PLANT SCIENCE TODAY
Vol 13(sp1): 01–09
https://doi.org/10.14719/pst.11511

eISSN 2348-1900

RESEARCH ARTICLE

Transforming coastal deltaic agriculture: A pathway to doubling farmers' income in Karaikal

Pavithra Rathnasamy[1], Mohan Ramalingam[1*], Aruna Lakshminarayan[2], Mala Subramanian[1], Thirumeninathan Subramanian[1] & Nivetha Chinnu[1]

[1]Department of Agronomy, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal 609 603, U. T. of Puducherry, India
[2]Department of Soil Science and Agricultural Chemistry, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal 609 603, U. T. of Puducherry, India

*Correspondence email - mohankkl@gmail.com

Received: 28 August 2025; Accepted: 05 December 2025; Available online: Version 1.0: 06 November 2025

Cite this article: Pavithra R, Mohan R, Aruna L, Mala S, Thirumeninathan S, Nivetha C. Transforming coastal deltaic agriculture: A pathway to doubling farmers' income in Karaikal. Plant Science Today. 2025;13(sp1):01–09. https:/doi.org/10.14719/pst.11511

Abstract

Rice cultivation in coastal river deltaic regions faces increasing challenges due to declining on-time river water availability, soil salinity and stagnating yields, which limit income growth for smallholder farmers. This study hypothesised that integrating water-saving irrigation, hydrogel application and intercropping could significantly improve aerobic rice performance and economic returns in coastal conditions. A field experiment was conducted during the summer season of 2022 at Karaikal, a coastal region in southern India, to assess the effects of two irrigation methods (drip irrigation and surface irrigation), two hydrogel levels (with and without application) and four intercropping systems (no intercrop, black gram, green gram and onion) on aerobic rice. The treatments were arranged in two separate two-factor randomised block designs under each irrigation method. The results showed that hydrogel application increased the grain yield of aerobic rice by 2.5 % from 4807 to 4923 kg ha^{-1}. Surface irrigation produced 28 % higher yield of aerobic rice (5464 kg ha^{-1}) than drip irrigation (4266 kg ha^{-1}). The most profitable treatment was surface-irrigated aerobic rice intercropped with black gram and supplemented with hydrogel, which achieved the highest gross return (₹ 219450 ha^{-1}), net return (₹ 162103 ha^{-1}) and benefit-cost ratio (3.83). Here, we demonstrate that the strategic integration of surface irrigation, hydrogel application and legume intercropping can substantially improve rice yield and profitability under coastal conditions. This is the first study to evaluate such combined interventions for aerobic rice in the deltaic ecosystem of Karaikal. The findings offer a practical and scalable approach to enhance resource-use efficiency, income and sustainability in climate-vulnerable rice farming systems.

Keywords: aerobic rice; drip irrigation; economics; hydrogel; intercropping; surface irrigation

Introduction

Rice (*Oryza sativa* L.) remains the staple food crop for more than half of the worlds' population, with nearly 90 % of global rice production concentrated in Asia. As of 2022, rice is cultivated over 166.54 Mha worldwide, yielding approximately 513.56 MMT annually (1). In India, rice-based cropping systems are fundamental to food security and rural livelihoods, particularly in coastal and river deltaic regions where agriculture is intricately linked to the release of dam water in rivers, monsoonal rainfall, groundwater dynamics and salinity intrusion. The coastal deltaic region of Karaikal, located within the Union Territory of Puducherry and forming part of the fertile river Cauvery delta, exemplifies both the promise and vulnerability of such rice-growing ecosystems. Despite its rich alluvial soils and historical reliance on the Cauvery irrigation system, Karaikal faces mounting challenges, including inconsistent release of dam water in rivers, erratic monsoonal patterns, saline irrigation water, declining groundwater levels and increased coastal vulnerability due to climate change impacts such as sea-level rise, storm surges and coastal erosion (2, 3). These agro-climatic stresses have constrained the potential of traditional rice cultivation, leading to stagnant yields, reduced input-use efficiency and limited income growth, particularly for the regions' small and marginal farmers.

Rice consumes 30 % of all fresh water used worldwide. The productivity of the Asian irrigated rice system is increasingly threatened by water scarcity. It is estimated that 2 M ha of Asian irrigated dry season rice and 13 M ha of its irrigated wet season rice may experience physical water scarcity by 2025 (4). For regions facing water scarcity, the aerobic rice system is proving to be a promising technology by reducing water use (5). Aerobic rice system had been developed in the mid-eighties and now aerobic rice is grown commercially in Brazil and Northern China (6, 7). Aerobic rice refers to growing rice in conditions of non-flooded and non-puddled lowland soil with supplemental irrigation. Aerobic rice recorded substantial water savings by minimising seepage, percolation and greatly reduced evaporation (8). Although aerobic rice yields are lower than conventional flooded lowland rice yields, it may be an attractive option to farmers where water is too scarce to grow lowland puddled and flooded rice (6). Aerobic rice generally requires 30 - 50 % less water, even though it results in a yield penalty of 20 to 30 % (9).

The looming threat of physical water scarcity in irrigated rice areas, as projected, highlights the urgent need for water-saving technologies and sustainable intensification strategies (10). Among these, alternate wetting and drying (AWD) has been shown to reduce irrigation water use by up to 30 % without compromising yield (11). Likewise, saturated soil culture (SSC) and aerobic rice systems have demonstrated improved water productivity and suitability for upland or water-limited environments (12). Hydrogels, commonly referred to as root watering crystals, water retention granules, or raindrops, are quasisolid-phase amorphous materials composed of three-dimensional networks of cross-linked, hydrophilic macromolecules. These organic polymers are interconnected *via* covalent bonds or physical interactions, offering high absorbency and biodegradability. Their superabsorbent structure enables them to rapidly absorb substantial amounts of water upon contact. During soil desiccation, they gradually release the stored moisture into the surrounding soil and rhizosphere in a uniform and sustained manner, thereby improving water availability to plants (13, 14). The use of hydrogels, which enhance soil moisture retention and reduce evapotranspiration losses, has further improved water and nutrient use efficiency in rice-based systems (15, 16). Additionally, drip fertigation has gained traction as a precision input-delivery system, allowing for significant savings in water and fertilisers while boosting crop response.

While these interventions offer individual benefits, their integration has the potential to yield synergistic effects on resource-use efficiency and profitability. For instance, the incorporation of intercropping, particularly with legumes or vegetables, not only improves land-use efficiency and biological nitrogen fixation but also buffers against income fluctuations. Rice-legume intercropping systems can enhance net returns by 20-40 % over monocropped rice, while improving soil health and system resilience (17, 18). Similarly, integrated farming systems (IFS)-combining crops, livestock and horticulture - have shown promising results in doubling farm income in comparable agro-ecological settings (19). The Government of Indias' committee on doubling farmers' income (DFI) emphasises transformation through increased productivity, cost reduction, diversification, market access and risk mitigation (20). In this context, climate-resilient agronomic technologies hold the key to sustainable growth in vulnerable regions like Karaikal. Despite national advances, integrated and region-specific evaluations of such approaches remain scarce in this coastal enclave.

The present study aims to address this research gap by scientifically evaluating the combined effects of aerobic rice cultivation, hydrogel application, drip fertigation and intercropping systems in the coastal river deltaic conditions of Karaikal. It seeks to assess their impact on crop growth, yield attributes, input-use efficiency, water productivity and profitability. This integrated approach aligns with the broader goal of sustainable intensification, offering a replicable model for similar coastal agro-ecosystems. With approximately 40 % of the worlds' population residing within 100 km of coastlines and over 171 million people living in Indias' coastal districts, building resilience in coastal agriculture is not only a local imperative but a global necessity (3). By advancing practical, economically viable and ecologically sound farming interventions, this study contributes toward the national mission of doubling farmers' income, enhancing rural livelihood security under the looming challenges of climate variability and land-water constraints.

Materials and Methods

Study area

The field study was carried out during the summer season of 2022 on clay loam soil at Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal, U.T. of Puducherry. The experimental site is located between 10°49′ and 11° 01' North latitude and 78° 43′ and 79° 52′ East longitude at an altitude of 4 m above mean sea level.

Experimental design

The experiment involved a thrice-replicated randomised block design testing two different irrigation methods (drip irrigation at 1.0 PE and surface irrigation at 1.0 IW/CPE) in the same field. Four different intercrops (no intercrop, black gram, green gram and onion) were tested with or without hydrogel treatment. Statistical analysis was conducted as a factorial RBD including irrigation methods as one factor, with treatments randomly allotted in each replication. The plot size was 6 m × 4.5 m. Aerobic rice was sown in paired rows by modifying the regular spacing to 15/25 × 10 cm. One row of intercrop was placed between paired rows of rice. Intercrops were also sown outside the treatment plot as sole crops for yield assessment. Hydrogel polymer mixed with sand was broadcast at 5 kg ha^{-1} for the respective treatments before sowing.

Experiment details

In the surface irrigation method, first irrigation was given on the sowing day, followed by lifesaving irrigation on the third day after sowing. Subsequent irrigations were provided once or twice weekly based on the IW/ CPE ratio. In drip irrigation plots, irrigation was scheduled once every alternate day based on real-time USWA open pan evaporation data from the meteorological observatory. The quantity of water to be applied by one lateral was computed based on the formula at Eqn (1) and the time of operation of the drip system was computed based on the formula at Eqn. (2) below:

$$V = Eo \, . \, A \qquad \text{(Eqn.1)}$$

$$T = V/(D \, . \, N) \qquad \text{(Eqn.2)}$$

Where, V is the volume of water (L) to be delivered by one lateral, Eo is the USWA open pan evaporation (mm day^{-1}), A is the area (m^2) covered by one lateral, T is the time of operation of drip system (h), D is the discharge rate (lph) of emitter and N is the number of emitters in a lateral.

Other crop management practices were followed as per crop production guides. Main and intercrops were harvested at physiological maturity. For yield comparison, crop yields of all intercrops were converted into rice equivalent yield (REY) on the price basis (Eqn. 3) (21).

$$REY\ (Kg\ ha^{-1}) = Y_r + \left[\frac{Y_i\ x\ P_i}{P_r}\right] \qquad \text{(Eqn.3)}$$

Where, REY denotes rice equivalent yield; Y_r = Grain yield of rice in intercropping system (kg ha^{-1}); Y_i = Grain / Seed yield of intercrops in intercropping system (kg ha^{-1}); P_i = Market price of intercrop produce (₹ kg^{-1}); P_r = Market price of rice grain (₹ kg^{-1}).

All growth, yield attributes and yields of main and intercrops recorded were subjected to statistical scrutiny as per the procedure (22). The surface irrigated aerobic rice treatment without hydrogel and intercrops was considered as the existing cropping system for analysing and comparing the proposed systems. Different budgeting techniques are available for comparing the economic viability of the proposed cropping systems with the existing system. The most common are resource budgeting, marginal analysis and parametric budgeting (23, 24). The efficiency of the resource used in the production processes are measured by return to labour (Eqn. 4), return to material cost (Eqn. 5) and return above variable cost (RAVC) (Eqn. 6). Similarly, the cost and return on making changes to an enterprise with the existing one are measured through marginal benefit cost ratio (MBCR) (Eqn. 7).

Return to labour cost (RLC) = (GR - MC)/ LC (Eqn.4)

Return to material cost (RMC) = (GR - LC)/ MC (Eqn.5)

RAVC = GR - TVC (Eqn.6)

Marginal benefit cost ratio (MBCR) = Δ GR/ Δ TVC (Eqn.7)

Where, GR is the gross return of the system, MC is the material cost of the system, LC is the labour cost of the system, TVC is the total variable cost of the system, Δ GR is the added returns of the proposed system above that of existing system, Δ TVC is the added cost of the proposed system above that of the existing system. However, the parametric budgeting includes the break-even yield point (BEP) and sensitivity analysis. BEP (YB) of existing and proposed cropping systems could be calculated from the following relationship (Eqn. 8) that exists between RAVC of the cropping system, total variable cost of the system (TVC) and the expected price of the produce (P_N):

P_N. YB = TVC + RAVC (Eqn.8)

With the help of the above equation (Eqn. 8), break-even yields (YB) of the existing cropping system could be calculated by substituting RAVC as 0, while the break-even yields (YB) of the proposed new system could be calculated by substituting the RAVC of the existing cropping system.

The sensitivity analysis of the system is done by working out the percentage change in price of the output (Eqn. 9) and input cost (Eqn. 10) so that RAVC will remain above zero.

Percentage change in produce cost = [(TVC - GR)/ TVC] × 100 (Eqn.9)

Percentage change in variable cost = [(TVC + RAVC)/TVC] × 100 (Eqn.10)

Where, TVC is the total variable cost of the system, GR is the gross return of the system and RAVC is the return above variable cost of the system.

Results and Discussion

Rice yield

The grain yield and equivalent yield of aerobic rice under two irrigation methods with or without hydrogel in different intercropping conditions are presented in Table 1. Significant differences were observed between hydrogel treatment and irrigation methods, while the intercrops had not produced a noticeable difference in the yield of aerobic rice. Hydrogel treatment resulted in a higher grain yield (4923 kg ha^{-1}) compared to no hydrogel (4807 kg ha^{-1}). Research has demonstared that soil water retention capacity of 23.7 - 37.2 % by hydrogel. A grain yield increase of 35.16 % over control in aerobic rice (25 - 27). However, in the present study, the hydrogel contributed an average yield increase of 2.5 % over control (28). This could be attributed to the polymers' ability to retain and gradually release water, ensuring adequate moisture availability under stress conditions. Additionally, it indirectly facilitated nutrient supply to plants, leading to efficient translocation of water, nutrients and photosynthates, ultimately resulting in higher economic yields.

Similarly, surface irrigation yielded 28 % more grain yield (5464 kg ha^{-1}) than drip irrigation (4266 kg ha^{-1}), mainly attributed to increased spikelet numbers and reduced ill-filled grains. Research has demonstrated that that providing water as flood irrigation to maintain a cyclic wet and dry soil condition in aerobic rice fields, otherwise continuous maintenance of saturated soil moisture through drip irrigation had resulted to register significantly higher numbers of filled grains coupled with significantly lower numbers of ill-filled grains, particularly at heading till milky dough stage (29).

Surface irrigation achieved an average grain yield of aerobic rice (5464 kg ha^{-1}), 17 % higher than the average rice productivity of the high-yielding group of farmers (30) during the same season in the region. However, the grain yield of aerobic rice in the present study under drip irrigation (4266 kg ha^{-1}) was 18 % higher than the average rice productivity of the low-yielding group of farmers during the same season in the region, yet 9 % lower than the average high-yielding group of farmers (30). The low yield of drip irrigation over surface irrigation was likely due to high air temperatures during maturity, increased soil moisture tension and reduced metabolite synthesis and translocation (29, 31-33). Individual factors like irrigation methods, hydrogel treatments and intercrops did not significantly affect straw yield.

Table 1. Effect of irrigation methods, hydrogel and intercrops on grain and rice equivalent yield of aerobic rice

Treatments	Grain yield (kg ha^{-1})					REY (kg ha^{-1})				
	I_1	I_2	H_0	H_1	Mean	I_1	I_2	H_0	H_1	Mean
C_1 – No intercrop	4264	5471	4802	4933	4867	4181	4238	4136	4283	4209
C_2 – Black gram	4250	5483	4783	4949	4866	7878	8133	7872	8138	8005
C_3 – Green gram	4285	5507	4914	4878	4896	7075	6887	6892	7070	6981
C_4 – Onion	4264	5396	4730	4931	4830	6747	6125	6769	6102	6436
H_0 – No hydrogel	4187	5428	-	-	4807	6638	6197	-	-	6417
H_1 – Hydrogel at 5 kg ha^{-1}	4345	5500	-	-	4923	6302	6495	-	-	6398
Mean	4266	5464	-	-	4865	6470	6346	-	-	6408
Sources	S.Ed		CD (p = 0.05)			S.Ed		CD (p = 0.05)		
Irrigation (I)	54.7		112			356.4		NS		
Hydrogel (H)	54.7		112			356.4		NS		
Intercrop (C)	77.4		NS			504.0		1029		
I × H	77.4		NS			504.0		NS		
I × C	109.4		NS			712.7		NS		
H × C	109.4		NS			712.7		NS		
I × H × C	154.8		NS			1008.0		NS		

S. Ed – Standard error difference, **CD** – Critical difference, ***p*** = 0.05 – 95 % confidence level

Rice equivalent yield

The aerobically cultivated rice crop, when intercropped with black gram, yielded a significantly higher rice equivalent yield (REY) of 8005 kg ha^{-1} (Table 1) compared to other intercrops such as green gram and onion, which produced 6981 and 6436 kg ha^{-1}, respectively. This increase can be attributed to the additional yield advantage provided by the intercropping system, along with the higher market value of black gram. Intercropping aerobic rice with other crops significantly enhanced biological yield, intercropping efficiencies and benefit-cost ratio, thereby demonstrating superior production and economic efficiency compared to sole aerobic rice cultivation (34). The lowest REY was observed in the aerobic rice + onion system (6436 kg ha^{-1}), due to the relatively lower additional yield of onion. Research has demonstrated that a maximum rice-equivalent yield of 2711 kg ha^{-1} under the rice + black gram intercropping system (35). Similar increases in REY as a result of intercropping have been documented (36-39). The total rice equivalent yield (REY) of rice + vegetables intercropping system (15.3–29.0 t ha^{-1}) was significantly higher than that of sole rice cultivation (4.9–6.5 t ha^{-1}) (40). In the present study, the REY of rice + black gram, rice + green gram and rice + onion are 8005, 6981 and 6436 kg ha$^{-1,}$ which were about 71, 49 and 38 % higher than the average rice productivity of the high-yielding group of farmers in the region.

Economics

The total cost of cultivation, gross returns, net returns and B:C ratio of individual treatments to ascertain the economic strength of each treatment are worked out and furnished in Table 2. The most profitable and net-return system is regarded as being economically significant. Among the treatments, surface irrigated aerobic rice with hydrogel application intercropped with black gram registered the highest gross return of ₹ 219450 ha^{-1}followed by the same set of treatment under no hydrogel condition (₹ 208031 ha^{-1}). Rice legume intercropping system was earlier reported to result in a 57.3 % increase in growing margins and additional net returns (USD 203 ha^{-1}) per cycle compared to sole rice cultivation (41).

Similarly, due to variation in the cost of cultivation and gross return, the net return also varied within the treatment (₹ 32396 to ₹ 162103 ha^{-1}). The highest net return was registered by surface irrigated aerobic rice + black gram along with hydrogel application (₹ 162103 ha^{-1}) and it was three times higher than the net return obtained in aerobic rice alone (without hydrogel) under surface irrigation (₹ 56673 ha^{-1}). Research has demonstrated that opined that the gross return and net return were maximum in the rice + black gram intercropping system (42-44). However, on the contrary, research indicates that sole black gram was found to be more remunerative than rice + black gram (45).

Among the treatment combinations, the aerobic rice + black gram with hydrogel application under surface irrigation registered the highest B: C ratio of 3.83, followed by the aerobic rice + black gram without hydrogel application under surface irrigation (3.81). Higher net returns and benefit-cost ratios in cereal + legume intercropping systems compared to sole cereal cropping were earlier reported by several authors (46-48). The application of hydrogel has been shown to enhance economic returns in different cropping systems. In the present study, it resulted in a gross return of ₹ 176043 ha^{-1}, net return of ₹ 131193 ha^{-1} and a benefit–cost ratio of 2.93 compared to the control (No hydrogel). In pearl millet, applying hydrogel at 4 kg ha^{-1} along with four irrigations has been reported to yield the highest economic benefits with a gross return of ₹ 69222.96 ha^{-1}, net return of ₹ 45066.76 ha^{-1} and a benefit cost ratio of 2.87 (49).

Partial budgeting

The additional cost involved for imposing treatments and the additional returns obtained by those treatments were worked out and furnished in Table 3. The partial budget analysis showed that the amount of additional cost involved was substantially higher in the case of onion intercrop when compared to the no intercrop aerobic rice system. On the other hand, the additional returns obtained under surface irrigated aerobic rice-based intercropping system were substantially higher (₹ 62308 ha^{-1}) when compared to the drip irrigated aerobic rice-based intercropping system (₹ 39111 ha^{-1}).

For better comparison of treatments, the net gain was worked out based on the additional returns and additional costs involved for the individual treatments. The aerobic rice intercropped with black gram, coupled with hydrogel application, had registered substantially higher net gain of ₹ 105430 ha^{-1} followed by the same intercropping without hydrogel (₹ 96761 ha^{-1}). The application of hydrogel at 2.5 and 5 kg per hectare was reported to reduce the number of irrigations by two and three times, with an economic benefit–cost ratio of 2.64 and 2.09, respectively, indicating improved input-use efficiency (50). In general, it could be seen that all the intercropping treatments had positive net gain except onion; however, the net gain of onion remains positive under the surface irrigation method.

Table 2. Economics of an aerobic rice-based intercropping system under different irrigation with or without hydrogel application

Treatments			Common cost	Treatment cost	Total cost	Gross return*	Net return	B:C ratio
			(₹ ha^{-1})			(₹ ha^{-1})		
Drip irrigation	Without hydrogel	No intercrop	41547.00	5083.00	46630.00	80256.00	33626.00	1.72
		Black gram	41547.00	14133.00	55680.00	183407.00	127727.00	3.29
		Green gram	41547.00	13933.00	55480.00	162830.00	107350.00	2.93
		Onion	41547.00	42496.00	84043.00	130625.00	46582.00	1.55
	With hydrogel	No intercrop	41547.00	7833.00	49380.00	81776.00	32396.00	1.66
		Black gram	41547.00	16883.00	58430.00	191881.00	133451.00	3.28
		Green gram	41547.00	16683.00	58230.00	163780.00	105550.00	2.81
		Onion	41547.00	45246.00	86793.00	136097.00	49304.00	1.57
Surface irrigation	Without hydrogel	No intercrop	41547.00	4000.00	45547.00	102220.00	56673.00	2.24
		Black gram	41547.00	13050.00	54597.00	208031.00	153434.00	3.81
		Green gram	41547.00	12850.00	54397.00	185155.00	130758.00	3.40
		Onion	41547.00	41413.00	82960.00	155287.00	72327.00	1.87
	With hydrogel	No intercrop	41547.00	6750.00	48297.00	105659.00	57362.00	2.19
		Black gram	41547.00	15800.00	57347.00	219450.00	162103.00	3.83
		Green gram	41547.00	15600.00	57147.00	180956.00	123809.00	3.17
		Onion	41547.00	44163.00	85810.00	159467.00	73657.00	1.85

*Price of rice grain - ₹ 19 kg^{-1}, Black gram - ₹ 80 kg^{-1}, Green gram - ₹ 65 kg^{-1},Onion - ₹ 30 kg^{-1}

Table 3. Partial budgeting of aerobic rice-based intercropping system under different irrigation with or without hydrogel application

Treatments			Added cost	Added return	Net gain
				(₹ ha^{-1})	
Drip irrigation	Without hydrogel	No intercrop	1083.00	(-) 21964.00	(-) 23047.00
		Black gram	10133.00	81187.00	71054.00
		Green gram	9933.00	60610.00	50677.00
		Onion	38496.00	28405.00	(-) 10091.00
	With hydrogel	No intercrop	3833.00	(-) 20444.00	(-) 24277.00
		Black gram	12883.00	89661.00	76778.00
		Green gram	12683.00	61560.00	48877.00
		Onion	41246.00	33877.00	(-) 7369.00
Mean			16286.00	39111.00	22825.00
Surface irrigation	Without hydrogel	No intercrop	--	--	--
		Black gram	9050.00	105811.00	96761.00
		Green gram	8850.00	82935.00	74085.00
		Onion	37413.00	53067.00	15654.00
	With hydrogel	No intercrop	2750.00	3439.00	689.00
		Black gram	11800.00	117230.00	105430.00
		Green gram	11600.00	78736.00	67136.00
		Onion	40263.00	57247.00	16984.00
Mean			15216.00	62308.00	47092.00

Parametric budgeting and sensitivity analysis

The total system productivity in terms of REY and various budget parameters, like parametric budgeting and sensitivity analysis to ascertain the economic strength of each treatment imposed, is furnished in Table 4. Parametrically analysing different cropping systems under study, it could be seen that the labour cost is 1.5 times more than the material costs in all the cropping systems except rice + onion, where the material cost is 1.25 times higher than the labour cost due to the higher cost of seed onion. As a consequence, the return above material cost was 1.5 to 1.75 times higher than the return above labour cost in all the cropping systems except rice + onion, in which the return above material cost is lower than the labour cost. The cost and return on making changes to a system with the existing one is measured through the marginal benefit-cost ratio (MBCR). Analysing the marginal benefit cost ratio (MBCR) of the proposed systems, it could be evident that sole aerobic rice without intercropping either with (-5.33) or without (-20.28) hydrogel application under drip irrigation did not prove to be better than the existing practice by registering negative MBCR values. All the other proposed cropping systems registered positive MBCR values ranging from 0.82 to 11.69. The surface irrigated aerobic rice + black gram without hydrogel proved to be 11.69 times more beneficial compared to the existing aerobic rice alone without hydrogel application.

Surface irrigated aerobic rice without an intercrop and hydrogel was considered the existing base practice for working out various economic sensitivity analyses. It is estimated that the yield obtained by the existing cropping practice was 1.16 times the calculated BEP yield (Considering RAVC = 0). Similarly, the BEP of different proposed intercropping systems were computed by considering RAVC = RAVC of the existing system. Among the different intercrops under study, surface irrigated aerobic rice + black gram with (91.73 %) or without hydrogel (62.70 %) had registered the highest percentage of increase over BEP, ensuring not only viable than the existing system but also ensuring to double the income of the farmers.

The sensitivity analysis of all the intercrop systems that were under study in both drip and surface irrigation methods was depicted to understand the changes in the price of the produce or the price of the production costs (Fig. 1-2). From the sensitivity graphs, in general, it could be evidenced that the surface irrigation method is less sensitive to changes in any input or output prices. The rice + black gram intercrop system grown under the surface irrigation method would tolerate a wider range of fluctuations in input-output prices, *i.e.* an increase of 3.7 times in the cost of input or a decrease of 2.8 times in the cost of produce, with a high return above variable costs (RAVC). On the other hand, the rice + black gram system under the drip irrigation method would tolerate up to 2.2 times increase in input cost or 3.3 times decrease in the cost of produce. Within the irrigation methods, aerobic rice + intercropping, particularly with black gram, is less sensitive and amenable to a wide range of input-output price fluctuations.

Conclusion

From the present study, it could be concluded that surface irrigated aerobic rice + black gram with hydrogel application shall be advocated in order to double the land use efficiency and income of the farmers. However, under water deficit conditions, drip irrigated aerobic rice + green gram with or without hydrogel could be advocated with a slight yield and income penalty.

Acknowledgements

The authors would like to express their sincere gratitude to Pandit Jawaharlal Nehru College of Agriculture and Research Institute for their invaluable, support and encouragement throughout the course of this research. Special thanks are extended to mentors for their constructive feedback and insightful suggestions, which greatly enhanced the quality of this work.

Authors' contributions

RP contributed to validation, formal analysis, investigation and writing the original draft. RM contributed to conceptualization, methodology development, validation, formal analysis, investigation, writing the original draft, reviewing and editing, supervision and funding acquisition. LA contributed to methodology development, investigation and funding acquisition. SM contributed to methodology development and investigation. ST contributed to methodology development and writing review and editing. CN contributed to writing the original draft and writing review and editing. All authors read and approved the final version of the manuscript.

Table 4. Parametric budgeting of aerobic rice-based intercropping system under different irrigation methods with or without hydrogel application

Treatments			TSY	GR	MC	LC	ICC	TVC	RAVC	RMC	RLC	MBCR	BEP	TSY on BEP (%)
			(1)	(2)	(3)	(4)	(5)	(6) = (3+4+5)	(7) = (2-6)	(8) = (2-4/3)	(9) = (2-3/4)	(10)	(11)	
Drip irrigation	No hydrogel	No intercrop	4224	80256.00	16230.00	30400.00	1725.00	48355.00	31901.00	3.07	2.11	-20.28	5439	-22.34
		Black gram	9653	183407.00	18680.00	37000.00	2059.00	57739.00	125668.00	7.84	4.45	8.01	5933	62.70
		Green gram	8570	162830.00	18480.00	37000.00	2052.00	57532.00	105298.00	6.81	3.90	6.10	5922	44.71
		Onion	6875	130625.00	47043.00	37000.00	3108.00	87151.00	43474.00	1.99	2.26	0.74	7481	-8.10
	Hydrogel	No intercrop	4304	81776.00	18980.00	30400.00	1826.00	51206.00	30570.00	2.71	2.07	-5.33	5589	-22.99
		Black gram	10099	191881.00	21430.00	37000.00	2161.00	60591.00	131290.00	7.23	4.61	6.96	6083	66.02
		Green gram	8620	163780.00	21230.00	37000.00	2154.00	60384.00	103396.00	5.97	3.85	4.85	6072	41.96
		Onion	7163	136097.00	49793.00	37000.00	3210.00	90003.00	46094.00	1.99	2.33	0.82	7631	-6.13
Surface irrigation	No hydrogel	No intercrop	5380	102220.00	15147.00	30400.00	1685.00	47232.00	54988.00	4.74	2.86	--	2486	116.42
		Black gram	10949	208031.00	17597.00	37000.00	2019.00	56616.00	151415.00	9.72	5.15	11.69	5874	86.40
		Green gram	9745	185155.00	17397.00	37000.00	2012.00	56409.00	128746.00	8.52	4.53	9.37	5863	66.21
		Onion	8173	155287.00	45960.00	37000.00	3068.00	86028.00	69259.00	2.57	2.95	1.42	7422	10.12
	Hydrogel	No intercrop	5561	105659.00	17897.00	30400.00	1786.00	50083.00	55576.00	4.21	2.89	1.25	5530	0.56
		Black gram	11550	219450.00	20347.00	37000.00	2121.00	59468.00	159982.00	8.97	5.38	9.93	6024	91.73
		Green gram	9524	180956.00	20147.00	37000.00	2114.00	59261.00	121695.00	7.15	4.35	6.79	6013	58.39
		Onion	8393	159467.00	48710.00	37000.00	3170.00	88880.00	70587.00	2.51	2.99	1.42	7572	10.84

TSY – Total system yield (kg ha^{-1}), **GR** – Gross return (₹ ha^{-1}), **MC** – Material cost (₹ ha^{-1}), **LC** – Labour cost (₹ ha^{-1}), **IC**C – Interest on capital cost (₹ ha^{-1}), **TVC** – Total variable cost (₹ ha^{-1}), **RAVC** – Return above variabl Cost (₹ ha^{-1}), **RMC** – Return above material cost (₹), **RLC** – Return above labour cost (₹), **MBCR** – Marginal benefit cost ratio (₹ ₹$^{-1}$), **BEP** – Break-even point yield (kg ha^{-1}).

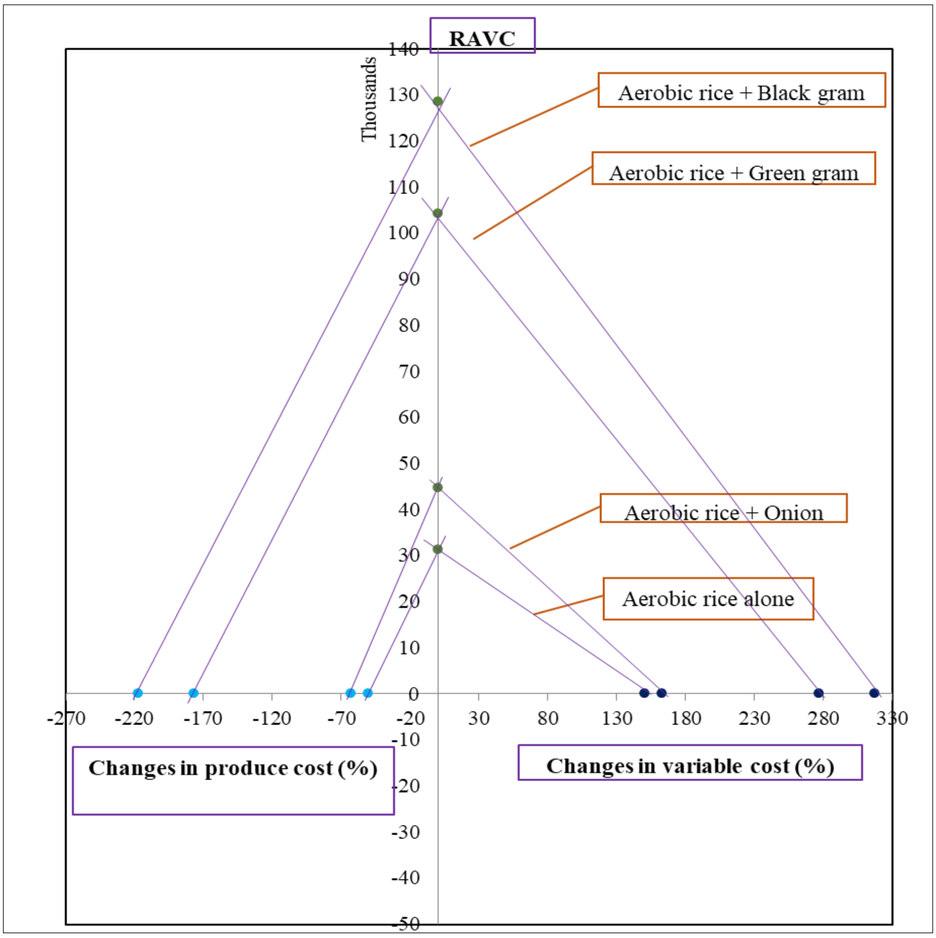

Fig. 1. Sensitivity analysis of drip irrigated aerobic rice-based intercropping systems.

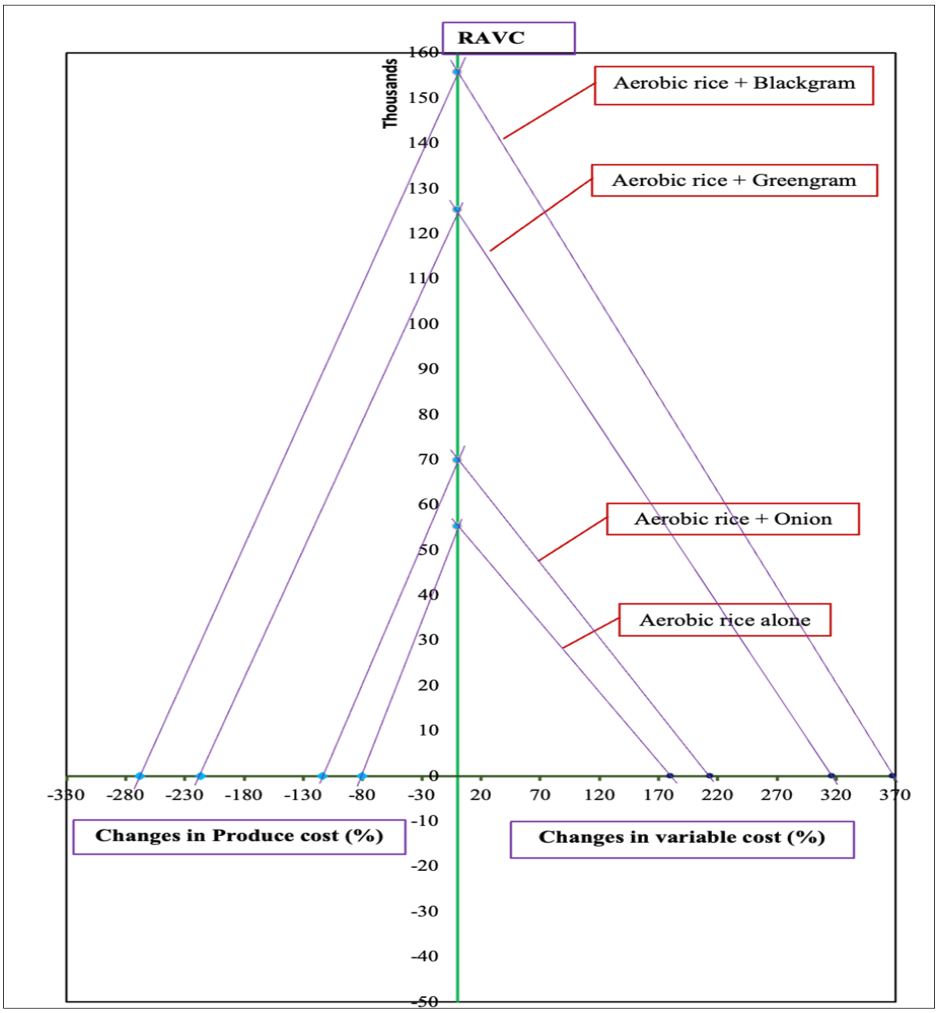

Fig. 2. Sensitivity analysis of surface irrigated aerobic rice-based intercropping systems.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. United States Department of Agriculture, World Agricultural Outlook Board. World agricultural supply and demand estimates. Washington (DC): USDA; 2022.
2. Mainuddin M, Kirby M, Gan TY. Climate change impacts on food security and livelihood in the Ganges delta. Clim Change. 2019;154 (3-4):327-43.
3. Mandal S, Sarangi SK, Mainuddin M, Mahanta KK, Mandal UK, Burman D, et al. Cropping system intensification for smallholder farmers in coastal West Bengal. Front Sustain Food Syst. 2022;6:1001367. https://doi.org/10.3389/fsufs.2022.1001367
4. Tuong TP, Bouman BAM. Rice production in water-scarce environments. In: Kijne JW, Barker R, Molden D, editors. Water productivity in agriculture. Wallingford (UK): CABI; 2003. p. 53-67. https://doi.org/10.1079/9780851996691.0053
5. Bouman BAM, Humphreys E, Tuong TP, Barker R. Rice and water. Adv Agron. 2007;92:187-237. https://doi.org/10.1016/S0065-2113(04)92004-4
6. Wang H, Bouman BAM, Zhao D, Wang C, Moya PF. Aerobic rice in northern China. In: Bouman BAM, et al., editors. Water-wise rice production. Los Baños: IRRI; 2002. p. 143-5.
7. Pinheiro BS, Castro EM, Guimaraes CM. Sustainability and profitability of aerobic rice production in Brazil. Field Crops Res. 2006;97:34-42. https://doi.org/10.1016/j.fcr.2005.08.013
8. Bouman BAM, Peng S, Castaneda AR, Visperas RM. Yield and water use of irrigated tropical aerobic rice systems. Agric Water Manag. 2005;74:87-105. https://doi.org/10.1016/j.agwat.2004.11.007
9. Yang X, Bouman BAM, Wang H, Wang Z, Zhao J, Chen B. Performance of temperate aerobic rice under different water regimes in north China. Agric Water Manag. 2005;74:107-22. https://doi.org/10.1016/j.agwat.2004.11.008
10. Tuong DF, Bouman BAM. On-farm strategies for reducing water input in irrigated rice. Agric Water Manag. 2003;56(2):93-112. https://doi.org/10.1016/S0378-3774(02)00007-0
11. Singh AK, Sinha SK, Kumar A. Water-saving technologies in rice: a review. Indian J Agron. 2020;65(1):1-7.
12. Sharma R, Dixit A, Rani M. Aerobic rice production: an alternative approach for water saving and sustainable agriculture. Agric Rev. 2021;42(2):107-13.
13. Gaikwad G, Soniya C, Vilhekar M, Mane PN, Vaidya ER. Impact of organic manures and hydrophilic polymer hydrogel on conservation of moisture and sunflower production under rainfed condition. Adv Res J Crop Improv. 2017:31-35. https://doi.org/10.15740/HAS/ARJCI/8.1/31-35
14. Patra SK, Poddar R, Brestic M, Acharjee PU, Bhattacharya P, Sengupta S, et al. Prospects of hydrogels in agriculture for enhancing crop and water productivity under water deficit condition. Int J Polym Sci. 2022:4914836. https://doi.org/10.1155/2022/4914836
15. Patel P, Shah D, Patel C. Drip fertigation in field crops. Int J Agric Sci. 2019;11(10):8804-7.
16. Meena RK, Yadav RK, Jatav RS. Hydrogel application in water-scarce rice ecosystem. J Soil Water Conserv. 2022;21(1):45-52.
17. Choudhary M, Nayak HS, Barman K. Productivity and profitability of rice-based intercropping systems under coastal saline soils. J Indian Soc Coastal Agric Res. 2020;38(1):35-40.
18. Kumar V, Tripathi RS, Singh RK. Intercropping for income and resource enhancement in rice-based systems. Legume Res. 2021;44 (9):1065-71.
19. Kumari A, Jha SK, Singh RK. Impact of integrated farming systems on farmers' income in eastern India. Agric Econ Res Rev. 2023;36 (1):70-78.
20. Government of India. Doubling farmers' income report. New Delhi: Ministry of Agriculture; 2018.
21. Verma SP, Modgal SC. Use of equivalent yields in cropping systems. Himachal J Agric Res. 1983;9(2):89-92.
22. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. New Delhi: Wiley; 2010.
23. Flinn JC, Surya KJ, Maranan C. Agro-economic budgeting procedures. Los Baños: IRRI; 1984.
24. Gonzales KA, Van Der Veen MG. Cropping pattern design. Sci Hortic. 1989;78:127-57.
25. Yangyuoru M, Boateng E, Adiku SGK, Acquah D, Adjadeh TA, Mawunya F. Effects of natural and synthetic soil conditioners on soil moisture retention and maize yield. West Afr J Appl Ecol. 2006;9 (1):186-94. https://doi.org/10.4314/wajae.v9i1.45676
26. Abobatta W. Impact of hydrogel polymer in agricultural sector. Adv Agric Environ Sci. 2018;1(2):59-64. https://doi.org/10.30881/aaeoa.00011
27. Roy T, Kumar S, Chand L, Kadam DM, Bihari B, Shrimali SS, et al. Impact of Pusa hydrogel application on yield and productivity of rainfed wheat in North West Himalayan region. Curr Sci. 2019;116 (7):1246-51. https://doi.org/10.18520/cs/v116/i7/1246-1251
28. Saini R, Umesha C. Influence of hydrogel and different sowing methods on growth and yield of aerobic rice. Int J Plant Soil Sci. 2023;35(7):34-39. https://doi.org/10.9734/ijpss/2023/v35i72859
29. Padmaja B, Reddy M. Drip irrigation and fertigation effects on aerobic rice (Oryza sativa) in semi-arid conditions of Telangana State, India. Int J Curr Microbiol Appl Sci. 2018;7(8):1156-71. https://doi.org/10.20546/ijcmas.2018.708.131
30. Aruna L, Surekha K, Brajendra. Soil quality and productivity assessment for bridging the yield gap in farmers' fields of coastal deltaic region of Karaikal. In: Lama T, Burman D, Mandal UK, Sarangi SK, Sen H, editors. Transforming coastal zone. Cham: Springer; 2022. https://doi.org/10.1007/978-3-030-95618-9_59
31. Sudhir Y, Humphreys E, Kukal SS, Gill G, Rangarajan R. Effect of water management on dry-seeded and puddled transplanted rice. Field Crops Res. 2011;120:112-22. https://doi.org/10.1016/j.fcr.2010.09.002
32. Natarajan SK, Duraisamy VK, Thiyagarajan G, Manikandan M. Evaluation of drip fertigation system for aerobic rice in western zone of Tamil Nadu. Int J Plant Soil Sci. 2020;32:41-47. https://doi.org/10.9734/ijpss/2020/v32i730303
33. Sharma H, Shukla MK, Bosland PW, Steiner R. Soil moisture sensor calibration, actual evapotranspiration and crop coefficients for drip-irrigated greenhouse chile peppers. Agric Water Manag. 2017;179:81-91. https://doi.org/10.1016/j.agwat.2016.07.001
34. Habimana S, Mbaraka SR, Karangwa A, Rucamumihigo FX, Musana FR, Mutamuliza E, et al. Effect of intercropping aerobic rice with leafy vegetables on crop growth, yield and economic efficiency. Afr J Biotechnol. 2021;20(7):313-17. https://doi.org/10.5897/AJB2021.17360
35. Midya A, Bhattacharjee K, Ghose SS, Banik P. Deferred seeding of black gram (Phaseolus mungo) in rice (Oryza sativa) field on yield advantages and smothering of weeds. J Agron Crop Sci. 2005;191 (3):195-201. https://doi.org/10.1111/j.1439-037X.2005.00157.x
36. Banik P, Bagchi DK. Evaluation of rice (Oryza sativa) and legume intercropping in upland situation of Bihar plateau. Indian J Agric Sci. 1994;64(3):175-82.

37. Saeed M, Shahid MRM, Jabbar A, Ullah E, Bismillah M. Agro-economic assessment of different cotton-based inter/relay cropping systems in two geometrical patterns. Int J Agric Biol. 1999;4(1):234-37.

38. Joshi M. Dynamics of rice-based cropping systems in the southern transitional zone of Karnataka. Int Rice Res Notes. 2002.

39. Ahmad R, Jabbar A, Ahmad A, Ehsanullah, Hussain IB. Evaluation of direct-seeded upland rice-based intercropping systems under strip planting geometry. Pak J Agric Sci. 2007;44(2):189-90.

40. Maniruzzaman M, Sarangi SK, Mainuddin M, Biswas JC, Bell RW, Hossain MB, et al. A novel system for boosting land productivity and income of smallholder farmers by intercropping vegetables in waterlogged paddy fields of the Ganges Delta. Land Use Policy. 2024;139:107066. https://doi.org/10.1016/j.landusepol.2024.107066

41. Erythrina E, Susilawati S, Slameto S, Resiani NMD, Arianti FD, Jumakir J, et al. Yield advantage and economic performance of rice-maize, rice-soybean and maize-soybean intercropping in rainfed areas of Western Indonesia. Agronomy. 2022;12(10):2326. https://doi.org/10.3390/agronomy12102326

42. Ghosh RK, Mandal BK, Dasgupta B. Studies on mixed and intercropping of black gram with direct-seeded rainfed upland rice varieties. Oryza. 1990;27:258-66.

43. Ramamurthy K, Balasubrananian A, Arokiaraj A. Effect of intercrop and row ratio on growth, yield parameters and economics of direct-sown rice. Indian J Agric Sci. 1992;67(6):280-81.

44. Ram B, Punia SS, Tetarwal JP, Meena DS, Singh P, Chaudhary HR. Effect of hydrogel and foliar nutrition sprays on productivity and profitability of lentil under rainfed conditions of Rajasthan. Int J Adv Sci Res Manag. 2018;1:67-70.

45. Mishra A, Behera B, Pal AK, Mohanty SK, Rath BS, Subudhi CR, et al. Performance of rice and black gram under different nutrient management practices in rainfed upland. Oryza. 2012;49(4):273-79.

46. Singh RS, Srivastava GP. Effect of fertilizer levels and pigeon pea-based intercropping systems on yield, nutrient removal and economics under rainfed condition. Int J Curr Microbiol Appl Sci. 2018;7:3554-61.

47. Maharajan M, Subramanian E, Gurusamy A, Senthil K. Irrigation scheduling and intercrop practices on yield, water use efficiency and economics of aerobic rice. Madras Agric J. 2020;107(7):254-59. https://doi.org/10.29321/MAJ.2020.000381

48. Srinivasa Reddy D, Savitha MS, Ramesh PR, Bhandi NH, Teggelli RG, Ravi S. Climate-resilient technology for sustainable livelihood and production. Mysore J Agric Sci. 2023;57(2):294-300.

49. Ray S, Umesha C, Meshram MR, Sanodiya LK. Influence of irrigation and hydrogel application on yield and economics of pearl millet (Pennisetum glaucum) under eastern UP conditions. Environ Conserv J. 2021;22(3):31-36. https://doi.org/10.36953/ECJ.2021.22304

50. Songara JC, Patel JN. Impact of guar gum-based hydrogel on yield and economics of sugarcane. Agron J. 2023;115(5):2533-43. https://doi.org/10.1002/agj2.21400

Additional information

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

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

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

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

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.