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Micro-level sustainability benefits through weather-based farm interventions in Bihar, India

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Weather-based farm interventions hold immense potential in mitigating climatic risks to crop production, thereby enhancing farm income under changing climatic scenarios. Moreover, these interventions have a significant positive impact on the environment through reduced energy consumption and the efficient use of precious farm inputs. In this context, a study was conducted to evaluate the sustainability benefits of weather-based advisory services concerning grain yield, farm economics (benefit–cost ratio and net return) and environmental aspects (carbon and energy consumption) in rice production. The study focused on weather-based adopted and non-adopted farmers in the Muzaffarpur district of Bihar, India, over three consecutive *kharif* (monsoon) seasons from 2018 to 2020. The results revealed a significant positive impact of weather-based advisories on farmers' income, as well as carbon and energy consumption patterns in rice production. Specifically, rice yield increased by 49.8% among farmers who followed weather forecast-based smart interventions. Additionally, for every unit currency invested, weather-based adopted farmers received benefits ranging from 1.79 to 2.01-units compared to 1.21 to 1.39 units for non-adopted farmers. The carbon sustainability index (CSI) and carbon efficiency ratio (CER) of weather-based farming practices adopted by the rice farmers were 90.8 and 76.4% higher, respectively than those of non-adopted farmers. Similarly, the energy footprint of the two groups of farmers differed significantly. The average energy productivity of adopted farmers was 0.34 kg MJ^{-1}, compared to 0.26 kg MJ^{-1} for rice grown by non-adopted farmers. The study highlights the critical role of weather-based advisories in reducing climatic risks, lowering the carbon footprint, and minimizing greenhouse gas (GHG) emissions, thereby contributing to sustainable rice production.

KEYWORDS

climate change, rice farming, yield, sustainability, carbon and energy footprint

1 Introduction

In recent years, variable and uncertain crop yields have become a major concern for both farmers and policymakers, particularly under the regime of climate change and erratic rainfall patterns (Sattar and Srivastava, 2021). The challenge extends beyond climate change-induced rainfall variability, to include other agricultural issues that exacerbate critical dimensions of climate change. One significant factor is the indiscriminate use of resource inputs in agriculture. Conventional farming methods, followed by the majority of farmers, involve high energy consumption due to inefficient use of energy, water and diesel as well as farm labor (Yuan et al., 2018). Additionally, the excessive use of chemicals, fertilizers, and irrigation negatively impacts ecosystems, depletes groundwater resources, and contributes to environmental pollution (Sridhara et al., 2023). In this context, suitable crop management strategies that emphasize low energy consumption and high input efficiency are essential for achieving sustainable agricultural production (Yuan et al., 2018). High energy efficiency, coupled with reduced energy utilization, is crucial for conserving natural resources and enhancing the sustainability of production systems (Hauck et al., 2017). Such practices support lower emissions of greenhouse gasses and promote the judicious use of precious resources and farm inputs, ultimately leading to sustainable higher productivity.

In the present scenario, the poor and marginal farmers tend to get affected most significantly due to weather extremes (Bal and Minhas, 2017). To mitigate the negative impact of climatic variability on crop production, weather-based farm advisories provided to the farmers under the project the "National Innovations on Climate Resilient Agriculture (NICRA)" funded by Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers' Welfare, Government of India have great potential to bring resilience in agriculture against climate variability and encouraging impact of technologies on farmers' income (Bal et al., 2023; Medhi et al., 2018). Through these advisories, farmers are armed with forewarning messages, latest improved management practices, high-yielding varieties of crop and other climate-smart production techniques, suitably tailored with weather forecasts issued for 5 days. Since the farmers are trained before the interventions, they are able to suitably modify their farming operations and accordingly, adopt new crop management tools and techniques for enhancing crop production. On the other hand, farmers who have no access to customized advisories rely mainly on traditional knowledge and experiences for crop production. An actionable medium-range weather forecast plays a decisive role in averting risks in association with farm advisories given in line with future weather outlook (Ramachandrappa et al., 2018; Mundhe et al., 2022). For example, if farmers are warned of impending rain, they skip their irrigation and can reschedule their plant protection and other important field operations in line with effective advisories. Since forecast tends to be reliable in over 85% of cases, costly inputs such as irrigation, labor and diesel/electricity are saved to a large extent.

The gain in terms of climatic risk reduction and enhanced farm yield accrued by adopting weather-based farm advisories is obvious (Maini and Rathore, 2011). Considering this, it would be prudent to assess the environmental impact of such interventions being advocated by the researchers as well as policymakers. The study of carbon footprint and energy use for the crops grown with and without weather-based advisories assumes great significance in understanding the environmental impact of such intervention. The carbon footprint refers to the quantity of emissions of greenhouse gasses per unit of grain yield (Zhang et al., 2018). It is used to quantify the environmental impacts of an agricultural practice measured in terms of CO_2 equivalents (Ghosh et al., 2022). On the other hand, energy footprint refers to the environmental footprint of the energy inflow-outflow pattern and its consumption per unit of production. In this context, both the footprints have a significant impact on the environment and agricultural sustainability.

To devise environment-friendly strategies for agricultural sustainability, many authors (Singh et al., 2008; Chaudhary et al., 2009; Ashraf et al., 2021) evaluated carbon emission and energy footprint of different crops, and cropping systems under diverse management practices. Studies of energy use and carbon footprint of rice grown with and without the use of weather forecast-based agrometeorological advisories have not been previously carried out elsewhere. Since weather-based advisories are mainly used by the farmers to mitigate weather-induced risks to enhance crop production, analyses of carbon and energy footprints of such crop production systems are rarely taken up to holistically assess environmental as well as agricultural sustainability in the context of intensive use of energy in agriculture. In this context, the question is whether such an intervention would provide any significant ecosystem services apart from reducing climatic risks for enhanced rice production? We will try to find an answer to this vital question to bring in resilience in the agri-food system by integrating weather-based farm strategies in sustainable rice production. Given this, in the present study, we have tried to assess the impact of weather-based advisories as well as carbon and energy footprints on rice production. This will offer an insight into the pattern of energy consumption and carbon emission in rice fields under two different sets of management practices, *viz.*, one with weather-based farm advisories and the other with traditional methods.

2 Materials and methods

2.1 Location and field criteria of the study

In this article, we have focused on two major issues, *viz.* the sustainability impact of weather-based interventions, and carbon and energy footprints in rice cultivation by two groups of farmers in Ballysaraiya (Saraiya) and Bhagwatpur (Marwan) villages in Muzaffarpur district of Bihar, India. The location of these two villages is given in Figure 1. The detailed characteristics of the farms and farmers in the study area are provided in Table 1. One group of farmers used to receive weather-based smart interventions regularly for rice cultivation and another group of farmers had no access to such interventions. They used to follow conventional methods and practices for rice cultivation. In the study, carbon and energy footprints of farming practices adopted by both groups of farmers were evaluated. In this endeavor, 25 rice farmers were selected from Saraiya village and another group of 25 rice farmers from Marwan village. The two villages are located within 12 km distance. The selected farmers of Saraiya village used to receive weather-based advisory on a weekly basis to manage their rice crop right from sowing to harvesting and threshing are henceforth termed as adopted farmers or NICRA farmers. The other group of farmers (non-adopted or non-NICRA farmers) of Marwan village was kept uninformed about the weather-based advisory bulletin. Hence, they depended on their experiences and local traditional knowledge to raise their crop. The study with rice crop was conducted during the *kharif* (wet season or monsoon) season of 2018, 2019 and 2020 under the Project "National Innovations on Climate Resilient Agriculture (NICRA)" funded by Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers Welfare, Govt. of India. The NICRA farmers availed weather forecast-based farm advisory bulletins

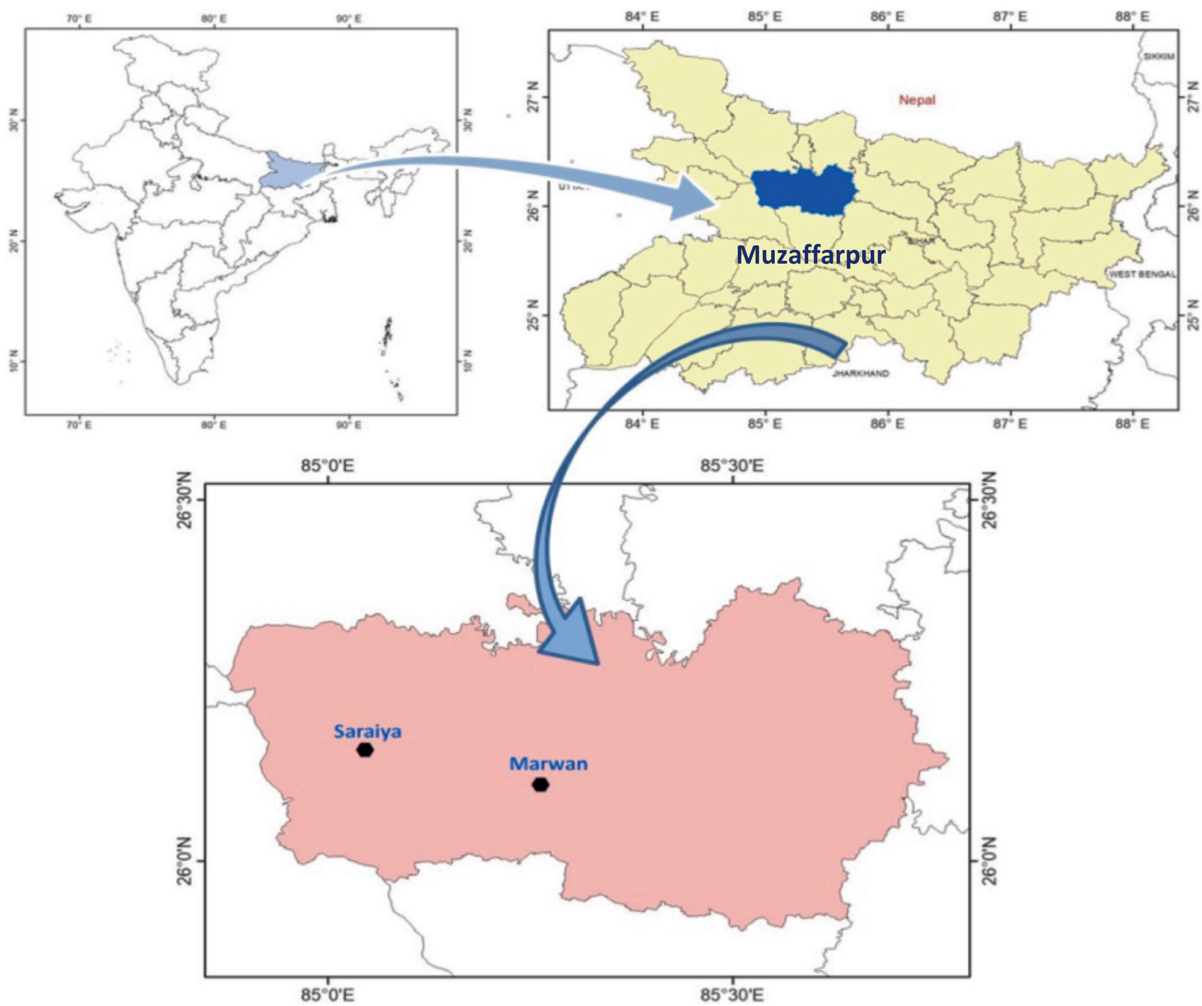

FIGURE 1
Location map of the study area.

TABLE 1 Farm and farmers' characteristics of the study area.

Sl No	Farm/farmers characteristics	Related information
1	Size of land holding of the selected farmers	Land holding < 2.0 ha, with 60% farmers having below 1.0 ha
2.	Major crops	Rice, maize, black gram, wheat, potato, chick pea, mustard, lentil, summer green gram
3.	Source of irrigation	Bore well
4.	Soil type	Loamy
5.	Organic carbon status	0.55–0.75%
6.	Normal rainfall (mm), (June–October)	1,105 mm
7.	Water table depth	5–7 m

regularly twice a week, on every Tuesday and Friday, in their WhatsApp group. These 25 farmers were trained to manage weather-related crop production risks and garner benefits from actionable weather-based advisories. A local person of the project in the village known as Field Information Facilitator (FIF) used to coordinate, monitor and implement advisories given to the NICRA farmers under the guidance of the agrometeorologist. We used to collect crop, weather, pest-disease information, agronomic management practices and irrigation scheduling information for the rice planted by the 25 NICRA farmers and another group of 25 non-NICRA farmers.

The data on raising of nursery, land preparation for puddling, transplanting, weeding, fertilizer application, labor, irrigation, plant protection measures, harvesting, threshing, grain and straw yield from the individual farmers (both NICRA and Non-NICRA) were collected for all three crop seasons. Cost of production of rice per hectare based on inputs (seeds, labor, fertilizers, plant protection measures and irrigation) used to raise the crop from sowing to post-harvest operation was worked out for both the NICRA and non-NICRA farmers. Grain and biological yields of paddy for each farmer of these two groups were recorded. Gross and net income of the farmers were calculated to assess the benefit–cost ratio. Rainfall data was collected from these two villages by installing ordinary rain-gauges. Each FIF was trained to collect rainfall and crop data throughout the crop growing period.

The significance of the difference between the two sample means of adopted and non-adopted farmers pertaining to net return, energy and carbon indices was tested by employing an independent *t*-test at a 0.05 level of significance. Relevant emission factors and carbon equivalents of various inputs used for the cultivation of rice by the farmers of NICRA and Non-NICRA farmers were taken from pertinent literature (Tables 2, 3). The input and output data of rice cultivation were collected from 25 NICRA and 25 Non-NICRA farmers. These data were used in the calculation of net return, carbon and energy footprints.

2.2 Calculation of carbon footprint

The total carbon footprint of *kharif* rice cultivated by the farmers of NICRA and Non-NICRA farmers was assessed by calculating the greenhouse gas emission from each input component such as seed, fertilizer, green manuring, irrigation, plant protection measures and diesel *etc*. The amount of CO_2 produced was worked out by multiplying the input used per hectare (e.g., labor, diesel fuel, chemical fertilizers, herbicides and pesticides) by its corresponding coefficients (Table 3). Emissions from farm inputs were converted to kg CO_2-equivalent. Each input component was recorded during the crop growing period by the individual farmers of both groups. The carbon footprint of an individual component is expressed in Carbon Equivalent (CE) units (kg-CE ha^{-1}). The following indices related to carbon footprint were calculated (Chaudhary et al., 2017; Basavalingaiah et al., 2020).

$$\text{Carbon intput} = \text{Total GHG emission in CE X} \frac{12}{44} \text{ (kg-CE ha}^{-1}\text{)}$$

$$\text{Carbon output} = \text{Total biomass X 0.4 (kg-CE ha}^{-1}\text{)}$$

$$\text{Carbon sustainability index}\left(\text{CSI}\right) = \frac{\text{carbon output} - \text{carbon input}}{\text{carbon input}}$$

$$\text{Carbon efficiency ratio}\left(\text{CER}\right) = \frac{\text{carbon output}}{\text{carbon input}}$$

$$\text{Carbon intensity}\left(\text{CI}\right)\left(\text{kg} - \text{CE kg}^{-1}\right) = \frac{\text{total carbon output}\left(\text{kg} - \text{CE ha}^{-1}\right)}{\text{grain yield}\left(\text{kg ha}^{-1}\right)}$$

$$\text{Carbon efficiency factor}\left(\text{CEF}\right)\left(\text{kg kg} - \text{CE}^{-1}\right) = \frac{\text{grain yield}\left(\text{kg ha}^{-1}\right)}{\text{total carbon output}\left(\text{kg} - \text{CE ha}^{-1}\right)}$$

2.3 Calculation of energy indices

Suitable coefficient factors were used to transform the unit quantity of input and output components into their equivalent energies. Based on energy input and output data, several energy indices were computed to compare the efficiency of paddy cultivation by the adopted and non-adopted farmers of the village. The following energy indices were calculated to compare the energy consumption pattern of adopted and non-adopted farmers. Sources of direct, indirect, renewable and non-renewable energy involved in different farming operations of rice were

TABLE 2 Equivalent energy coefficients of different inputs and outputs of rice cultivation.

Input	Unit	Equivalent energy (MJ $unit^{-1}$)	References
1. Human labor			
(i) Male	h	1.96	Singh et al. (2018)
(ii) Female	h	1.57	Singh et al. (2018)
2. Chemicals fertilizers			
(i) Nitrogen	kg	66.14	Rafiee et al. (2010)
(ii) Phosphorus	kg	12.44	Rafiee et al. (2010)
(iii) Potassium	kg	11.15	Rafiee et al. (2010)
3. Seed	kg	15.7	Ozkan et al. (2004)
4. Diesel	L	56.31	Canakci et al. (2005)
5. Machinery (tractor and farm implement)	kg	62.7	Singh and Mittal (1992)
6. Chemicals			
(ii) Chemicals	kg	120.0	Chaudhary et al. (2009)
(ii) Chemical	L	102	Chaudhary et al. (2009)
7. Biological yield			
(i) Rice grain	kg	15.7	Ozkan et al. (2004)
(ii) Rice straw	kg	12.5	Ozkan et al. (2004)
8. Green manure	kg	18.0	Mittal et al. (1985)

TABLE 3 Equivalent carbon coefficients of different inputs and outputs of rice cultivation.

Input/output	(kg CO_2 eq. ha^{-1})	References
1. Diesel, L	2.76	Dyer and Desjardins (2003)
2. Fertilizer		
(i) Nitrogen, kg	1.3	Pathak and Wassmann (2009) and Lal (2004)
(ii) Phosphorous (P_2O_5), kg	0.2	Pathak and Wassmann (2009) and Lal (2004)
(iii) Potassium (K_2O), kg	0.2	Pathak and Wassmann (2009) and Lal (2004)
3. Agro-chemicals		
(i) Herbicide, kg	6.3	Pathak and Wassmann (2009) and Lal (2004)
(ii) Insecticide, kg	5.1	Pathak and Wassmann (2009) and Lal (2004)
(iii) Fungicide, kg	3.9	Pathak and Wassmann (2009) and Lal (2004)
4.Economic output		
(i) Grain, kg	0.4	Pratibha et al. (2019)
(ii) Straw, kg	0.4	Pratibha et al. (2019)

TABLE 4 Grain yield, benefit–cost ratio and net return for rice grown by NICRA and non-NICRA farmers.

Type of farmers	Grain yield (Mg ha^{-1})	Benefit-cost ratio	*t*-test for net return			
			Net return per hectare (USD)	Standard error of mean	*t*-value	Significance
NICRA	3.84–5.12	1.79–2.01	659.8	53.28	13.23	0.001
Non-NICRA	2.61–3.67	1.21–1.39	293.7	86.37		

USD, US dollar.

evaluated. Direct energy sources included labor and fuel, while indirect energy consisted of fertilizers, machineries, chemicals, seeds and green manuring. While categorizing renewable and non-renewable sources of energy, labor, seed and green manuring were regarded as renewable sources. On the other hand, fertilizers, machinery, fuel and chemicals were taken as non-renewable sources of energy (Rafiee et al., 2010; Basavalingaiah et al., 2020; Sridhara et al., 2023).

$$\text{Energy use efficiency} = \frac{\text{total energy output}\left(\text{MJ ha}^{-1}\right)}{\text{total energy input}\left(\text{MJ ha}^{-1}\right)}$$

$$\text{Energy productivity}\left(\text{kg MJ}^{-1}\right) = \frac{\text{grain yield}\left(\text{kg ha}^{-1}\right)}{\text{total energy input}\left(\text{MJ ha}^{-1}\right)}$$

$$\text{Net energy}\left(\text{MJ ha}^{-1}\right) = \text{total energy output}\left(\text{MJ ha}^{-1}\right) - \text{total energy input}\left(\text{MJ ha}^{-1}\right)$$

$$\text{Energy profitability} = \frac{\text{net energy}\left(\text{MJ ha}^{-1}\right)}{\text{total energy input}\left(\text{MJ ha}^{-1}\right)}$$

$$\text{Human energy profitability} = \frac{\text{Total output energy}\left(\text{MJ ha}^{-1}\right)}{\text{human labour energy}\left(\text{MJ ha}^{-1}\right)}$$

3 Results and discussion

3.1 Sustainability benefits of rice production through weather-based advisories

The data of grain yield and net return per hectare of rice cultivated by NICRA and non-NICRA farmers over 3 years of the study are presented in Table 4. The results reveal a significant increase in both yield and net return for NICRA farmers compared to non-NICRA farmers. The rice yield of NICRA farmers ranged from 3.84 to 5.12 Mg ha^{-1} over the 3 years. In contrast, the yield of non-NICRA varied from 2.61 to 3.67 Mg ha^{-1}. Overall, NICRA farmers experience a 49.8% increase in yield through the adoption of weather-based advisories. Several studies have also reported significant yield enhancement and economic benefits from such practices (Maini and Rathore, 2011; Nirwal et al., 2019; Khichar et al., 2020). To critically analyze the yield reduction observed in non-adopted farmers, data on the occurrence of dry spells of varying intensities in NICRA and non-NICRA villages are presented in Table 5. It is observed that from June to September, 873–881 mm rainfall was recorded in NICRA and

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TABLE 5 Frequency of dry spells of different intensities in NICRA villages during *kharif* (monsoon) seasons of 2018–2020.

District	Village	Dry spell Intensity	2018					2019					2020	
			Jun	Jul	Aug	Sep	Total rainfall (mm)	Jun	Jul	Aug	Sep	Total rainfall (mm)	Jun-Sep	Total rainfall (mm)
Muzaffarpur	Marwan	5–7 days	0	1	3	0	880.5	2	2	2	0	1087.5	No significant dry spell was observed	1165.5
	(Bhagwatpur)	>10 days	1	1	0	1		1	0	0	1			
		>15 days	0	1	0	0		0	0	0	0			
	Saraiya	5–7 days	0	1	2	0	872.5	2	2	1	0	1065.8		1135.7
	(Ballysaraiya)	>10 days	1	1	0	1		1	0	0	1			
		>15 days	0	1	0	0		0	0	0	0			

non-NICRA villages during the *kharif* season of 2018, followed by 1,066–1,088 mm and 1,136–1,165 mm in 2019 and 2020, respectively. The data revealed that the rainfall received during the *kharif* season of 2018 was much lower than in the other 2 years. However, rainfall was almost normal during the *kharif* seasons of 2019 and 2020. An analysis of dry spells of different durations, *viz*. 5–7 days, >10 days and >15 days across villages located within a 12 km distance reveals that, despite normal rainfall in 2019, dry spells of varying intensities occurred during the rice growing season. As a result, the rice crops of non-adopted farmers in Marwan village experienced moisture stress during critical growth stages. In contrast, adopted farmers in Saraiya village effectively avoided moisture stress by scheduling irrigation based on weather forecasts-based farm advisories. The implementation of smart irrigation practices, informed by prior weather information, along with improved farm techniques and management practices adopted by NICRA farmers, contributed to higher productivity even in the presence dry spells. Irrigation provided by the NICRA farmers during dry spells, based on actionable weather information, resulted in better field water conditions, leading to more stable and higher grain yields compared to fields without irrigation, as observed in non-NICRA farmers (Sattar and Srivastava, 2021). While the application of irrigation does contribute to an increase in GHG emissions, the overall higher yields achieved by adopted farmers effectively offset this rise in emissions (Zhang et al., 2018). In terms of monetary benefits, a sum of USD 659.8 was accrued as net return by the NICRA farmers, while non-NICRA farmers generated a net return of only USD 293.7 per hectare. Thus, the NICRA farmers gained an additional return of USD 366.1 per hectare. Managing dry spells during critical growth phases of rice growth through weather-based intervention was key to achieving higher production by NICRA farmers in conjunction with other smart practices. Narasimha et al. (2023) reported an 18% higher net return in cotton by following weather-based advisories through the adoption of forewarning information, timely agricultural operations, recommended doses of fertilizers, and efficient use of agrochemicals. Significant benefits of weather-based services on crop production were reported by Ray et al. (2017) in Odisha, India. They observed that the farmers realized an additional benefit of 41.2, 20.8 and 34.8%, in green gram, rice and maize crops, respectively. Considering benefit–cost ratio, a significant improvement in the cost–benefit ratio has been observed in the present study. A unit currency invested by NICRA farmers fetched them 1.79-to-2.01-unit benefits compared to 1.21 to 1.39 units in the case of non-NICRA farmers. Nirwal et al. (2019) reported 55.5 percent additional benefits by adopting weather-based advisories in the soybean crop in Maharashtra, India. In a study conducted to assess the economic impact of weather-based advisories, Maini and Rathore (2011) reported a net benefit of 10–15% in the overall yield and a reduction in cost of cultivation by 2–5% over non-adopted farmers.

3.2 Carbon footprint of rice production by NICRA and non-NICRA farmers

Carbon emission is a by-product of production processes of different energy sources such as machinery application, fertilizers, electricity and chemicals. Providing irrigation to the crop also contributes to emissions of greenhouse gasses. The values of carbon input and output for rice production during 2018–2020 by NICRA and non-NICRA farmers are presented in Table 6, which shows that carbon utilization was 483.5 kg-CE ha^{-1} for rice cultivated by the non-NICRA farmers against the value of 394 kg-CE ha^{-1} for NICRA farmers. The reason for higher carbon utilization by non-NICRA farmers was associated with higher consumption of fertilizers, pesticides and labor. The farmers guided by weather-based advisories, which included weather warnings, improved farm techniques, recommended varieties, optimum doses of fertilizers, irrigation scheduling information and plant protection measures, were able to reduce carbon utilization. Zhang et al. (2018) showed that integrative management practices in agriculture could significantly lower carbon footprint by optimizing crop, fertilizers and water management. In their study, the carbon footprint of the irrigated system was found to be 37% lower than non-irrigated system. Sridhara et al. (2023) reported higher values of carbon input due to higher consumption of fertilizers and other inputs. Carbon output in the form of grain and biological yield of rice grown by NICRA farmers was estimated as 4302.1 kg-CE ha^{-1}. On the other hand, the carbon equivalent yield of non-NICRA farmers was 2874.0 kg-CE ha^{-1}. To explain it in terms of yield and climatic risk, it is evident that the adopted farmers, who used weather-based NICRA advisory (NICRA farmers), provided need-based irrigation to their rice crop because of the dry spell during the crop growing season. In other words, unlike non-NICRA farmers, the production system followed by NICRA can be considered as irrigated. Irrigation substantially increased the yield of rice by reducing the negative impact of a dry spell on crop growth. The utility of weather-based services for managing dry spells in crop production was demonstrated for higher benefits in the eastern dry zone of Karnataka, India (Ramachandrappa et al., 2018).

Different carbon indices were calculated and presented in Table 6. To begin with, the Carbon Sustainability Index (CSI) is defined as the efficient utilization of a unit quantity of carbon input to produce a higher carbon output. In the present study, NICRA farmers were found to be the most carbon-efficient, with an average CSI of 10.0, compared to 5.3 for non-NICRA farmers. The lower CSI value among non-NICRA farmers can be attributed to the lower productivity of rice observed over the 3 years. The Carbon Efficiency Ratio (CER) for NICRA farmers was estimated to be 11.0, compared to 6.3 for non-NICRA farmers. This difference is largely due to the higher rice productivity of NICRA farmers, indicating a greater carbon output per unit of carbon input in rice cultivation (Sridhara et al., 2023). Additional fertilizers and improper methods of application led to lower carbon efficiency in rice cultivated by non-NICRA farmers, since they had no access to customized information. Higher contribution of fertilizer application to GHG emissions in agriculture is well documented (Ghosh et al., 2022). For instance, Jat et al. (2019) reported a significant impact of fertilizer application on CO_2 emissions, thereby increasing the carbon footprint in maize-based permanent bed systems. This highlights the need for the precise application of fertilizers at the right quantity and right time, guided by weather-based farm advisory bulletins. Additionally, there was a significant difference in Carbon Intensity (CI) values between NICRA (0.91) and non-NICRA (1.07) farmers. Carbon Efficiency Factor (CEF) values were also significantly higher for NICRA farmers, NICRA farmers demonstrated a CEF value of 1.16, indicating that for every kilogram of carbon equivalent, 1.16 kg of rice grains were produced. In contrast, non-NICRA farmers had a CEF value of 0.95, underscoring the need to adopt smart farming practices as advocated through weather-based advisories.

3.3 Energy consumption pattern of NICRA and non-NICRA farmers

A comparative analysis of the energy consumption patterns of NICRA and Non-NICRA farmers is presented in Table 7. Significant energy indices were calculated for the rice during *kharif* seasons of 2018, 2019 and 2020. The data revealed that the energy input by the NICRA farmers remained consistently lower over these years compared to non-NICRA farmers. The average energy input for NICRA farmers was 13985.5 MJ ha^{-1}, while for non-NICRA farmers, it was 14531.0 MJ ha^{-1}. This suggests that non-adopted farmers used resources without proper guidance or a scientific basis. For comparison, the average energy consumption in rice production within the wheat-rice crop rotation system in the arid region of Pakistan was estimated as 44.37 GJ ha^{-1} (Ashraf et al., 2021). Nayak et al. (2023) reported an average energy input of 32,956 MJ ha^{-1} for rice cultivation in Ambala (Punjab), India. In contrast, the energy input in rice farming in the present study is notably lower, possibly because rice cultivation in Punjab is highly energy-intensive, with farmers typically apply higher amounts of fertilizers compared to those in Bihar. Ranuguwal and Singh (2021) recorded total energy input and output for rice cultivation in Punjab at 61204.13 and 242,012 MJ ha^{-1}, respectively. In this study, NICRA farmers demonstrated higher energy output compared to non-NICRA farmers. Higher grain yield and optimum use of resources guided through advisories contributed to higher energy output for NICRA farmers. Sridhara et al. (2023) echoed similar findings in their research on the energy dynamics of rice cultivation in Karnataka. In line with these observations, the energy efficiency of the production system adopted by the NICRA farmers was estimated at 10.1 compared to 8.7 for non-NICRA farmers. The lower energy use among NICRA farmers can be attributed to their reduced input usage, owing to regular farming practices and guidance provided through weather-based advisories. The results indicated that weather-based advisories have a significant impact in reducing energy use, suggesting their potential for scaling up across the farming community. In the context of changing climate, prioritizing efforts to develop energy-efficient rice production systems is crucial. Livsey et al. (2019) demonstrated that water saving technologies reduced carbon equivalent emissions by 18.6%. Our study further reveals that the actional weather-based farm advisories hold great potential for enhancing the carbon and energy efficiency of rice production systems, primarily by conserving irrigation and other critical inputs while boosting productivity.

The NICRA farmers in the selected village conducted all intercultural operations based on weather-based bulletins. This approach enabled them to optimize input usage according to the appropriate sowing window and recommended crop varieties. In contrast, non-NICRA farmers primarily relied on traditional knowledge and experiences to manage their crops, without the valuable support of weather information. Adopted farmers effectively utilized weather information as a risk management tool, saving four irrigations through weather-based advisories. On the contrary, non-adopted farmers lacked critical information on irrigation input, leading to the use of four additional irrigations during the rice growing period. This practice resulted in increased consumption of diesel and fuel, which are valuable resources. Weather-based advisories not only helped NICRA farmers mitigate the risks of impending dry spells, but also enabled timely actions that reduced moisture stress, facilitating better crop yields. The development and adoption of energy-saving techniques and efficient field management practices are critical for ensuring food and energy security (Yuan et al., 2018). In the present study, four irrigations applied by non-NICRA farmers consumed 3,164 MJ of energy per hectare. Beyond energy consumption, these farmers incurred an additional cost of USD 165.6 per hectare for these irrigations. Another perceptible difference in the energy usage was observed in the green manuring operations adopted by NICRA farmers. While this practice required higher energy input compared to non-NICRA farmers, it significantly improved soil health and soil fertility (Das et al., 2020), and maintained optimal soil moisture, thereby promoting better growth and yield. Crop residues serve as a carbon and energy for various soil macro- and micro-organisms, enhancing renewable energy within the soil ecosystem to support their growth and functioning (Singh et al., 2018; Ghosh et al., 2022). When evaluating energy output in terms of grain yield and biomass production, NICRA farmers demonstrated significantly higher values. This success can be attributed to their adherence to advisories from sowing to post-harvest operations.

3.4 Energy indices

To assess the pattern and efficient energy use among NICRA and non-NICRA farmers, several energy indices were calculated. These included energy use efficiency, energy productivity, net energy, energy profitability, direct energy, indirect energy, renewable and non-renewable energy, and human energy profitability and are presented in Table 7. The data revealed significantly higher values of energy efficiency, energy productivity and human energy profitability among NICRA farmers. This indicates a more efficient use of inputs and a less of energy required to produce a given quantity of output. These findings support the hypothesis that a weather-based farming systems, supported by regular access to smart information, positively impact environmental sustainability and enhances farm production by mitigating climatic risks. Chaudhary et al. (2017) emphasized the importance of designing and developing energy energy-efficient cropping systems to reduce environmental impacts. In recent years, farming has become increasingly dependent on high energy inputs due to the extensive use of fertilizers and pesticides. This underscores the need for energy-efficient production systems that are environmentally sustainable (Talukder et al., 2019). The data revealed that the higher energy use efficiency of NICRA farmers boosted energy productivity by 0.8 kg MJ^{-1}, primarily due to reduced energy consumption from fuels, fertilizers and chemicals (Paramesh et al., 2018). The significantly higher rice productivity achieved under the weather-based interventions of NICRA farmers led to greater energy output and higher energy productivity compared to non-NICRA farmers. The average net energy of NICRA farmers was calculated at 125937.8 MJ ha^{-1}, significantly higher than that of non-NICRA farmers (107745.6 MJ ha^{-1}). Energy profitability of rice cultivation was also assessed, revealing an energy profitability index of 9.1 for adopted farmers, compared to 7.7 for non-NICRA farmers. The higher energy profitability in the case of NICRA farmers could be attributed to substantial reduction in energy inputs compared to non-NICRA counterparts. Basavalingaiah et al. (2020) also reported higher energy use efficiency, energy productivity and energy profitability in direct-seeded rice (DSR) compared to transplanted

TABLE 6 Carbon input, carbon output and carbon indices for rice production.

S No	Parameters	2018		2019		2020		Mean	
		NICRA	Non-NICRA	NICRA	Non-NICRA	NICRA	Non-NICRA	NICRA	Non-NICRA
1	Carbon input (kg-CE ha^{-1})	414.75^b	610.13^a	414.75^b	485.93^a	352.55^{ns}	354.53^{ns}	394.02^b	483.53^a
2	Carbon output (kg-CE kg^{-1})	3889.60^a	2840.40^b	4331.60^a	2860.00^b	4685.20^a	2921.62^b	4302.13^a	2874.01^b
3	CSI	8.38^a	3.66^b	9.44^a	4.89^b	12.29^a	7.24^b	10.04^a	5.26^b
4	CER	9.38^a	4.66^b	10.44^a	5.89^b	13.29^a	8.24^b	11.04^a	6.26^b
5	CI (kg-CE kg^{-1})	0.97^b	1.20^a	0.88^b	1.14^a	0.87^{ns}	0.88^{ns}	0.91^b	1.07^a
6	CEF(kg kg-CE^{-1})	1.03^a	0.84^b	1.21^a	0.88^b	1.25^a	1.13^b	1.16^a	0.95^b

CSI, carbon sustainability index; CER, carbon efficiency ratio; CI, carbon intensity; CEF, carbon efficiency. The means with different letters are significantly different from each other according to *t*-test ($p < 0.05$), ns-non significant.

TABLE 7 Energy input–output ratio and energy indices for rice production by NICRA and non-NICRA farmers.

S No	Parameters	2018		2019		2020		Mean	
		NICRA	Non-NICRA	NICRA	Non-NICRA	NICRA	Non-NICRA	NICRA	Non-NICRA
1	Energy input (MJ ha^{-1})	11480.49^{b}	16663.37^{a}	14630.49^{ns}	14185.50^{ns}	15845.58^{a}	12744.27^{b}	13985.52^{ns}	14531.05^{ns}
2	Energy output (MJ ha^{-1})	135630.00^{a}	99034.5^{b}	151042.50^{a}	99775.00^{b}	163372.50^{a}	101876.63^{b}	150015.00^{a}	100228.71^{b}
3	Energy use efficiency	10.91^{a}	6.11^{b}	9.21^{ns}	7.73^{ns}	10.08^{ns}	12.19^{ns}	10.07^{ns}	8.68^{ns}
4	Energy productivity (Kg MJ^{-1})	0.35^{a}	0.20^{b}	0.27^{a}	0.23^{b}	0.41^{a}	0.34^{b}	0.34^{a}	0.26^{b}
5	Net energy (MJ ha^{-1})	113819.51^{a}	85146.63^{b}	120059.51^{a}	95444.50^{b}	143934.42^{ns}	142645.73^{ns}	125937.81^{a}	107745.62^{b}
6	Energy profitability	9.91^{a}	5.11^{b}	8.21^{ns}	6.73^{ns}	9.08^{ns}	11.19^{ns}	9.07^{ns}	7.68^{ns}
7	Direct energy (MJ ha^{-1})	2866.59^{b}	8034.97^{a}	2866.59^{b}	5501.02^{a}	2623.43^{b}	4443.35^{a}	2785.54^{b}	5993.11^{a}
8	Indirect energy (MJ ha^{-1})	8613.90^{ns}	8628.40^{ns}	11763.02^{a}	8684.49^{b}	13222.16^{a}	8300.92^{b}	11199.69^{a}	8537.94^{b}
9	Renewable energy (MJ ha^{-1})	1724.64^{ns}	1903.62^{ns}	4874.64^{a}	1903.62^{b}	6215.38^{a}	1379.34^{b}	4271.55^{a}	1728.86^{b}
10	Non-renewable energy (MJ ha^{-1})	9755.85^{b}	14759.75^{a}	9755.85^{b}	12281.88^{a}	9630.20^{b}	11364.93^{a}	9713.97^{b}	12802.19^{a}
11	Human energy profitability	94.06^{a}	71.07^{b}	101.11^{a}	76.52^{b}	146.72^{a}	130.47^{b}	113.96^{a}	92.69^{b}

The means with different letters are significantly different from each other according to *t*-test ($p < 0.05$), ns, non-significant.

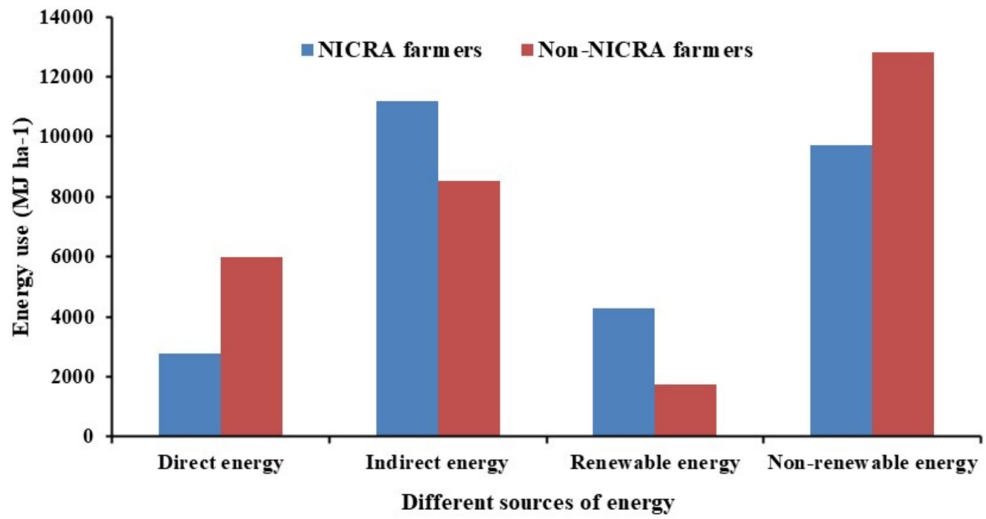

FIGURE 2
Comparison of different types of energy used by NICRA and non-NICRA farmers in rice cultivation.

rice, due to reduced energy inputs in DSR. In terms of human energy profitability, NICRA farmers achieved a value of 114.0, compared to 92.7 for non-NICRA farmers. This difference is likely due to higher net energy consumed per unit area of cultivation. Lesser use of inputs (fertilizer and labor) as suggested by the advisory resulted in lower input energy, thereby enhancing profitability.

3.5 Sources of energy for rice production

The different sources of energy used by NICRA and non-NICRA farmers are presented in Figure 2, which reveals that NICRA farmers utilized significantly less direct and non-renewable energy compared to non-NICRA farmers. Direct energy, in the form of labor and fuel, was calculated at 2785.5 MJ ha^{-1} for NICRA farmers, representing 53.5% reduction compared to non-NICRA farmers. Among the two sources of direct energy in rice cultivation, fuel accounted for about 55.09% of direct energy for NICRA farmers and 77.44% for non-NICRA farmers (Figure 3a). This indicates a more energy-efficient rice production system among NICRA farmers. Ashraf et al. (2021) investigated energy efficiency in rice-wheat crop rotation and recorded higher energy efficiency for wheat due to greater yields. Indirect energy sources for rice production include fertilizers, machinery, chemicals and seeds. The study showed that NICRA farmers used 31.2% more indirect energy for rice cultivation compared to non-NICRA farmers. Considering the percent share of inputs used in indirect energy, non-NICRA farmers invested a higher percent in fertilizers, machinery and chemicals (Figure 3b). The higher use of indirect energy by NICRA farmers was mainly because they adopted modern technologies, mechanization and green manuring techniques.

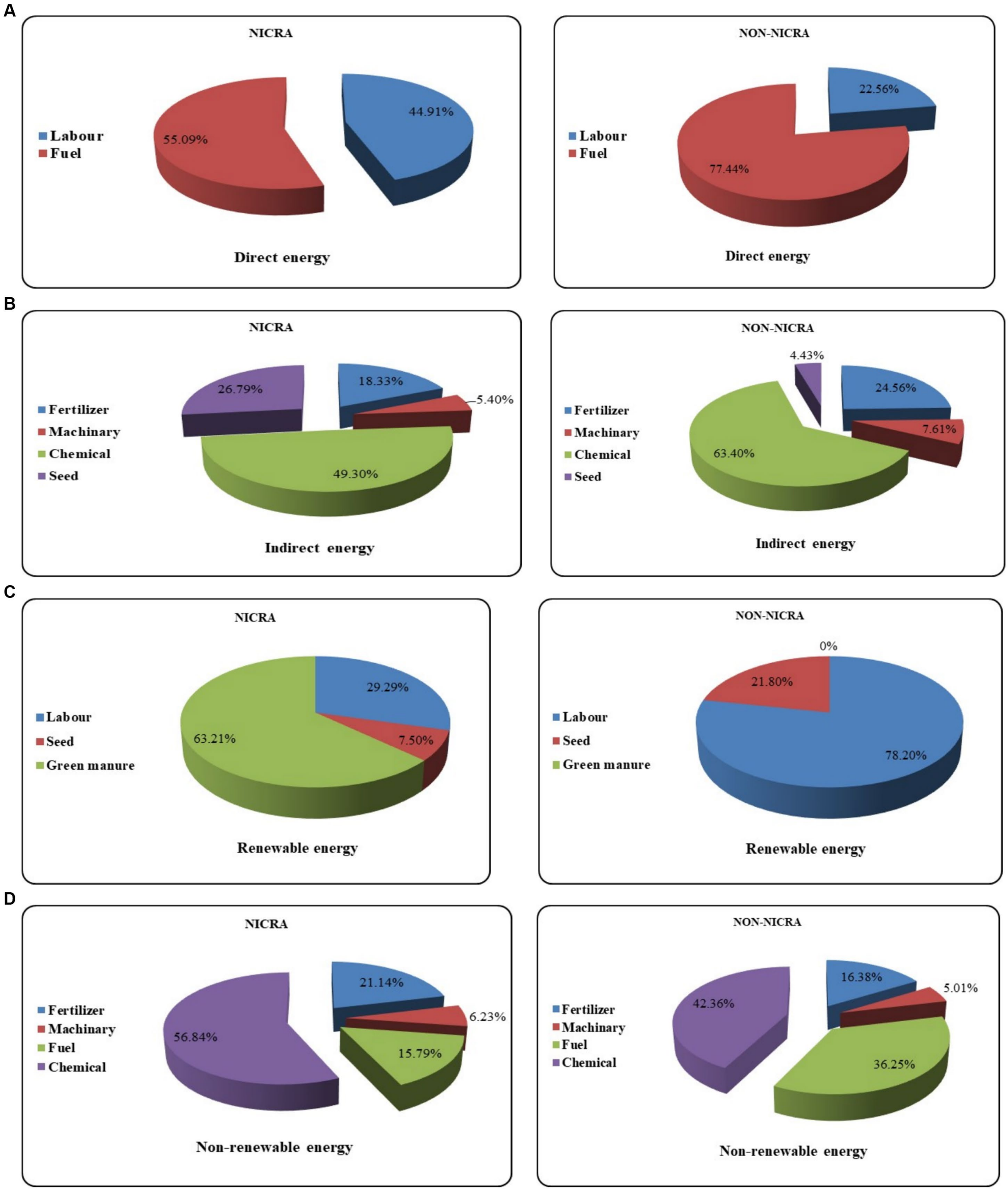

FIGURE 3
(a) Direct energy sources used by NICRA and non-NICRA farmers for rice production. **(b)** Indirect energy sources used by NICRA and non-NICRA farmers for rice production. **(c)** Renewable energy sources used by NICRA and non-NICRA farmers for rice production. **(d)** Non-renewable energy sources used by NICRA and non-NICRA farmers for rice production.

The practice of green manuring advocated in the advisories, improved soil health and increased soil water retention capacity (Prajapati et al., 2023), ultimately enhanced rice yields of NICRA farmers in the event of dry spells.

Adopted farmers also utilized more renewable energy compared to non-adopted farmers. The average renewable energy for NICRA farmers was 4271.6 MJ ha^{-1}, while for non-NICRA farmers, it was 1728.9 MJ ha^{-1}. The higher value of renewable energy has resulted from the use of green manuring. A greater share (63.21%) of renewal energy for rice production by NICRA farmers is attributed to green manuring (Figure 3c). In contrast, non-NICRA farmers' renewable energy was derived from labor, which contributed 78.21% of the total renewable energy used. Regarding non-renewable energy sources, NICRA farmers used 9713.9 MJ ha^{-1}, whereas non-NICRA farmers expended 12802.2 MJ ha^{-1}. The higher consumption of fuel and fertilizers by non-NICRA farmers significantly contributed to their total non-renewable energy usage. Previous studies, such as those by Bockari-Gevao et al. (2005) and Basavalingaiah et al. (2020) reported an energy input of 12,400 MJ ha^{-1} in rice crops, with major contributions from chemical fertilizers (7,700 MJ ha^{-1}). For non-NICRA farmers, agricultural chemicals and fuels accounted for 42.36 and 36.25% of total non-renewable energy, respectively. In contrast, NICRA farmers' non-renewable energy was primarily derived from agricultural chemicals (56.84%) and fuels (15.79%) (Figure 3d).

4 Conclusion

The study brought out significant findings regarding the impact of weather-based advisories on both farm economics and the environment. Farmers who adopted these advisories were able to modify their field operations accordingly, leading to substantial improvements in productivity. The smart weather-based interventions resulted in a 49.8% increase in rice yield for adopted farmers compared to non-adopted farmers, who primarily relied on traditional farming practices. The adopted NICRA farmers registered a carbon efficiency value of 1.16, indicating that for every kilogram of carbon equivalent emitted, 1.16 kilograms of rice grain yield produced. In contrast, the carbon efficiency value for non-NICRA farmers was 0.95.

When considering energy output in terms of grain yield and biomass production, NICRA farmers demonstrated significantly higher energy productivity. This success can be attributed to their consistent adherence to weather-based advisories, which guided them from sowing to post-harvest operations. These findings demonstrate that weather-based farm interventions have immense potential mitigating climatic risks in crop production, leading to enhanced productivity. Beyond promoting agricultural sustainability in the face of climate change, such interventions also offer considerable benefits for reducing environmental pollution. Furthermore, these practices can bring about positive changes in the local agro-ecosystem, enhancing resilience in crop production under changing climatic conditions.

Data availability statement

The data used in this article is sourced from the project "National Innovations on Climate Resilient Agriculture (NICRA)", RPCAU, Pusa, Bihar. Further inquiries can be directed to the corresponding author.

Author contributions

ASa: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. RJ: Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. SK: Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft. GN: Data curation, Formal analysis, Software, Supervision, Validation, Visualization, Writing – review & editing. RK: Data curation, Formal analysis, Supervision, Validation, Writing – review & editing. GS: Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. ASi: Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing. SB: Data curation, Project administration, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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