating high flood vulnerability due to frequent exposure to flooding, significant susceptibility to flood impacts, and limited adaptive capacity to respond and recover. The flood vulnerability index (FVI) for the Dingapota Haor area was estimated at 0.95 (**Table 1**), indicating very high vulnerability to floods. According to Balica (2012), an FVI value between 0.75 and 1 represents high flood vulnerability because it reflects a combination of frequent exposure to flooding, significant susceptibility to flood impacts, and limited adaptive capacity to respond and recover. It has been reported that the FVI value for the Hatia union was 0.703, indicating that this area is highly vulnerable to flooding (Mukta et al., 2022); consequently, the agricultural farming system may be severely hampered.

Table 1. Dingapota haor FVI scale indicators and their value.

Components	Indicators	Acronym	Unit	Value	FVI Values
Social Component	Population in flood-prone area	P_{FA}	People	51,044	0.22
	Rural Population	R_{POP}	%	94.4	
	Disable People	% Disables	%	18.2	
	Child Mortality	C_M	Count	24.7	

Continued

Social Component	Past Experience	P_E	People	42,876	
	Awareness and Preparedness	A/P	-	8	
	Communication Penetration Rate	C_{PR}	%	82	
	Warning System	W_S	-	10	
	Evacuation Roads	E_R	%	35	
Economic Component	Land Use	L_U	%	74	0.04
	Urbanized Area	U_A	%	7	
	Flood Insurance	F_I	-	1	
	Amount of Investment	AmInv	-	31	
	Storage Capacity over Yearly Discharge	S_C/Vyear	m^3/m^3	400	
Environmental Component	Rainfall	$R_{ainfall}$	m/year	3.6	0.68
	Degraded Area	D_A	%	10.9	
	Urban Growth	U_G	%	5	
	Land Use	L_U	%	13	
	Unpopulated Area	U_{npop}	%	22	
Physical Component	Topography	T	-	1.2	0.01
	Evaporation Rate/Rainfall	$E_V/R_{ainfall}$	-	0.78	
	Storage Capacity over Yearly Discharge	S_C/Vyear	m^3/m^3	400	
	Dikes_Levees	D_L	km/km	0.72	
	Total FVI Value				0.95

3.2. Loss and Damages Due to Flood Hazard in Dingapota Haor

According to the respondent's answers, moderate floods occur in some areas of the Dingapota haor every year, but devastating floods occurred in 1984, 1988, 1996, 2002, 2004, 2008, 2012, 2014, 2017, and 2022**.** Flood disaster vulnerabilities affected agricultural productivity, such as maximum damage and loss occurred for Boro rice and vegetation, fisheries, house and property, livestock, human, roads, and other infrastructure, respectively, as shown in Figure 1.

Natural Capital Vulnerability Index Assessment

Dingapota Haor was mostly vulnerable because the natural conditions were very fragile. The land vulnerability of agricultural resources focused on land availability, use, and exposure to submergence. The average per-household land area for agricultural activities was limited to 0.5 acres, with a vulnerability index (VI) of 0.25, indicating constraints on land availability. However, 90% of the land was used for rice cultivation, showing optimal use but with a VI of 0.90, indicating dependency on this single crop. Additionally, agricultural land remains submerged for an average of 5 months annually (VI = 0.46), reflecting moderate exposure to waterlogging. Collectively, these factors result in a land vulnerability index of 0.54, indicating moderate challenges in sustainable land use for agriculture (Table 2).

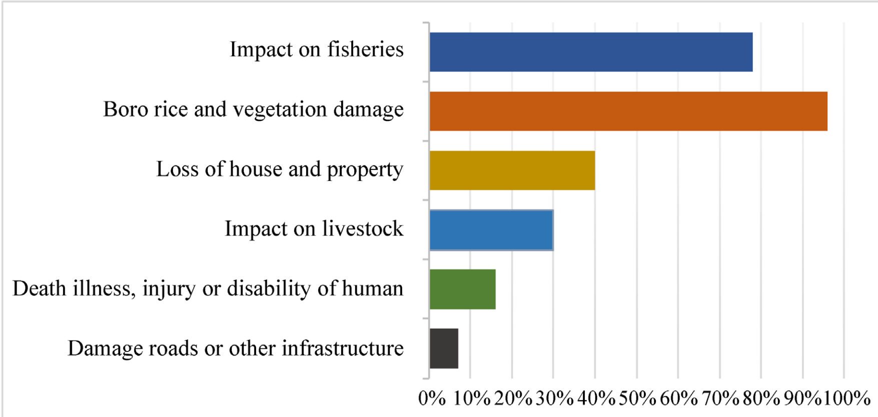

Figure 1. Loss and damage due to floods around Dingapota Haor, Mohanganj.

Table 2. Natural capital vulnerability assessment.

Capital	Components	Subcomponents	Unit	Observed Value	Maximum Value	Minimum Value	VI
Natural	Land	Per household land area for agricultural activities	Acre	0.5	1	0	0.25
		The area of rice planted land	Percent	90	100	0	0.90
		How much time is submerged agricultural land	Month	5	12	0	0.46
		Land Vulnerability (F)					**0.54**
	Water	The availability of irrigation water for crop production	Percent	80	100	0	0.80
		HHs reporting water conflicts within their community	Percent	18	100	0	0.18
		HHs that easily obtain water from their source (tube well/shallow well/deep well)	Percent	91.2	100	0	0.91
		HHs have safe drinking water	Percent	60	100	0	0.60
		Water Vulnerability (G)					**0.62**
	Biodiversity	Fish diversity and fish population are decreasing continuously due to overcatching	Percent	91	100	0	0.91
		Frog populations in paddy fields are decreasing continuously due to climate change	Percent	84	100	0	0.84
		Biodiversity Vulnerability (H)					**0.88**
	Climate Variability and Natural Disasters	The average number of floods during the last 30 years that HHs reported	Count	9	12	6	0.53
		Percentage of HHs that receive a warning about the pending flood disaster	Percent	54	100	0	0.54
		Gradually increasing floodwater in the last 10 years	Percent	63	100	0	0.63
		Gradually increasing temperature in the last 10 years	Percent	76	100	0	0.76

Continued

Natural	Climate Variability and Natural Disasters	The percentage of gradual increases in lighting and thunderstorms in the last 10 years	Percent	84	100	0	0.84
		The percentage of gradually increased hailstorms in the last 10 years	Percent	58	100	0	0.58
		The percent of the gradual increase in rainfall in the last 10 years	Percent	67	100	0	0.67
		Climate Variability and Natural Disasters Vulnerability					**0.64**
		Natural Capital Vulnerability					**0.67**
Physical	Housing and Assets	Percent of HHs have a solid house	Percent	21	100	0	0.21
		HHs affected by floods	Percent	74	100	0	0.74
		Percent of deep wells in agricultural land	Percent	64	100	0	0.64
		Number of livestock per household	Count	3	20	0	0.15
		Assets Vulnerability (O)					**0.44**
	Agricultural machinery	Improved equipment and farm machinery reduce the cost of production and enhance the physical status	Percent	90	100	0	0.90
		Possession of vehicles such as bullock carts, tractors, and other vehicles indicates the status	Percent	72	100	0	0.72
		Agricultural Machinery Vulnerability (P)					**0.81**
	Access to roads/ market, and transportation facilities	Percent of connecting roads from the agriculture field to the home, agricultural land to market, and home to market	Percent	35	100	0	0.35
		Percent of solid road infrastructure	Percent	30	100	0	0.30
		Availability of transportation facilities	Percent	58	100	0	0.58
		Access to Roads/Market, and Transportation Facilities Vulnerability (Q)					**0.68**
	Energy	Percent of HHs has conventional stoves	Percent	97	100	0	0.97
		Percent of HHs have access to LPG gas stoves	Percent	34	100	0	0.34
		Energy Vulnerability (R)					**0.66**
	Electricity Access	Percent of HHs have REB electricity access	Percent	100	100	0	1.00
		Percent of houses not having solar power	Percent	28	100	0	0.28
		Electricity or Solar Power Vulnerability (S)					**0.64**
		Physical Capital Vulnerability					**0.60**

Water vulnerability was focused on the availability, accessibility, and quality of water for agricultural and household use. While 80% of households reported sufficient irrigation water for crops (VI = 0.80), only 60% have access to safe drinking water (VI = 0.60), exposing a significant gap in water quality. A notable 91.2% of households can easily access water sources like tube wells, yielding a VI of 0.91, highlighting good accessibility. However, 18% of HHs reported water conflicts within their community; the vulnerability index was 0.18. Overall, the water vulnerability index was 0.62, reflecting substantial vulnerability due to water quality and availability concerns (Table 2).

The biodiversity component revealed alarming trends in the ecosystem, particularly due to overexploitation and climate change. Fish diversity and fish population were decreasing continuously due to overfishing, with a VI of 0.91, highlighting severe ecological pressure and haor ecosystem degradation. In addition, most households (88%) reported decreasing frog populations in paddy fields, which also accelerated biodiversity degradation, resulting in a high biodiversity vulnerability index of 0.88, representing significant ecological risks that threaten long-term environmental sustainability (**Table 2**). It was noted that 88% of households were dependent on agriculture as a major income source, and the remaining households, on non-farm activities, were unfortunately affected by floods or other natural disasters. Rice-duck mixed farming provided a source of income for 70% of households. Households reported an average of nine floods that occurred in the past 30 years, with a VI of 0.53, and only 54% receive timely flood warnings (VI = 0.54). The data highlights a gradual increase in climate-related risks over the past decade, including rising floodwater (VI = 0.63), temperature (VI = 0.76), lightning and thunderstorms (VI = 0.84), hailstorms (VI = 0.58), and rainfall (VI = 0.67). Combining the indices for land, water, biodiversity, and climate variability, the overall Natural Capital Vulnerability Index was obtained as 0.67, indicating the natural capital of the Dingapota haor area is in a vulnerable condition.

Physical Capital Vulnerability Index Assessment

The housing and assets were seriously affected by floods, as reported by 74% of HH, and the housing and assets vulnerability index was ultimately found to be 0.44 (**Table 2**). The agricultural machinery vulnerability index was 0.81, while the access to roads/markets and transportation facilities vulnerability index was 0.68 (**Table 2**). Regarding energy, the energy vulnerability index was 0.66, while the electricity access vulnerability index was 0.64 (**Table 2**). Overall, the Physical Capital Vulnerability Index was found to be 0.60, indicating a highly vulnerable physical condition in the selected haor area.

CH_4 emission rates and soil redox potential (soil Eh) during the rice cultivation period

CH_4 emission rates showed significant variation across the four treatments during the rice growth period in the wet Aman season (**Figure 2**). CH_4 flux measured at 14 to 21 days after rice transplanting was low, which increased significantly with plant growth and the development of soil reductive conditions at both locations of the rice field (Showair and Tetulia Union). In all treatments, CH_4 emissions gradually increased after transplanting, peaked at 42 DAT, and then steadily decreased until harvest. Among the treatments, the rice sole cropping system (T_1) consistently revealed higher CH_4 emissions compared to other mixed farming methods. The maximum CH_4 emission rate, 21 - 28 mg m^{-2} h^{-1}, was recorded in rice sole cropping (T_1) at active tillering to early panicle initiation stage, while the CH_4 emission rate dropped sharply at rice maturation to rice harvesting stage at both locations, even though the soil redox value was low enough to produce CH_4. This decline in CH_4 emission could be related to rice plant aging and drainage of water. Similar findings were reported by Haque and Biswas (2021), who found that CH_4 emission rates were low during the early stages of rice growth and gradually increased as soil reductive conditions and plant maturity increased.

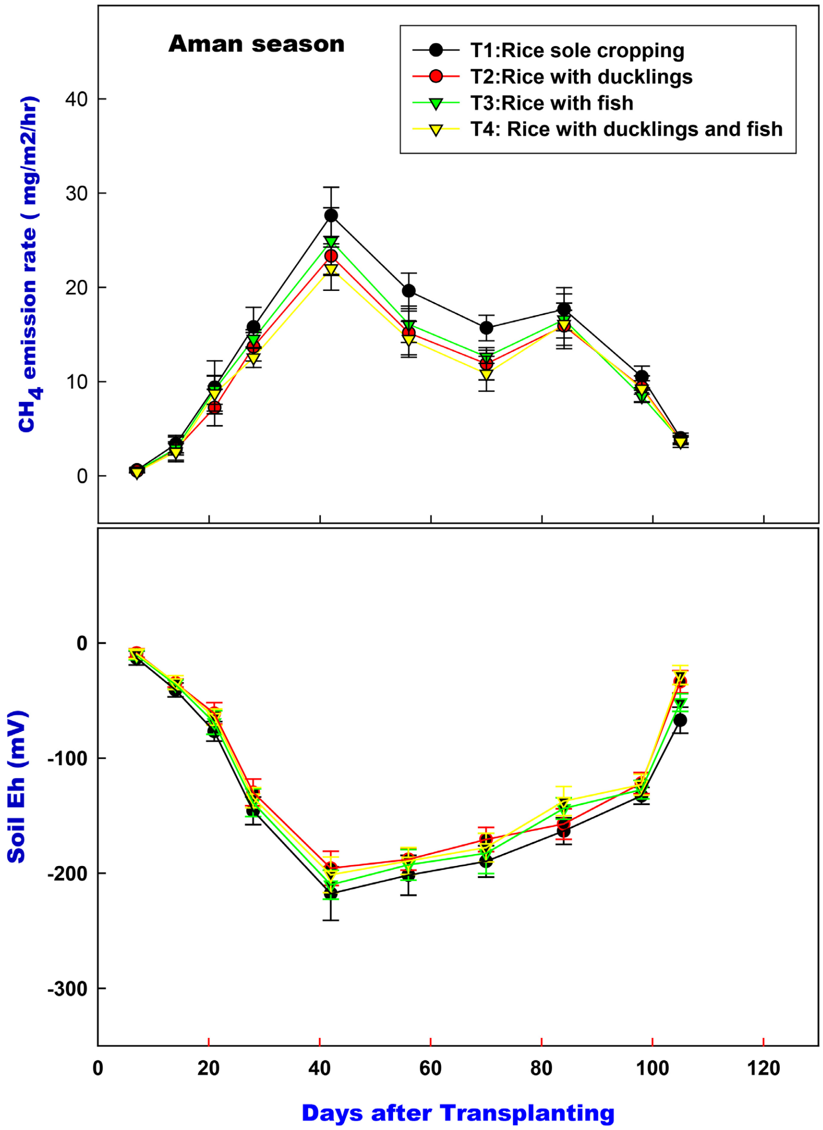

Figure 2. Changes in CH_4 emission rates and soil redox potential value under rice, fish, and duck mixed farming during Aman season rice cultivation.

The rice-fish-duck mixed farming (T_4) decreased CH_4 emissions by approximately 22.37%, Rice-Duck (T_2) by 22.90%, and Rice-Fish (T_3) by 13.63% compared to the rice sole cropping (T1) system, respectively. The variation in CH_4 emission may be due to fish species and ducklings' mobility, activities, and floodwater properties. Li et al. (2024) showed that rice-fish and rice-crab co-cultures reduced CH4 emissions by approximately 23% while improving yields and economic returns. Yuan et al. (2009) found that the peaks of CH_4 emission fluxes from Rice-Duck (RD) and Rice-Fish (RF) appeared at the full tillering stage and at the heading stage, and the average emission fluxes were significantly ($p < 0.05$) lower than those from Rice only (CK). In RD and RF, the activities of ducks and fish, such as feeding, disturb the soil, quicken the gas exchange between the soil and the atmosphere, and increase the opportunity of CH_4 emission. In addition, because plankton are consumed by ducks and fish, DO consumption in the water body by weeds and aerobic organisms is reduced, the DO content in the water body is accordingly increased, and thus, CH_4 produced in the soil could be oxidized more quickly. At the same time, the soil Eh value also increased, which inhibited the activities of methanogens and therefore decreased CH_4 production. Frei and Becker's research showed fish activities boosted the diffusive fluxes of floodwater oxygen. Moreover, fish dropped the floodwater DO and consumed the planktons, reducing the content of floodwater DO and soil Eh value, which might therefore be a cause of higher CH_4 emissions (Frei & Becker, 2004). The changes in soil redox potential (Eh) under the rice-based farming system during the Aman season are shown in **Figure 2**. In all treatments, soil Eh values gradually declined after transplanting and reached highly reduced conditions of −201 mV to −217 mV at about 42 DAT. Therefore, soil redox status showed an up and down trend, and finally, before rice harvest, soil Eh value increased due to water draining out. In general, the growing period, T_2 (rice with ducklings), T_3 (rice with fish), and T_4 (rice with ducklings and fish) showed considerably greater Eh values than rice sole cropping (T_1).

CH_4 emission rates during the Boro season exhibited a comparable temporal trend across all treatments (**Figure 3**). CH_4 emissions increased gradually after transplantation, peaked at 70 - 77 DAT, and then steadily decreased until harvest. The maximum CH_4 emission rate occurred in the rice sole cropping system (T_1), reaching an approximate peak of 36 mg m^{-2} h^{-1} at around 70 DAT, probably due to the most intensive anaerobic soil conditions, more available C from decomposed organic materials, which accelerated methanogenic microbial activity. Comparatively lower CH_4 emissions were observed in all mixed farming systems (rice-duck, rice-fish, rice-duck-fish) than those of the rice sole cropping system (T_1). Among these, the rice-duck mixed farming (T_2) revealed the least CH_4 emissions, trailed by rice-fish-duck (T_4) and rice-fish (T_3). After reaching the peak, CH_4 emissions gradually declined towards rice harvesting stage. Ali (2017) stated that the highest CH_4 peak was observed at the flowering to milking/booting stage (77 - 91 days after rice transplanting) of rice plant. This was most probably due to the development of intensely reduced conditions, e.g., Eh value −200 mV to −230 mV in the rice rhizosphere. The maximum CH_4 emissions in rice sole cropping (T_1) may be related to flooded conditions, which create strongly anaerobic soil environments that are favorable for methanogenic microbial activity. The rice-duck (T_2) and rice-fish-duck (T_4) mixed farming system decreased CH_4 emissions to a greater extent compared to rice sole cropping and rice-fish farming. This may be due to ducks' movement, paddling, and foraging, which disturbed the soil and enhanced oxygen diffusion into the floodwater-soil interface, thereby suppressing methanogenesis. In rice-fish (T_3) mixed farming, fish activity improved water circulation and sediment mixing, which may also increase soil aeration and reduce CH_4 production, although the reduction was lower than in duck-integrated treatments. In rice-fish-duck (T_4) mixed farming, the combined effect of ducks and fish further improved aeration and reduced anaerobic conditions, resulting in lower CH_4 emission compared with rice sole cropping (T_1). On the other side, Ducks and fish may accelerate organic matter decomposition and reduce the accumulation of CH_4-producing substrates in the soil.

Frei and Becker (2004) stated that the presence of fish in paddy fields boosted net atmospheric CH_4 emissions, perhaps through two mechanisms: 1) dropping the floodwater dissolved oxygen, thus fostering the anaerobic character of the soil environment; 2) releasing a rising portion of CH_4 entrapped in the soil via ebullition. Sun et al. (2021) stated that the impact of rice-fish co-culture on greenhouse gas emissions remains controversial.

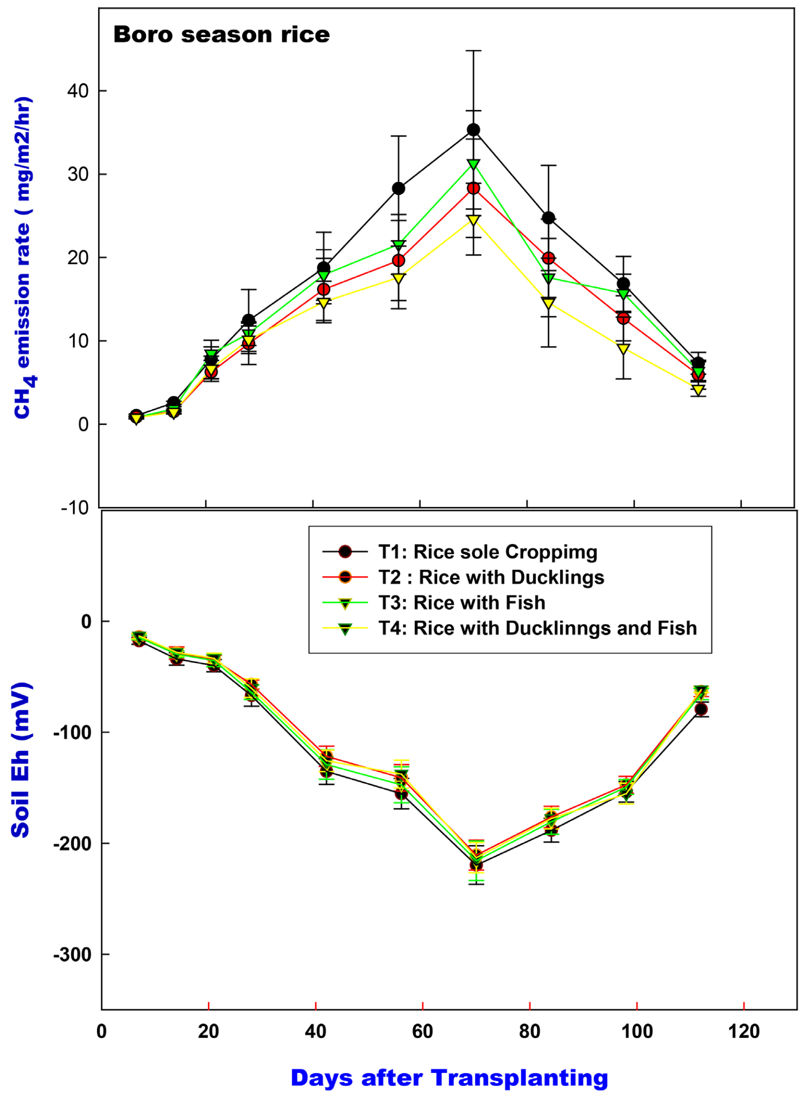

Figure 3. Trends of CH_4 emission rates and soil redox status (Eh) during Boro season rice, fish and duck mixed farming.

The changes in soil redox potential (Eh) under the rice-based farming system during the Boro season are shown in Figure 3. The soil redox potential (Eh) decreased gradually across all treatments from transplanting to about 70 DAT and reached a highly reduced condition of −213 to −239 mV. The soil redox status showed ups and downs between the treatments, and finally, Eh values increased gradually toward harvest. Among the treatments, sole rice cropping (T_1) generally showed the lowest Eh value (around −228 to −239 mV), while mixed farming systems with fish and ducklings (T_2, T_3, and T_4) maintained comparatively higher Eh values.

Flood water quality parameters significantly affected CH_4 emissions (Table 3). In the rice-duck, rice-fish-duck mixed farming field, water, dissolved oxygen, dissolved iron, phosphate, and nitrate concentrations were significantly higher than in the rice sole farming field plot water (Table 3), which influenced a decrease in CH_4 emissions. This is probably due to negative correlations of CH_4 emissions with the water quality parameters, e.g., DO, nitrate, phosphate, and dissolved iron. Furthermore, nitrate and iron, acting as electron acceptors, decreased methanogenesis and eventually decreased CH_4 emissions.

In both experimental locations, the water quality parameters were quite good for the aquatic living organisms, such as the fish population and ducklings' growth (Table 3). In this study, a large amount of organic matter was formed from the submerged biomass of rice plants. The decomposition of these organic materials and the dead organisms at the bottom of the haor basin produced CH_4, CO_2, and ammonia (NH_4^+) gases, which diffuse from the sediment into the water column and finally to the atmosphere. Fish species must discharge CO_2 to take in fresh oxygen O_2 gas in their bloodstream, which might slow down or be badly affected under higher CO_2 concentration in an anaerobic floodwater paddy ecosystem. Significant amount of NH_4^+-N formed under the intensive reductive conditions of flood water paddy ecosystem, especially in rice sole cropping, rice duck, and rice fish duck mixed farming field plots, which also converted into nitrate-N due to movement of ducklings and fish species, thereby enhanced O_2 penetration from land surface air into flood water column, which increased DO concentration suitable for ducklings and fish population.

Table 3. Water quality parameters in rice-fish-duck mixed farming system.

Rice Growing Season		Treatments	pH	DO (ppm)	TDS (ppm)	EC (μS cm^{-1})	NH_4^+-N (mg L^{-1})	NO_3^--N (mg L^{-1})	Dissolved Iron (mg Fe L^{-1})	PO_4^{-3} (mg L^{-1})
Aman Season	Showar Union	Rice sole cropping (T_1)	6.9ab	6.7c	929b	672d	1.83a	0.67b	0.85b	1.85d
		Rice-Duck mixed farming (T_2)	6.7b	7.3a	997ab	834b	1.85a	0.95a	0.93a	4.7b
		Rice-fish mixed farming (T_3)	7.1a	6.9b	985ab	729c	1.76a	0.73b	0.89b	3.6c
		Rice-Fish-Duck mixed farming (T_4)	7.0ab	7.1ab	1057a	983a	1.73a	0.81a	0.97a	5.3a
		LSD	0.292	0.302	69.34	38.25	0.433	0.188	0.245	0.45
		Level of significance	NS	**	*	**	NS	*	**	**

Continued

Aman Season	Tetulia Union	Rice sole cropping (T_1)	7.05a	6.79c	891a	694d	1.77a	0.64a	0.81b	2.1c
		Rice-Duck mixed farming (T_2)	6.80a	7.29a	1036b	857b	1.89a	0.93a	0.89a	5.3a
		Rice-fish mixed farming (T_3)	7.21a	6.88bc	985b	736c	1.78a	0.68a	0.85ab	3.6b
		Rice-Fish-Duck mixed farming (T_4)	6.90a	7.09ab	1126c	991a	1.87a	0.85a	0.93ab	4.7a
		LSD	0.266	0.273	63.21	40.32	40.32	0.292	0.298	0.596
		Level of significance	*	*	**	**	NS	NS	*	**
Boro Season	Showar Union	Rice sole cropping (T_1)	6.7ab	6.9c	935c	779d	1.89a	0.73b	0.93b	2.3d
		Rice-Duck mixed farming (T_2)	6.6b	7.8a	1027b	945a	1.93a	0.98a	1.13a	6.3b
		Rice-fish mixed farming (T_3)	6.8ab	7.4bc	978bc	853c	1.87a	0.83b	0.97b	4.5c
		Rice-Fish-Duck mixed farming (T_4)	6.9a	7.6b	1143a	897b	1.78a	0.87a	1.15a	6.9a
		LSD	0.231	0.146	61.21	40.14	0.034	0.245	0.188	0.542
		Level of significance	NS	**	**	**	NS	**	*	*
	Tetulia Union	Rice sole cropping (T_1)	7.14ab	6.82b	823c	729d	1.95a	0.83b	0.89b	1.9c
		Rice-Duck mixed farming (T_2)	6.81a	7.35a	1043a	874b	1.87a	0.95ab	1.10a	5.1a
		Rice-fish mixed farming (T_3)	7.31a	6.94b	937b	781c	1.83a	0.87b	0.95b	4.2b
		Rice-Fish-Duck mixed farming (T_4)	7.00b	7.19a	1050a	929a	1.79a	0.89a	1.17a	5.6a
		LSD	0.119	0.266	45.03	36.91	0.372	0.238	0.179	0.61
		Level of significance	NS	**	**	**	NS	*	**	**

**indicates significant at the 0.01 level (2-tailed). *indicates significant at the 0.05 level. NS means non-significant.

Rice Duck Fish Farming Productivity, GWP, Net profit, and Benefit Cost ratio (BCR)

The effects of different mixed farming treatments on grain yield, economic return, CH_4 emissions, and global warming potential (GWP) during the Aman and Boro rice cultivation seasons are shown in **Table 4** and **Table 5**. During the Aman season, the higher grain yield of 4194 - 4330 kg ha^{-1} and 3858 - 3980 kg ha^{-1} were recorded in rice-fish-duck (T_4) and rice-duck (T_2) mixed farming compared to rice monoculture (3550 - 3820 kg ha^{-1}). On average, rice yield was increased by 14.5% and 6.15% over the rice sole cropping. Similarly, in the Boro season, the maximum rice grain yield 6050 - 6230 kg ha^{-1} was recorded in rice-fish-duck (T_4), followed by 5980 - 6460 kg ha^{-1} in rice-duck (T2) and 5230 - 5650 kg ha^{-1} in rice sole cropping (T_1). On average, rice yield was increased by 9.1% and 10.4% over the rice sole cropping system. The increased yield in mixed farming treatments may be due to improved nutrient recycling, soil fertility enhancement, biological pest control, and better nutrient availability resulting from fish and duck activities in the rice field ecosystem. Fish and ducks contributed organic manure through excreta and improved nutrient circulation within the system. Hossain et al. (2005) reported a higher rice yield (20%) in the rice-duck system compared to the traditional rice sole-cropping system, thereby ensuring about a 50% higher net return and rice-provisioning ability. Sasmal et al. (2025) reported rice yield was increased by 57.8% in rice-duck-fish mixed farming compared to rice sole cropping. Zhang et al. (2023) also showed that the integrated rice-animal co-culture system, such as fish, frogs, or crayfish raised in paddy fields, increased rice yield by 7.8%, enhanced soil and water nutrients retention, and provided sustainable animal protein while optimizing land and water use.

Table 4. Rice-based mixed farming productivity, net profit, and benefit cost ratio (Two Years Mean Data, Aman Season).

Treatments	Flood water paddy field (Showair Union)								Flood water paddy field (Tetulia Union)							
	Rice Grain yield (Kg ha^{-1})	Cumulative CH_4 flux (Kg ha^{-1} Season^{-1})	GWP (Kg CO_2 eq. ha^{-1})	GHGI (Kg CH_4/kg Grain yield)	Gross return (Tk. ha^{-1})	Total variable cost (Tk. ha^{-1})	Net return (Tk. ha^{-1})	BCR	Rice Grain yield (Kg ha^{-1})	Cumulative CH_4 flux (Kg ha^{-1} Season^{-1})	GWP (Kg CO_2 eq. ha^{-1})	GHGI (Kg CH_4/kg Grain yield)	Gross return (Tk. ha^{-1})	Total variable cost (Tk. ha^{-1})	Net return (Tk. ha^{-1})	BCR
T1: Rice sole cropping	3550b	198.7a	5364a	0.05	85,638	81,200	4438	1.05d	4125a	208.6a	5632a	0.051	98,947	81,200	17,747	1.22c
T2: Rice-duck farming	3860ab	168.8bc	4558bc	0.043	392,787	236,533	156,235	1.66b	4330a	173.6c	4687c	0.039	403,968	236,533	167,435	1.71a
T3: Rice-fish farming	3650b	179.8b	4855b	0.049	286,585	201,200	85,385	1.42c	3980a	197.3b	5327b	0.049	305,660	201,200	104,460	1.52b
T4: Rice fish duck farming	3980a	161.7c	4636c	0.04	626,573	356,533	270,040	1.76a	4194a	178.6b	4823b	0.043	640,794	356,533	284,260	1.80a
LSD	320.10	14.82	400.08	–	–	–	–	0.08	404.39	17.48	472.06	–	–	–	–	0.15
Level of Significant	*	**	**	–	–	–	–	**	NS	**	**	–	–	–	–	**

Table 5. Rice-based mixed farming productivity, net profit, and benefit cost ratio (Two Years Mean Data, Boro Season).

Treatments	Flood water paddy field (Showair Union)								Flood water paddy field (Tetulia Union)							
	Rice Grain yield (Kg ha^{-1})	Cumulative CH_4 flux (Kg ha^{-1} Season^{-1})	GWP (Kg CO_2 eq. ha^{-1})	GHGI (Kg CH_4/kg Grain yield)	Gross return (Tk. ha^{-1})	Total variable cost (Tk. ha^{-1})	Net return (Tk. ha^{-1})	BCR	Rice Grain yield (Kg ha^{-1})	Cumulative CH_4 flux (Kg ha^{-1} Season^{-1})	GWP (Kg CO_2 eq. ha^{-1})	GHGI (Kg CH_4/kg Grain yield)	Gross return (Tk. ha^{-1})	Total variable cost (Tk. ha^{-1})	Net return (Tk. ha^{-1})	BCR
T1: Rice sole cropping	5230b	213.0a	5751a	0.041	125,895	95,167	30,728	1.32c	5650b	228.0a	6156a	0.041	135,458	95,167	40,291	1.42c
T2: Rice-duck farming	5980a	172.0b	4644b	0.028	443,140	250,500	191,640	1.77a	6460a	183.0c	4941c	0.029	454,828	250,500	204,328	1.82ab
T3: Rice-fish farming	5750a	181.0ab	4887ab	0.031	349,535	209,333	140,201	1.67b	6080ab	191.0b	5157b	0.031	3,584,412	209,333	149,078	1.71b
T4: Rice fish duck farming	6030a	176.0b	4752b	0.029	662,220	364,667	297,553	1.75a	6230a	179.0c	4839c	0.028	684,255	364,667	319,588	1.88a
LSD	381.82	23.45	633.3	–	–	–	–	0.11	466.97	17.48	472.06	–	–	–	–	0.19
Level of Significant	**	*	*	–	–	–	–	**	*	**	**	–	–	–	–	**

In this study, the total cumulative CH_4 flux was recorded as 198.7 - 208 kg ha^{-1} season^{-1} during aman growing season, in rice sole cropping (T_1), while 213 - 228 kg ha^{-1} season^{-1} during the Boro rice cultivation. The total seasonal CH_4 flux was decreased by 19.5%, 15.4%, and 20.0% under rice-duck, rice-fish, and rice-duck-fish mixed farming, respectively, compared to rice sole cropping in the boro growing season. Similarly, seasonal CH_4 fluxes decreased by 15.7%, 7.4%, and 16.0% under rice-duck, rice-fish, and rice-duck-fish mixed farming, respectively, compared to rice sole cropping in the Aman growing season. Reduced CH_4 emissions in integrated systems might result from the movement of fish and ducks, which disrupted the soil and enhanced oxygen diffusion in flooded areas, consequently inhibiting anaerobic methanogenic activity. Du et al. (2023) reported that rice-duck co-culture decreased CH_4 emissions by 8.8% - 16.7% while maintaining or increasing rice yield. Xu et al. (2023) stated that rice-duck systems substantially mitigated greenhouse gas emissions by reducing CH_4 and CO_2, leading to a 19% - 25% decline in global warming potential without compromising rice yield. Ali (2017) also reported that rice-duck mixed farming decreased seasonal cumulative CH_4 emissions by 18.0% - 24.0%, while increasing rice yield by 19% - 22.0% compared to rice sole cropping. Ma et al. (2026) reported that microalgae biofertilizer combined with a reduced amount of chemical fertilizer significantly decreased CH_4 emissions, the GWP, and GHGI, while increasing the rice yield. Azolla cyanobacterial mixture has been used as biofertilizer to supplement the N demand of the rice crop through partial replacement of the costly chemical N fertilizer under conditions of sustainable agriculture, while its effect on CH_4 and N_2O emissions reduction has been reported by Bharati et al. (2000), Prasanna et al. (2002), Ali et al. (2012), and Kollah et al. (2015).

The maximum GWP value calculated is 5364 - 5632 kg CO_2 eq. ha^{-1} for rice sole cropping (T_1) during Aman season, while 5751 - 6156 kg CO_2 eq. ha^{-1} for the Boro rice growing season. Rice-based mixed farming treatments significantly decreased the GWPs' value. The Rice-Duck and Rice-Fish-Duck mixed farming systems reduced GWPs by 15% - 19% and 16% - 20%. Sun et al. (2021) reported that the rice-crayfish and rice-duck modes significantly decreased GWP by 18.0% and 11.0%, respectively, whereas the rice-fish mode enhanced the GWP by 20.8%. Feng et al. (2024) revealed the superiority of the rice-duck co-culture system over the traditional rice monoculture in China by enhancing agricultural sustainability, improving the rural economy and sustainable diets, and, above all, reducing GHG emissions and the overall carbon footprint (9934.0 vs 10875.8 kg CO_2 e/hm2) per hectare of land. In the rice-fish-duck system, the activities of fish and ducks agitated the water, loosened the soil, significantly increased dissolved oxygen content (Wang et al., 1989), greatly reduced soil reductant content, and increased the redox potential. Therefore, the emission of CH_4 was reduced, and the control effect on the peak period of CH_4 emission from the paddy field is the most obvious (Liu et al., 2006).

Economic analysis showed significant variations among rice-based mixed farming practices. During the Boro season, rice-fish-duck (T_4) mixed farming yielded the maximum benefit-cost ratio of 1.88, followed by 1.82, 1.71, and 1.42 for rice-duck (T_2), rice-fish (T_3), and rice sole cropping (T_1), respectively. Comparable patterns were found in the Aman season, where rice-fish-duck (T_4) farming revealed the maximum benefit-cost ratio (BCR) of 1.76, while rice sole cropping

Table 6. Correlation of CH_4 emissions with flood water properties.

Correlations												
		Yield	CH4	pH	DO	TDS	EC	Eh	NH_4^+-N	NO_3^--N	Dissolved Iron	PO_4^{-3}
Yield	Pearson Correlation	1										
	Sig. (2-tailed)											
	N	12										
CH_4	Pearson Correlation	−0.086	1									
	Sig. (2-tailed)	0.790										
	N	12	12									
pH	Pearson Correlation	−0.049	0.082	1								
	Sig. (2-tailed)	0.881	0.799									
	N	12	12	12								
DO	Pearson Correlation	0.431	−0.676*	0.160	1							
DO	Sig. (2-tailed)	0.161	0.016	0.619								
	N	12	12	12	12							
TDS	Pearson Correlation	0.365	−0.741**	−0.153	0.546	1						
	Sig. (2-tailed)	0.243	0.006	0.636	0.066							
	N	12	12	12	12	12						
EC	Pearson Correlation	0.359	−0.707*	−0.300	0.576	0.946**	1					
	Sig. (2-tailed)	0.251	0.010	0.344	0.050	0.000						
	N	12	12	12	12	12	12					
Eh	Pearson Correlation	−0.053	−0.772**	−0.101	0.602*	0.225	0.324	1				
	Sig. (2-tailed)	0.870	0.003	0.756	0.038	0.482	0.304					
	N	12	12	12	12	12	12	12				
NH_4^+-N	Pearson Correlation	0.145	−0.040	0.097	0.304	0.398	0.381	−0.272	1			
	Sig. (2-tailed)	0.652	0.902	0.765	0.337	0.200	0.222	0.393				
	N	12	12	12	12	12	12	12	12			
NO_3^--N	Pearson Correlation	0.429	−0.311	0.286	0.517	0.649*	0.611*	−0.059	0.638*	1		
	Sig. (2-tailed)	0.164	0.325	0.368	0.085	0.022	0.035	0.854	0.026			
	N	12	12	12	12	12	12	12	12	12		
Dissolved Iron	Pearson Correlation	0.177	−0.051	0.267	0.154	0.601*	0.513	−0.461	0.676*	0.820**	1	
	Sig. (2-tailed)	0.582	0.874	0.402	0.633	0.039	0.088	0.131	0.016	0.001		
	N	12	12	12	12	12	12	12	12	12	12	
PO_4^{-3}	Pearson Correlation	0.396	−0.765**	0.217	0.785**	0.841**	0.788**	0.411	0.472	0.766**	0.508	1
	Sig. (2-tailed)	0.202	0.004	0.498	0.002	0.001	0.002	0.185	0.122	0.004	0.092	
	N	12	12	12	12	12	12	12	12	12	12	12

*Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

(T_1) resulted in the least net return with the lowest BCR value of 1.03. These findings suggest that integrated rice-fish-duck farming is more economically feasible than traditional rice monoculture since farmers earn extra income from fish and duck rearing. Xu et al. (2023) found that the economic benefits of the rice-fish-duck symbiosis model increased by 17.2% compared with the rice-fish symbiosis model. Meng et al. (2021) showed that the rice-fish-duck model also showed higher economic benefits than the rice-fish model and the rice-duck model, with an increase in income by 32.9% and 229.0%, respectively. The integrated rice-fish-duck farming systems improved grain yield and economic profitability while decreasing seasonal cumulative CH_4 emissions. Ali (2017) reported an increased net return of Tk. 54,432 - 57,308 with a BCR value of 2.14 from rice duck mixed farming compared to rice sole cropping (net return Tk. 14,686, BCR 1.46) across Dingapota haor. It has also been shown that the net profit is Rs. 3.1 lakh/ha and Rs. 1.56 lakh/ha water area from integrated fish cum duck farming and fish traditional farming, respectively (Saikia et al., 2020). In this study, rice-fish-duck mixed farming and rice-duck farming revealed significantly higher productivity and net return compared to rice sole cropping and rice fish mixed farming. Similar results were also reported by Sasmal et al. (2025). In this study, seasonal cumulative CH_4 emissions were positively correlated with flood water pH, whereas negative correlations were observed with DO, EC, TDS, nitrate, dissolved Fe, Eh, ammonium, and phosphate contents (**Table 6**), being supported by our previous research studies (Ali et al., 2008, 2015). Nayak et al. (2020) recorded significantly higher rice equivalent yield 7.74 t ha^{-1}, $p < 0.001$ in Rice-Fish-Duck, followed by 5.48 t ha^{-1}, $p < 0.005$ in Rice-Duck and 5.34 t ha^{-1}, $p < 0.005$ in Rice-Fish as compared to rice alone 3.81 t ha^{-1}.

4. Conclusion

The Flood Vulnerability Index value of 0.95 was found across the Dingapota haor area, indicating very high vulnerability to flood disasters. This research revealed some feasible adaptation strategies, such as integrated rice-duck, rice-fish, and rice-duck-fish farming practices for sustainable agricultural productivity against the flood-driven vulnerability around the selected Haor community. Although the Dingapota haor areas are much more fertile land for agricultural production, flash floods, seasonal floods, and other natural disasters very often pose a threat to food security by damaging rice crops and fisheries, which ultimately impacts the regional and the country's food security and economy. The experimental findings reveal the superiority of rice-duck fish mixed farming over the traditional rice monoculture system. On average, rice yield was increased by 9.1% - 14.5% and 6.1% - 10.4% for rice duck fish and rice duck mixed farming over rice sole cropping. The total seasonal CH_4 flux was decreased by 15.7% - 19.5%, 7.4% - 15.4%, and 16.0% - 20.0% under rice-duck, rice-fish, and rice-duck-fish mixed farming, respectively, compared to rice sole cropping. Rice-fish-duck (T_4) mixed farming contributed to the maximum benefit-cost ratio (BCR) of 1.88, followed by 1.82, 1.71, and 1.03 for rice-duck (T_2), rice-fish (T_3), and rice sole cropping (T_1), respectively. Inoculation of spirulina with azolla compost reduced the application of inorganic fertilizers in rice-duck fish farming and improved the overall productivity of the wetland paddy ecosystem. Conclusively, rice-duck fish and rice-duck mixed farming systems with a spirulina-based bio-fertilizer are recommended for sustainable agricultural productivity, reduced GHG emissions, and improved rural economy. Finally, policy-making authority should actively support suitable agro-based farming technologies for the flood-prone haor areas to ensure food security, mitigate GHGs, and reduce agricultural vulnerability to climate change.

Author Contributions

Muhammad Aslam Ali, being supervisor and principal investigator, was responsible for overall research activities monitoring and helped in draft write-up; **Zidan Ali Fagun** conducted field experiments and collected experimental data; **Shahroz Mahean Haque**, being Co-PI, contributed to fish and ducklings rearing with a special mixture of conventional feeds and Azolla Spirulina; **Md. Shahadat Hossen** was involved in water samples analysis; **Tanver Hossain** helped in collecting gas samples from the field; **Biddut Kumar Paul** helped in figure preparation and sigma plot; **Md. Saimur Rashid** contributed to the Acrylic Chamber placement in the field; **A. B. M. Shafiul Alam** helped in the compilation of field data and Statistical analysis; **Md. Mozammel Haque** contributed to gas samples analysis and validation of experimental data; **Md. Shamsur Rahman** helped with the water and soil parameters analysis.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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