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Environmental Efficiency and Greenhouse Gas Emission Abatement Potential in Paddy Production Systems

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RICE production management practices in India, aimed at increasing crop productivity, have attracted policy concerns as to how the associated high environmental costs, especially greenhouse gas (GHG) emissions, can be efficiently mitigated. Among others, optimal resource usage and combinations that can ensure sustained production levels and effectively mitigate GHG emissions in rice production systems at a reduced environmental cost have not been explored. So, this investigation was carried out to assess emission reduction potential from the perspective of environmental and production economics. A Cross-sectional panel data obtained from cost of cultivation surveys by government of India was used for the study. The stochastic nonparametric envelopment of data appraoch (StoNED) through the framework of convex nonparametric least square regression (CNLS) approach was used to estimate the marginal abatement potential, input readjustment potential and the environmental technical efficiency of paddy production systems in Karnataka state, India. The results of the study on environmental efficiency assessment showed that the production processes of paddy farming were inefficient. This was explained by inefficiencies in farm management and scale operational defects; and inadequate adoption of farm level technology. Variability in production efficiency, energy productivity and sustainability across production systems and farm size were observed. The study further revealed that farmers could adjust and reduce existing input utilization mix by 7% and could enhance economic output by approximately 5%. It is recommended that energy conservation measures through optimum resource combination and technological application be prioritized. Future technological development and adoption should factor environmental costs management practices into productivity enhancement strategies.

Keywords: Convex nonparametric least squares; rice production; stochastic envelopment of data.

1. Introduction

In development economics, agricultural production plays a fundamental and significant role in rural transformation especially in least developed countries (LDCs), like India, both in terms of size of the economy and as an element of development strategy. The most vulnerable economic sector in India, which will encounter drastic economic costs if climate change is not addressed, is the agriculture sector where over 43.96 of the labour force were employed in 2021 (Statista, 2024). However, the rapid development and transformation of the Indian agriculture as a result of the adoption of green revolution technology to ensure food sufficiency, reduction in nutritional insecurity and improvement in livelihood have exposed most production systems to be environmentally unfriendly due to their high usage of high carbon-intensive inputs (Benbi, 2018; Ramesh and Rathika, 2020).

Agricultural production is recognized as a substantial source of human-induced emissions, accounting for approximately 23% of the total global anthropogenic GHG emissions, with CH_4 accounting for 44%, N_2O for 81%, and CO2 for 13% (He et al., 2024). It is critical to address growing environmental concerns related to greenhouse gas (GHG) emissions which are often associated with high input usage

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pattern especially water and energy consumption, and fertilizer and pesticide pollution (Blay et al., 2024; Wassmann, 2019). Compared to other crop production systems, rice production systems play a more critical role in global agricultural GHG emissions (Smith et al., 2008). It has been estimated that rice accounts for roughly half of total global crop production emissions in terms of carbon dioxide (CO_2) equivalents per kilocalorie produced (Carlson et al., 2017). In the context of India, paddy cultivation occupied the largest area of 43.8 million hectares with production of 115.6 million tons during 2018-19 (Sangeeta, 2019; Ramesh and Rathika, 2020) and the most intensively grown crop among farmers in the country. Paddy production contributes behemoth to the anthropogenic greenhouse gas (GHG) emissions, primarily releasing nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2), thus playing a crucial role in driving climate change (Li et al., 2024; Jiao et al., 2024). It is established that the dynamics in cropping pattern in India has been impacted by the recent changes in climate, aided by increase in greenhouse gas (GHG) emissions at increased compound annual growth rate of 0.77 per cent (MoEF, 2021; Sharma and Praveen, 2019; Sharma et al, 2021) with substantial reduction in land productivity. India is the third-largest emitter of greenhouse gases with total annual emission of 2.59 Giga tons (Gt) carbon dioxide equivalent (CO_2eq) after China (10.0 Gt) and the United States (5.2 Gt). In respect of global GHG emission attributable to agriculture, it is estimated that India and China, annually, contribute about 650 million tons (Mt) CO_2 eq emission each, accounting for 7 per cent of global GHG emissions in the agriculture sector (FAO, 2019). In 2018, India was ranked among the top three emitters of total GHG emissions due to agriculture, i.e., crop and livestock production as well as other associated land use processes (FAO, 2019). To create more efficient, inclusive, resilient, and sustainable agrifood systems for better production, nutrition and environment, agricultural production systems require a pivotal role of innovation adoption in the production process. Thus, agriculture and food systems in India and other developing countries must urgently adapt and transform in order to respond to the imperatives of climate change. This requires the integration among the environment and its quality, economic and production efficiency, social and economic equity as well as maintaining or conservation of the water and land resources (Alshaal and El-Ramady, 2017).Within this context, Indian government ratified the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) to reduce the emissions intensity of its GDP by 33 to 35 per cent by 2030 from the 2005 level (Indian Network for Climate Change Assessment, 2022) and net zero carbon by 2070. To achieve these, the government is to introduce GHG emissions reduction program framework for inducing carbon abatement which can lead to economy-wide reductions in the CO_2 emissions and production of important co-benefits product (Indian Network for Climate Change Assessment, 2022) to ensure sustainable transformation of agrifood systems.

Therefore, it becomes imperative for policy makers to have knowledge on environmental production efficiency and carbon dioxide abatement potential to inform carbon dioxide reduction targeted policies to meet the national emission goals. Mitigation process, thus, focuses extensively on scientific experimentation, environmental and economic measures. To this effect, this study evaluates the greenhouse emission reduction potential in paddy production systems in Karnataka state of India, from the perspective of environmental and production economics analysis. Specifically, the estimation was done on environmental efficiency in relation to GHG emission abatement potentials across production systems and farm sizes. The insights from this study are critical to guide how existing agriculture production systems can potentially be restructured, and to accelerate transformation of food production systems towards more inclusive, resilient, sustainable and healthy technological innovation and farming practices.

2. Materials and Methods

The study employed a microlevel analysis using cross-sectional plot level data on inputs used in paddy production. The data was obtained from the surveyed data of Cost of Cultivation Scheme (CSS) pertaining to Karnataka State from 2009 to 2019 production seasons. The study area, represented in its agricultural and climatic map, is displayed in figure 1 below. In order to estimate the environmental efficiency and GHGs abatement potential, the quantity of GHGs was measured and estimated as CO_2 eq for the production process.

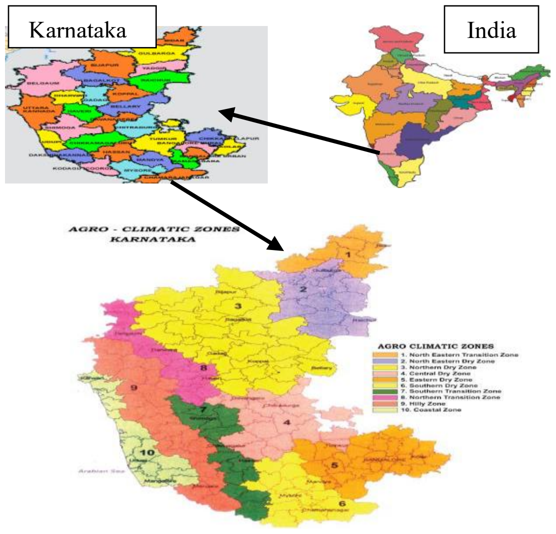

Fig. 1. Study Area.

2.1. Estimation of greenhouse gas (CO_2 eq) emission (Conceptual framework)

The estimation of GHG emission in the present study, concentrated on emission levels at the farm gate (cardle-gate). Also, emphasis was primarily placed on CO_2 emission and GHG will be used from here onwards to connotes CO_2 emission. Greenhouse emission was estimated according to an internationally accepted method of accounting for GHG emission (Tier 1 of IPPC methodology). The conceptual framework in this context is presented in figure 2 below. The figure identifies three major components, namely; emission sources, production activity and main type of GHG emission.

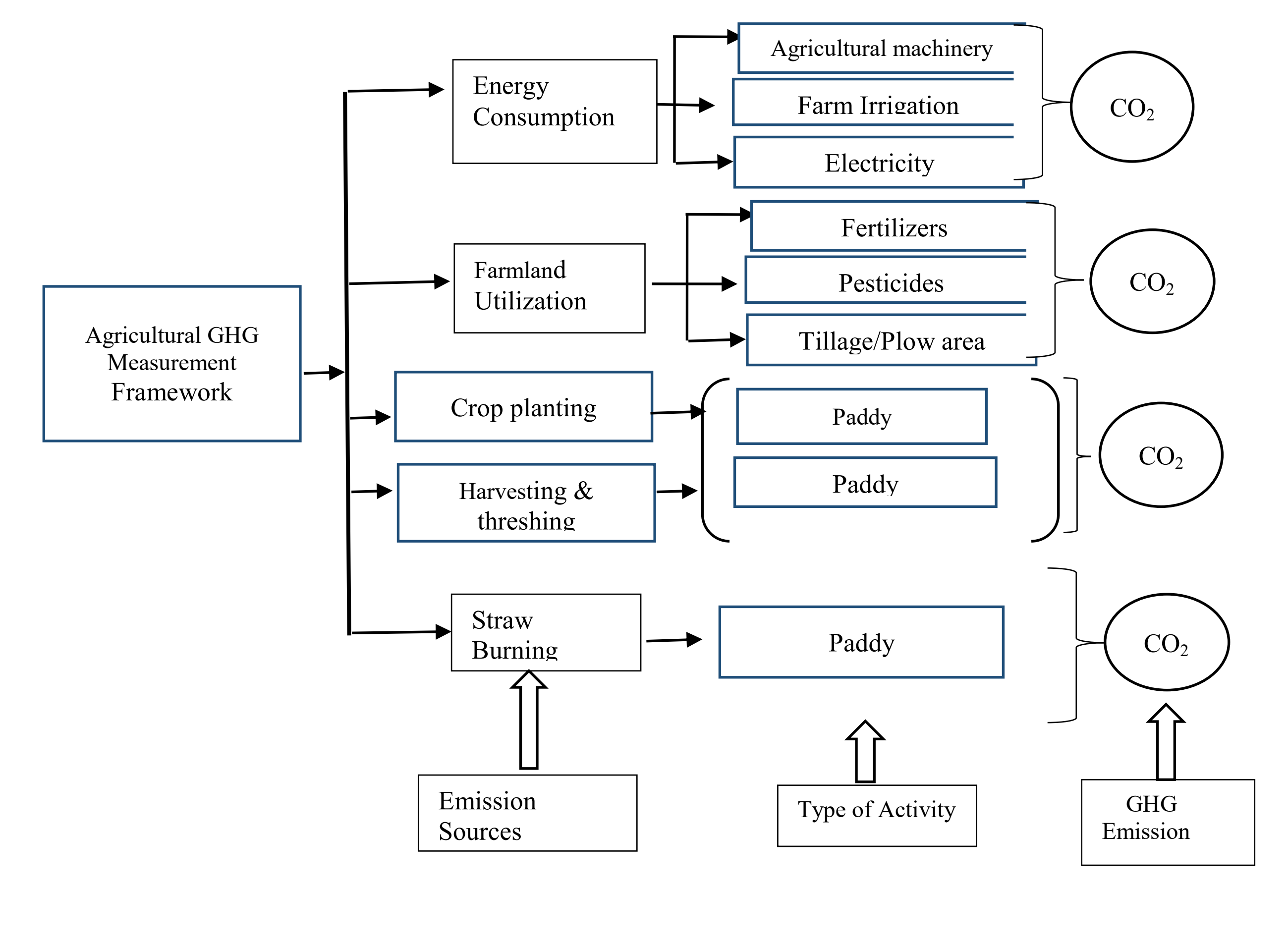

Fig. 2. Conceptual Framework.

2.2. Carbon emission from burning of residues

The total biomass produced during the production process was computed using the relationship:

$$Total\ Biomas = \frac{Economic\ Yield\ (Agronomic\ Yield)}{Harvest\ Index\ (HI)} \ldots \quad (1)$$

The HI value of 0.4 for coarse cereal was adopted from Maheswarappa et al. (2011) for paddy. The emission released from burning of remaining straw generated from the biomass produced was estimated using the formula (IPPC, 2007) below:

$$CE = Total\ Biomass \times Average\ Dry\ Matter\ Fraction \times Fraction\ \ Actually\ Burnt \times Fraction\ Oxidised \times Carbon\ Fraction \times E_f \ldots\ldots \quad (2)$$

CE is the carbon equivalent produced, dry matter fraction =0.4, carbon fraction = 0.4709, fraction of oxidation =0.90, fraction actually burnt = 0.10 (10%), carbon emission factor (E_f)= 11.7 g/kg = 0.0117 kg/kg.

2.3 Sustainability index

Sustainability indices for each year were computed using equation (3):

$$C_s = \frac{(C_O\ -\ C_i - GHG\ emission)}{C_i} \ \ldots\ldots \quad (3)$$

where C_s defines the sustainability indices, C_O and C_i are the carbon content of output and input respectively. The carbon-based output includes operations that involved harvesting, threshing of paddy grain and the management of crop residues whereas the carbon-based inputs included farm operation management practices such as fertilizer application, irrigation and tillage operation.

2.4. Assessment of environmental efficiency and GHG abatement potential

In the production process of agricultural commodities, combination of inputs results in the production of desirable (bags of paddy) and undesirable (CO_2eq) outputs. To incorporate undesirable outputs in assessing technical efficiency of a production process, the study adopted environmental production technology (EPT) models developed by Fare et al. (2005), Wang et al. (2017) and Delnava et al. (2023) as illustrated in the diagram below.

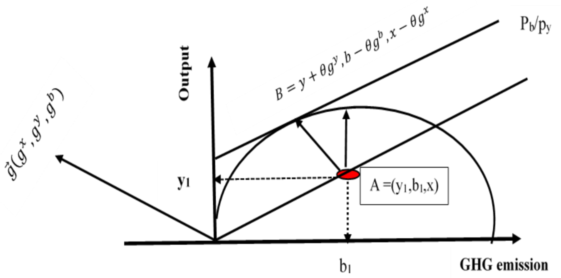

Fig. 3: Environmental production technological set

The technological set (Fig. 1) can be described in terms of economic and environmental performance.

Let $x = (x_1, x_2, \ldots\ldots\ldots . x_l) \in \mathbb{R}_+^l$ be a vector of inputs employed in the production process, , $y = (y_1, y_2, \ldots\ldots\ldots . y_j) \in \mathbb{R}_+^j$ be the vector of desirable outputs, and $b = (b_1, b_2, \ldots\ldots\ldots . b_L) \in \mathbb{R}_+^L$ be the vector of undesirable outputs. The environmental production technology is thus defined as

$$T = \{(x, y, b) | x\ can\ produce\ (y, b)\} \ \ldots\ldots \quad (4)$$

In order to ensure appropriate modelling of the given technological function, the assumptions of strong disposability of inputs and desirable outputs, weak disposability of undesirable outputs and null-jointness of desirable and undesirable outputs were introduced. Given these axioms and technological set, the desirable-undesirable directional distance function that seeks to maximize the production of desirable output and minimize undesirable output was constructed as:

$$\overrightarrow{D_T}(x, y, b, g^x, g^y, g^b) = \sup\{\theta | x - \theta g^x, y + \theta g^y, b - \theta g^b) \in T\} \ldots \ (5)$$

where $(g^x, g^y, g^b) \in \Re_+^{m+s+q}$ is the directonal vector. The directional distance function (DDF) is a general functional representation of the technology: assuming g-disposability (Färe et al., 2005; Njuki and Bravo-Ureta, 2015), the production possibility set T was defined as:

$$T = \{(x, y, b) \in \ \Re_+^{m+s+q} | \overrightarrow{D_T}(x, y, b, g^x, g^y, g^b) \geq 0$$
$$\text{for any}(g^x, g^y, g^b) \ \in \Re_+^{m+s+q} \ldots\ldots . \quad (6)$$

To account for measurement errors, unobserved heterogeneity, and other random noise in estimation of the production technological set as illustrated in Eqn (5), the stochastic nonparametric data envelopment appraoch (StoNED) through the framework of convex nonparametric least square regression (CNLS) estimation approach (Kuosmanen and Johnson, 2010) was adopted as specified below in equation (7):

$$\min_{\alpha,\beta,\gamma,\delta,\varepsilon} \sum_{l=1}^{n} \varepsilon^2 \quad \ldots(7)$$

$$\text{s.t. } \gamma_i' y_i = \alpha_i + \beta_i' x_i + \delta' b_i - \varepsilon_i \qquad \forall i$$

$$\alpha_i + \beta_i' x_i + \delta_i' b_i - \gamma_i' y_i \leq \alpha_j + \beta_j' x_i + \delta_j' b_i - \gamma_j' y_i \quad \forall i, j \text{ and } i \neq j$$

$$\gamma_i' g^y + \beta_i' g^x + \delta_i' g^b = 1 \qquad \forall i$$

$$\beta_i \geq 0, \delta_i \geq 0 \text{ and } \gamma_i \geq 0 \qquad \forall i$$

where the residual ε_i represents the estimated directional distance function (DDF) for observation i, evaluated as d $(\overrightarrow{D_T}(x, y, g^x, g^y) + b_i$, and the $\beta_i, \gamma_i and\ \delta_i$ are the estimated marginal propensity to inputs readjustment potential, good outputs enhancement, and emission reduction potential respectively. The computation of ε_i was formulated separately for each firm i, such that estimating the values of the DDF for all firms minimizes the sum of ε_i (Delnava et al., 2023; Wang et al., 2014; Kuosmanen and Johnson, 2010). In this study, the observed input-output vectors (x,y) among the farmers were random in nature and assumed the expectation E(x_i, y_i) to be constant across all farmers (Lee, 2014) as the aim of the farmer is profit maximization in a competitive market. Under such condition, all farmers take the same input-output prices as given, and that the optimal solution (x_i^*, y_i^*) is exactly the same for all the farmers. Since the study employed panel data (x_{it}, y_{it}), $t = 1, \ldots, T$, we assumed that E (x_i, y_i) to be constant over time. Thus, the sample variance was evaluated as $\sigma_x^2(g^x) = \frac{1}{T}\sum_{t-1}^{T}(x_{it} - \bar{x}_i)^2$, $\sigma_y^2(g^y) = \frac{1}{T}\sum_{t-1}^{T}(y_{it} - \bar{y}_i)^2$ and $\sigma_b^2(g^b) = \frac{1}{T}\sum_{t-1}^{T}(b_{it} - \bar{b}_i)^2$. Thus, the study employed the directions vector of $\vec{g} = (-\sigma_x^2(g^x), \sigma_y^2(g^y), -\sigma_b^2(g^b)$ for the inputs, desirable output and undesirable output respectively, in order to map the evaluated decision-making unit (DMU) towards the production technological set.

In order to evaluate the technical inefficiencies, the nonparametric kernel deconvolution procedure proposed by Hall and Simar (2002) was adopted to estimate the expected inefficiency, μ. The residual $\hat{\varepsilon}_i^{CNLS}$ is a consistent estimator of $e^o = \varepsilon_i + \mu$ for production function model. Thus, density function of e^o following Kuosmanen and Johnson (2010) is expressed as equation (8):

$$\hat{f}_{e^o}(z) = (nh)^{-1} \sum_{i=1}^{n} K\left(\frac{z - e_i^o}{h}\right) \ldots\ldots\ldots\ldots \quad (8)$$

where $K(\cdot)$ is a compactly supported kernel, and h is a bandwidth. The first derivative of the density function of the composite error term (f_ε') is proportional to that of the inefficiency term (f_u') in the neighborhood of μ (Hall and Simar, 2002; Kuosmanen and Johnson, 2010). Hence, the nonparametric estimator of expected inefficiency μ is obtained by the formulation in equation (9):

$$E[u_i|\hat{\varepsilon}_i] = \hat{\mu} = arg \max_{z \in C}(\widehat{f'}_{e^o}(z)) \ \ldots\ldots \quad (9)$$

where C is a closed interval in the right tail of f_{e^o}. To implement the procedure empirically, a bandwidth (h) must be chosen, and C must be defined (see Delaigle and Gijbels, 2004). From equation (8), the firm-level technical efficiency (TE) is then measured based on the estimated conditional mean. using equation (10):

$$TE = \exp(-E[u_i|\hat{\varepsilon}_i]) \ldots \quad (10)$$

To account for the changes in farm efficiency, we evaluated farm level total factor productivity change by decomposing directional distance function model as

$$\text{TFP} = \left[\frac{\left(1 + \mathrm{D_o^t}(\mathrm{X^t}, \mathrm{y^t}.\mathrm{b^t}; \mathrm{y^t}, -\mathrm{b^t})\right)}{\left(1 + \mathrm{D_o^{t+1}}(\mathrm{X^{t+1}}, \mathrm{y^{t+1}}.\mathrm{b^{t+1}}; \mathrm{y^{t+1}}, -\mathrm{b^{t+1}})\right)} \times \frac{(1 + \mathrm{D_o^{t+1}}(\mathrm{X^t}, \mathrm{y^t}.\mathrm{b^t}; \mathrm{y^t}, -\mathrm{b^t}))}{(1 + \mathrm{D_o^t}(\mathrm{X^{t+1}}, \mathrm{y^{t+1}}.\mathrm{b^{t+1}}; \mathrm{y^{t+1}}, -\mathrm{b^{t+1}}))}\right]^{1/2} \ldots 11)$$

where t=1…,T denotes periods of study and $D_O^t(X^t, y^t.b^t; y^t, -b^t)$ is the distance function from frontier in period t+1 while assessing a DMU from period t.

3. Results and discussions

3.1 Environmental efficiency and factor productivity in paddy production

Results on assessment of efficiency of the production systems with regard to environmental sustainability and factor productivity in paddy production are presented in Table 1. The results indicated that during the study period, environmental sustainability of paddy production system declined from 4.25 to 3.09 at a rate of 0.51 %. The decline in environmental sustainability during the study period was due to technological deficiency indicated by the negative growth rate in environmental efficiency. Again, while the study results showed that total factor productivity increased at an increasing rate, average productivity was less than unity implying decline in the overall performance of the production system. Most of the decline in total factor productivity was due to retrogression in technical change (see Blay et al., 2024). This implies that farmers did not adapt to high levels of new technology during the study period despite introduction of new technology in paddy production in India. The deterioration in factor productivity was due to inefficiency in the utilization of resources as indicated by the decline in eco-efficiency score. The average eco-efficiency score was estimated at 0.95 implying that the farmers are operating below the frontier. This result supports a study conducted by Bhoi et al. (2021) on the assessment of rice ecological system in India. The authors estimated average technical efficiency scores of 0.64 and 0.95 for Gujarat and Odisha states in India respectively. Sub-system assessment based on farming systems revealed that canal irrigated farming system was environmentally efficient and sustainable as compared to ground water extracted irrigated farming system. The higher sustainability in canal paddy production is attributable to technical change to an extent of 2 % as compared to 1 % in ground water irrigated farms. Moreover, the energy use efficiency and productivity were higher in large farms as compared to small and medium farms indicating improvement in resource use efficiency (0.95). The study found that during the period under study, though efficiency was relatively high in large farms, technological improvement in large farm declined by 5 % while small farms decelerated in improvement in farm management as indicated by the less than unity in technological change score (0.88). These results contradict those of Prasannakumar (2016) who reported that smallholder farmers were more efficient in energy utilization in rice agroecological system in Karnataka state.

With regards to environmental efficiency, the general production process of paddy in Karnataka state was inefficient. The wide variations in environmental efficiencies scores across farming system, and farm sizes imply that virtually all the farmers were not fully acquainted with the right combination of inputs. The results also showed that most of the farmers were environmentally inefficient in the utilization of the production inputs leading to increased greenhouse gas emission level (Table 1). The results, thus, affirm that paddy production is one of the major crops which contribute significantly to agricultural sector GHG emissions. This finding is supported by Wang et al. (2014), Shah et al. (2024) and Blay et al. (2024).

Table 1. Eco-efficiency and sustainability in paddy production from 2008 -2019.

Years	S. I	Eco-eff	Effch	Techch	Pech	Sech	TFPCH
2008	4.25	0.94					
2009	3.18	1.00	1.00	0.79	1.00	1.00	0.79
2010	2.65	0.94	1.00	0.39	1.00	1.00	0.39
2011	3.91	0.97	1.00	0.64	1.00	1.00	0.64
2012	3.35	1.00	1.00	0.82	1.00	1.00	0.82
2013	4.41	0.93	1.00	1.24	1.00	1.00	1.24
2014	4.22	0.95	1.00	1.03	1.00	1.00	1.03
2015	3.21	0.92	1.00	0.57	1.00	1.00	0.57
2016	3.44	1.00	1.00	1.33	1.00	1.00	1.33
2017	1.44	0.92	1.00	1.93	1.00	1.00	1.93
2018	3.54	0.91	1.00	1.43	1.00	1.00	1.43
2019	3.09	0.91	1.00	1.66	1.00	1.00	1.66
Average	3.39	0.95	1.00	0.97	1.00	1.00	0.97
CAGR (%)	-2.63	-0.51	0.00	11.92	0.00	0.00	11.92
Farming systems							
Borewell system	2.29	0.95	1.00	1.01	1.00	1.00	1.01
Canal system	3.71	0.98	1.00	1.02	1.00	1.00	1.02
Farm size groups							
Large farms	13.27[a]	0.95	1.00	0.95	1.00	1.00	0.95
Medium farms	6.23[b]	0.93	1.00	0.86	1.00	1.00	0.86
Small farms	2.80[c]	0.91	1.00	0.88	1.00	1.00	0.88

Eco-eff = Green efficiency score, Techch= Technological change, Effch = Efficiency change,
Pech = Pure efficiency change, Sech = Scale efficiency, TFPch = Total factor productivity change,
S.I = Sustainability index;

The study results indicated that improvement in technology such as introduction of high yielding varieties (HYV) especially in paddy has caused a rebound effect as revealed by the increasing greenhouse gas, indicated by retrogression in environmental sustainability, efficiency and factor productivity growth over the study period. However, Blay and Lokesha (2022) noted that improvement in farmer level technical efficiency level accompanied by high level of factor productivity can cause immense reduction in greenhouse emission level among farmers in India. Thus, adoption of recommended management practices (RMPs) by the farmers such as timely and required application of fertilizer, effective on-farm demonstration and operational training on carbon-intensive implements could raise the performance of farmers to a higher level, thus moving them to the frontier, as the inefficiencies were purely technological in nature.

3.2. Greenhouse gas emission reduction potential in paddy production

The results of the estimation procedure are presented in Table 2 below. In paddy production, the point estimate from the CNLS-DDF model (Table 2) revealed that improvement in the present output was possible to an extent of 7.7 % from the existing production level (γ), by improving farm level resource use and technology application. These ensure optimal adjustment in input structure mix which will lead to energy saving and emission reduction. The results imply that energy optimization through adjustments in input usage structure, by strict adherent to the recommended farm level production practice in paddy, could reduce GHG emissions by approximately 769.20 kg CO_2 eq ha^{-1} yr^{-1} during the study period. The estimated results indicate that input energy readjustment and optimization on an average could save 5.74 % of the total input emissions annually during the production process of paddy in Karnataka state without jeopardizing economic output. This result supports a study conducted by Li et al. (2024).

Table 2. Greenhouse gas emission abatement potential based on CNLS-DDF.

Year	Gamma (γ)*	Beta (β)*	Delta (δ)*	Target GHG (kg CO_2eqha^{-1})	Emission Reduction (kg CO_2eqha^{-1})	ESTR (%)
2008	0.154	0.125	0.042	11696.8	491.3	12.5
2009	0.097	0.045	0.105	11088.5	1164.3	4.5
2010	0.061	0.069	0.058	12856.3	745.7	6.9
2011	0.04	0.053	0.048	11941.8	570.8	5.3
2012	0.015	0.051	0.018	11205.2	201.7	5.1
2013	0.034	0.042	0.049	11626.7	569.7	4.2
2014	0.079	0.053	0.051	9805.2	500.1	5.3
2015	0.042	0.027	0.052	12662.2	658.4	2.7
2016	0.063	0.019	0.216	9245.9	1997.1	1.9
2017	0.016	0.057	0.038	15682.8	595.9	5.7
2018	0.048	0.038	0.051	12855.4	655.6	3.8
2019	0.273	0.068	0.021	17251.6	362.3	6.8
Average	0.077	0.054	0.062	12326.5	769.2	5.4
Farming systems						
Irrigated	0.028	0.064	0.087	20042.3	1743.7	6.4
Non-irrigated	0.107	0.108	0.278	10614.6	2950.9	10.8
Farm size groups						
Large farms	0.146	0.088	0.134	12659.1	1696.3	8.8
Medium farms	0.089	0.111	0.29	10135.2	2939.2	11.1
Small farms	0.016	0.068	0.013	12138.6	157.8	6.8

*Results are indices derived from non-parametric estimation; all are statistically significant at 5% level of significance.

These results show that a significant reduction in emissions can be achieved by just focusing on the reduction in inefficiencies in the input utilization pattern by adopting the recommended package of farm management practices. The results suggest that policies for improving energy saving would be more effective than those that target emission reduction through investment in the farm by shifting towards clean energy structure. This follows, as the economic cost (shadow price) of emission reduction potential factor in paddy cultivation increases over the period under study as indicated by the values of greenhouse emission abatement potential factor (δ) from the table. The average point parameter of β was less than δ indicating that the relative elasticity of reducing emission is lower than energy saving for any given technology intended for reducing emission in paddy cultivation in Karnataka state. These results are supported by those of a study conducted by Zhang et al. (2024) who noted that reduction in energy inputs mainly by optimization in agrochemical usage could significantly reduce total emission from paddy fields. However, the results across farming systems and farm size categories show that energy saving reduction potentials differ significantly. Based on the framework of the constructed model, with the focus on improvement in economic output, energy and emission reduction, the results showed that small farms had the maximum energy reduction potential from inputs energy adjustment, without jeopardizing economic output levels. Thus, desirable output could be enhanced by 1.6 per cent from the current output level and still achieve a reduction in emission levels by 157.8 kg CO2eq ha-1 simultaneously, by improving adoption of farm level technology. Large and medium farms had the potential of reducing emissions by 1696.3 and 2939.20 kg CO2eq ha-1, and still achieve 14.6 and 8.9 per cent improvements in desirable output respectively. The variation in reduction potentials is due to the differences in the input structure and the different emission factor of the respective inputs.

In summary, the estimated parameters indicated that expansion in production will result in increase in greenhouse emission (expansion decoupling) without proper management. The results also indicate that the farmers prefer to increase desirable output without cognizance to undesirable output (when CO_2 emissions are unregulated). Thus, to ensure food security and avert the adverse impact of the production process on the environment, improvement in environmental law in agricultural production and adjustment in input use structure will result in emission reduction potential as the increase in emission is due to inefficiencies in the production process. The results are in line with studies conducted by Liu and Feng (2018) who reported that quantitative improvement in efficiency was an important element of the emission reductions strategy to achieve the emission reduction targets in the global economy.

3. Conclusions

Paddy production ecological systems in India have undergone drastic changes after the inception of the green revolution. The increasing pressure for the country to feed its growing population has forced the production of agricultural commodities to be intensively managed to boost and sustain the demand for economic growth. The intensification process has contributed tremendously to ensure food and nutritional security and livelihood for millions of rural people in India but at an environmental cost. With increasing pollution levels in the Indian agrarian sector, the need to address the challenges for meeting food production in India while controlling and reducing the GHG emissions becomes double exigent. Given the deepening concerns of global ecological degradation due to food production system, the need for revitalizing the intensification process, increasing the productivity of agricultural lands and decoupling greenhouse emission in agriculture to ensure sustainability through environmental modelling and assessment becomes relevant. It also provides powerful framework to evaluate the potential impact of production system on ecological systems. However, the mitigation process has focused severally on scientific experimentation, environmental and economic measures. Therefore, this study has made a modest attempt to evaluate the greenhouse emission reduction potential in paddy production systems that contributes significantly to the policy discourse of greenhouse gas emission in agriculture sector, from analytical perspective. The results of the study on environmental efficiency assessment showed that the production processes of paddy production were inefficient and characterized by retrogression of energy productivity and sustainability with rebound effect of technology. The study observed variability in production efficiency, energy productivity and sustainability across production systems and farmer size (large, medium and small) signifying divergence and heterogeneity in the production practices in the state with small scale paddy farmers characterized by high usage of input inefficiency. The study, again revealed possible adjustment and reduction in existing input utilization structure by 7% and to enhance economic output by approximately 5 per cent among paddy farmers by improving technical efficiency and technological adoption by farmers. We, therefore, conclude that reducing energy input through rational adjustment and allocation of energy resources by learning from innovative practices of production would be more cost-effective way to abate CO_2 emissions as the relative elasticity of improving energy structure was faster in reducing emission for any given technology intended for reducing emission in Karnataka state.

Conflicts of interest

“There are no conflicts to declare”.

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