RESEARCH PAPER

Measuring the Sustainability Implications of Rice Production in India: An Entropy-Weighted Multidimensional Index Approach

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ABSTRACT

Rice production plays a critical role in India's food security and agricultural economy; however, its sustainability is increasingly shaped by resource-use intensity, environmental pressures, and climatic variability. This study develops an entropy-weighted Rice Sustainability Index (RSI) to evaluate the temporal dynamics of rice-production sustainability in India during 2007–08 to 2022–23. Eight indicators representing climatic, environmental, resource-use, and economic dimensions were normalized and aggregated using the entropy-weighting method. The results reveal variation in the degree of divergence (0.037–0.117) and indicator weights (0.062–0.196), reflecting differences in their discriminatory information within the study dataset. Irrigation intensity receives the highest weight (0.196; divergence 0.117), followed by fertilizer use (0.163; divergence 0.097) and mean monsoon temperature (0.141; divergence 0.084). In contrast, rice area intensity records the lowest weight (0.062; divergence 0.037), indicating comparatively limited variation-based information. The RSI exhibits substantial inter annual fluctuations alongside an overall improvement. It declined from 0.466 in 2007–08 to 0.276 in 2009–10, followed by an uneven recovery and a subsequent rise to 0.621 in 2022–23. The final value represents a 33.26% increase over the initial observation, indicating an improvement in the composite sustainability profile despite periodic setbacks. The findings suggest that rice sustainability evolved unevenly rather than through a consistent upward trajectory. The prominence of irrigation intensity, fertilizer use, and monsoon temperature in the entropy-weighting results highlights their comparatively greater contribution to differentiating sustainability outcomes within the observed data. These weights, however, measure informational variation rather than causal influence or intrinsic policy importance. The proposed RSI provides a systematic framework for monitoring temporal sustainability patterns and informing evidence-based agricultural policy.

Keywords: Rice production; Sustainability; Rice Sustainability Index (RSI); Entropy weighting; Multidimensional; Climate variability.

How to cite this article: Vig V, Kumar D, Kaur N, Measuring the Sustainability Implications of Rice Production in India: An Entropy-Weighted Multidimensional Index Approach. Int J Drug Deliv Technol. 2026;16(87s): 1250-1261; DOI: 10.25258/ijddt.16.87s.131

Source of support: Nil

Conflict of interest: None

INTRODUCTION

Rice (Oryza sativa L.) is one of the world's most important staple crops and plays a central role in global food security, particularly in Asia. More than half of the world's population depends on rice as a major source of dietary energy, while millions of farm households derive their livelihoods directly or indirectly from its cultivation, processing and trade. India occupies a strategic position in the global rice economy as the world's second-largest rice producer after China. Within Indian agriculture, rice serves not only as a major staple food but also as an important source of farm income, rural employment and export earnings. Rice accounted for approximately 42% of India's total food-grain production in 2024–25, while its production increased substantially from 20.58 million tonnes in 1950–51 to approximately 149.07 million tonnes in 2024–25. This long-term expansion reflects major technological and institutional changes in Indian agriculture, including the expansion of irrigation, adoption of improved varieties, increased fertilizer use, mechanization and supportive agricultural policies (RBI, 2024; Madhu et al., 2023). The expansion of rice production has, however, been accompanied by increasing dependence on land, water, fertilizers, energy and other agricultural resources. The long-term increase in production has

been driven largely by improvements in productivity rather than by a proportionate expansion of cultivated area. Rice yield increased from 668 kg ha^{-1} in 1950–51 to approximately 2,899 kg ha^{-1} in 2024–25, whereas rice area increased from 30.81 million hectares to approximately 51.4 million hectares during the same period (RBI, 2024). Although these changes demonstrate a substantial increase in productive capacity, they also indicate an increasingly intensive production system in which gains in output are associated with greater resource requirements and environmental pressures. Irrigation dependence, fertilizer use and methane emissions have consequently become important concerns for the long-term sustainability of rice production (Jatav et al., 2023; Suresh et al., 2022; Pan et al., 2024). In addition, variations in temperature and rainfall influence the production environment and may contribute to fluctuations in rice production, particularly in climate-sensitive regions (Dhanya et al., 2015; Mahajan et al., 2017).The sustainability challenge is particularly relevant because rice production is closely linked with water use and greenhouse-gas emissions. Flooded rice cultivation is highly water-intensive and has been estimated to require approximately 3,000–5,000 litres of water per kilogram of rice (Bouman, 2009; Geethalakshmi et al., 2011). At the same time, flooded rice systems are an important source of methane emissions, while changes in temperature and rainfall regimes can further influence crop-growing conditions and water availability (Wassmann et al., 2009; Pothapakula et al., 2020). Thus, the sustainability of rice production cannot be adequately assessed through production or yield performance alone. It requires consideration of the interaction between resource use, environmental pressures, climatic conditions, land allocation and economic incentives. Accordingly, crop intensity, irrigation intensity, methane emissions, fertilizer use, rice area, mean monsoon temperature, monsoon rainfall and MSP growth represent complementary dimensions through which the sustainability conditions of rice production can be examined (Jatav et al., 2023; Suresh et al., 2022; Tiyndel et al., 2025). However, existing assessments often examine individual aspects of rice sustainability separately, with limited integration of resource, environmental, climatic and economic dimensions into a single composite measure for India. This study addresses this gap by developing an entropy-weighted multidimensional Rice Sustainability Index (RSI). Against this backdrop, the present study constructs an Entropy-Weighted Multidimensional Rice Sustainability Index (RSI) for India using annual national-level data for 2007–2023. The index incorporates eight indicators representing resource use, environmental pressure, climatic conditions and economic incentives: rice area intensity, irrigation intensity, methane emissions, fertilizer use, MSP growth rate, area under rice cultivation, mean monsoon temperature and monsoon rainfall. The indicators are normalized according to their respective sustainability orientations and objectively weighted using the entropy method before being aggregated into a composite annual RSI. The resulting index provides an integrated measure of temporal changes in the sustainability performance of Indian rice production and enables the overall sustainability trajectory.

Literature Review

(1) **Dhanya et al(2015)** evaluate how smallholder farmers' climate risk perceptions intersect with empirical meteorological trends in Kancheepuram, Tamil Nadu. While farmers' acute awareness of warming aligns with statistically verified temperature increases ($p < 0.0001$), their perception of declining rainfall diverges from aggregate precipitation trends ($p = 0.571$), demonstrating that agrarian vulnerability is primarily dictated by intra-seasonal dry spells and erratic monsoon onset rather than cumulative rainfall totals. Farmers mitigate these water deficits autonomously by replacing water-intensive cereals (paddy) with short-duration pulses, vegetables, and floriculture; however, the simultaneous rise in leaving land fallow signals the limits of autonomous adaptation and poses a threat to regional food security. Ultimately, the authors highlight an institutional deficit—marked by a lack of insurance penetration and early warning tools—underscoring the urgent need for planned, site-specific policies such as decentralized water storage, micro-irrigation subsidies, and tailored agro-advisories.

(2) **Dai et al.** (2024) evaluate the impact of university-led agricultural technology extension on efficient and sustainable agriculture (ESA) using panel data from 90 counties in Anhui Province, China (2008–2020) and a difference-in-differences (DID) framework based on Anhui Agricultural University's pilot experiment stations. Their empirical analysis demonstrates that university extension significantly increases the comprehensive ESA index by 3.3% ($p < 0.01$), driven primarily by improvements in the coordinated and green development dimensions rather than immediate gains in technical efficiency. Modern agricultural

industrial parks act as a positive moderator by amplifying these technology diffusion and training benefits, though substantial regional and developmental heterogeneity exists: significant positive gains are confined to southern and central Anhui as well as areas with high baseline development, while traditional, resource-constrained northern areas and less-developed counties show no significant short-term effects. Consequently, the authors argue for tailored, region-specific extension models and stronger integration with industrial park platforms to overcome local absorptive capacity barriers and support sustainable agricultural modernization.

(3) **Gao et al.** (2024) develop a data-driven evaluation framework using the entropy weight method to assess agricultural sustainability across six major grain-producing cities in Northern Anhui, China, from 2011 to 2020 across four core dimensions: agricultural production, economics, resource environment, and rural society. Their empirical assessment reveals an overall 52.4% increase in the regional sustainability index (rising from 0.328 in 2011 to 0.500 in 2020) alongside a narrowing inter-city disparity, driven primarily by gains in production capacity and rural social living standards, even as resource and environmental sustainability remained stagnant due to persistent agrochemical dependency. Econometric panel regressions demonstrate that rural transportation infrastructure ($\beta=0.198, p<0.01$) and human capital ($\beta=0.115, p<0.10$) serve as the principal positive drivers of sustainability by reducing market transaction costs and providing skilled labor, whereas macro science and technology patents and industrial upgrading show no significant direct impact. Crucially, broader regional economic strength displays a slight negative association with agricultural sustainability ($\beta=-0.027, p<0.10$), indicating that urban-industrial expansion continues to siphon resources without adequate feedback mechanisms into the rural primary sector. Based on these findings, the authors argue for targeted investments in high-tech ecological farming, agricultural supply-chain industrialization, and rural transport infrastructure to balance grain security with eco-environmental preservation.

(4) **Viegas et al. (2025)** evaluate the sustainability of smallholder sugarcane production systems in Sofala Province, Mozambique, by integrating an adapted SustenAgro Index framework with the Entropy Weight Method (EWM) across 30 farms supplying the Mafambisse sugar factory. Across 38 Delphi-validated indicators, the authors establish that while overall sustainability remains moderately positive (with 76.7% of surveyed systems achieving an index above zero), performance varies widely across triple-bottom-line dimensions: the social dimension made the highest positive contribution to the index (mean = 0.5145), supported by absence of child labor, high workplace safety, and lack of land conflict, followed by economic performance (mean = 0.2555), whereas the environmental dimension exerted a strong negative pull (mean = –0.3043) due to critical deficits in irrigation monitoring, water-capture infrastructure, and agricultural waste disposal. Multiple regression analysis further revealed that geographic location was the only statistically significant determinant of overall sustainability ($\beta = – 0.594, p < 0.01$), as greater transit distance from production fields in Búzi district (111 km) to the processing mill substantially eroded net economic returns and overall sustainability relative to closer farms in Nhamatanda district (58 km). Consequently, the study emphasizes that promoting sustainable sugarcane production in Sub-Saharan Africa requires prioritized capital investments in decentralized water-management infrastructure, formal worker training, and optimized transportation logistics.

METHODOLOGY

The study employs national-level secondary data for the period 2007–2023, compiled from authoritative government and institutional sources, including the Ministry of Agriculture and Farmers Welfare (MoAFW), Reserve Bank of India (RBI), and India Meteorological Department (IMD). The study period was determined primarily by the availability of sufficiently consistent and comparable time-series observations for the selected variables. Data from these sources were harmonized to ensure temporal consistency and comparability prior to the construction of the composite index.

The selection of sustainability indicators was undertaken through a structured three-stage procedure. First, potential indicators were identified through a comprehensive review of the literature on agricultural sustainability, sustainable intensification, and rice production systems. Second, conceptually overlapping variables and alternative terminologies

were examined and consolidated to minimize redundancy and ensure that each retained indicator captured a distinct aspect of rice-sector sustainability. Third, the candidate indicators were screened according to four criteria: (i) relevance to rice sustainability, (ii) conceptual and empirical importance, (iii) measurability using quantitative data, and (iv) availability of reliable, consistent, and comparable time-series observations (Jatav et al., 2023). This screening procedure was particularly important given the longitudinal and national-level scope of the analysis.

On the basis of these criteria, eight sustainability indicators were retained for the construction of the composite Rice Sustainability Index (RSI): rice area intensity, irrigation intensity, methane emissions, fertilizer use, MSP growth rate, area under rice cultivation, mean monsoon temperature, and monsoon rainfall. Collectively, these indicators capture key aspects of rice production intensity, resource dependence, environmental pressure, climatic conditions, and economic incentives. The selected variables therefore provide a multidimensional representation of the sustainability performance of India's rice production system rather than relying solely on output or productivity measures.

Table 1. Indicators Used in Previous Studies for Assessing Sustainability

Sr. No.	Indicators	Index/Dimension	Authors/ Years
1	Rice Area Intensity	Environment dimension, Environment Sustainability Index, Ecological Efficiency Index	Suresh et al,(2022); Jatav et al,(2023);Tiyndel et al,(2025)
2	Irrigation Intensity,	Economic Security Index, Sustainable of Agriculture Production, Environment Dimension	Jatav et al,(2023);Gao et al,(2024);Viegas et al,(2025)
3	Methane Emissions	Environment Dimension	Pan et al,(2024)
4	Fertilizer Use	Environment Efficiency Index, Green Development	Tiyndel et al,(2025); Dai,(2024)
5	Area Under Rice Cultivation	Environment Sustainability Dimension	Jatav et al,(2023)
6	Monsoon Rainfall	Environment Dimension, Environment Sustainability Index, Economic Efficiency Indicators, Environment Sustainability	Suresh et al,(2023); Tiyndel et al,(2025); Jatav et al,(2023)

Source: Author's compilation from the literature on Sustainability index

Table 2. Selected indicators, their measurement units, and their directional relationship with rice sustainability

Sr. No.	Indicators	Unit	Definition	Reasons/ Importance of Farm Sustainability	Type of Indicators	Source
1	Rice Area Intensity	**%**	Crop intensity = total cropped area/ total sown area 100% (%)	High cropping intensity significantly contributes to agricultural sustainability	+	**MoAFW**
2	Irrigation Intensity	**%**	Irrigation intensity = total irrigated area/total sown area 100% (%)	Irrigation positively imparts resilience to crops and influences agricultural sustainability	+	**MoAFW**
3	Methane Emissions	**kilotonnes**	Methane emissions are the amount of methane released into atmosphere from rice.	Reduce the environmental sustainability of rice production by contributing to greenhouse gas emissions.	–	**MoAFW**
4	Fertilizer Use	Rs/hectare	The application of nutrients such as nitrogen, phosphorus, and potassium to rice fields to enhance crop growth and improve	Excessive fertiliser use can degrade soil and water quality and reduce the environmental sustainability.	--	**MoAFW**

			yield.			
5	Area Under Rice Cultivation	In lakh hectare	The total land area devoted to growing rice	A large cultivation area can increase pressure on land, water, and other natural resources	+	**RBI site**
6	Monsoon Rainfall	In mm	The rainfall received during monsoon season that support rice cultivation	Adequate rainfall supports rice growth	+	**IMD**
7	Mean Monsoon Temperature	0C	The average temperature recorded during the monsoon season.	It affects crop growth, flowering, grain formation, and ultimately rice yield.	–	**IMD**
8	Growth Rate of MSP	%	The annual percentage change in the Minimum Support Price announced by the Government of India for paddy rice.	It reflects changes in price support and farm-income incentives, influencing farmers' production decisions and the economic sustainability of ricecultivation.	+	**RBI site**

Source: Author's Compilation based on data from Reserve Bank of India(RBI),Ministry of Agriculture & Farmers Welfare, and India Meteorological Department(IMD).

Standardization of the Value of Indicators

1. Normalize the Indicators

The study employed an indicator-based approach to standardize heterogeneous indicators before constructing the rice sustainability index. This method provides a systematic framework for integrating indicators measured in different units and enables sustainability assessment across different spatial scales. It also facilitates the identification and

prioritization of key sustainability dimensions, while converting complex and multidimensional information into a concise and comparable index. Thus, the approach is useful for evaluating the overall sustainability performance of rice production and for supporting evidence-based policy formulation (Singh & Alka, 2019; Singh & Singh,2019; Singh & Nayak,2020; Jatav et al.,2022; Jatav et al., 2023).

Prior to constructing the sustainability index, the nature of the indicators and the objectives of the composite index were considered during standardization (Chetri et al., 2022). The sustainability index was constructed following the UNDP's Human Development Index (HDI) methodology, wherein the indicators were transformed into standardized normalized values(Suresh et al.,2022; Mukherjee,2022).The min–max method was used to normalize the indicators to a common 0–1 scale, accounting for their positive or negative relationship with sustainability (Iyengar & Sudarshan, 1982). Equations (1) and (2) were adopted for larger-better-type and smaller-worse-type indicators, respectively. When the observed values were related positively to the sustainability, normalisation was achieved by using the equations:

$$N \square X ij \quad \square X \min \quad (1)$$

$$ij \qquad X \max \square X \min$$

$$j \qquad J$$

On the other hand, when the values were negatively related to the sustainability, the normalised values were computed by the formula

$$X \max \square X \quad N \square \quad ij \quad (2)$$

$$ij \qquad X \max \square X \min$$

$$j \qquad j$$

Where Nij □ Normalized value of indicator j in year i, ranging from 0 and 1

$X ij$ □ Actual value of indicator j in year i,

X min □ Minimum value of indictor j during the study period

max

j

□ Maximum value of indicator j during the study period

1. Proportion of each Indicator

$$Pij \quad \square \quad Nij \quad \square Nij \; i \square 1$$

(Where i=1,2,3,4……16)

Where

Pij □

The proportion of indicator j in year i, and m is the number of years.

2. Calculate entropy

$$E j \square \square k \square Pij \ln(Pij) \text{ (Where i=1,2,3,4……16)}$$

$i \square 1$

And k= 1

ln(m)

Here,

$E j$ = The entropy value of indicator j m = The number of observations

3. The Degree of diversification

$$Dj \square 1 \square E j$$

$D j$ = The information degree of diversification of indicator j

4. Entropy weight

$$WJ \square \quad Dj \quad \square Dj \; j \square 1$$

Where Wj □ The objective weight assigned to indicator j n = Total number of indicators

The weights satisfy :

□Wj □ 1

j□1

5. The composite rice sustainability Index

$RSIi$ □ □Wj Nij j□1

Where $RSIi$ = The rice sustainability index for year i

Wj □ The entropy -derived weight of indicator j

Nij □ Normalized value

RESULTS AND DISCUSSIONS

Entropy-Based Assessment of the Informational Contribution of Sustainability Indicators

The entropy-based weighting results provide a comparative assessment of the relative information contribution of eight indicators selected to construct the Rice Sustainability Index (RSI) for India.

Table 3: Information Entropy, Degree of Divergence, and Objective Indicator Weights

Rank	Indicator	Direction	Information Entropy(e_j)	Degree of Divergence(d_j)	Indicator Weights(Wj)
1	Monsoon Rainfall(mm)	(+)	0.948	0.052	0.087
2	Methane Emission from Rice(kt)	(-)	0.928	0.072	0.121
3	Fertilizer Use(₹/ht)	(-)	0.903	0.097	0.163
4	Mean Monsoon Temperature(oC)	(-)	0.916	0.084	0.141
5	Area Under Rice Cultivation(lakh ha)	(+)	0.932	0.068	0.114
6	Irrigation Intensity (%)	(+)	0.883	0.117	0.196
7	Rice Area Intensity(%)	(+)	0.963	0.037	0.062
8	Growth Rate of MSP(%)	(+)	0.931	0.069	0.116
	Total	---------	7.405	0.596	1

Source: Calculated by author

In table 3.The estimated entropy values range from 0.883 to 0.963, while the degree of divergence varies between 0.037 and 0.117, indicating differences in the discriminatory information provided by individual indicators over the study period. Irrigation intensity emerges as the highest-weighted indicator, with an entropy value of 0.883, divergence of 0.117 and weight of 0.196, accounting for 19.6% of the total weight. This is followed by fertilizer use, which records an entropy value of 0.903, divergence of 0.097 and weight of 0.163 (16.3%), and mean monsoon temperature, with corresponding values of 0.916, 0.084 and 0.141 (14.1%). Collectively, these three indicators account for 50.0% of the total weight, suggesting that irrigation intensity, fertilizer use and monsoon temperature provide comparatively

greater discriminatory information for differentiating annual sustainability observations. The relatively high weight of irrigation intensity highlights the importance of examining changes in irrigation patterns and agricultural water management, while the weight assigned to fertilizer use reflects its contribution to distinguishing variations in agricultural input use. Similarly, the comparatively high weight of mean monsoon temperature emphasizes the informational relevance of climatic variability within the sustainability assessment. Methane emissions from rice cultivation receive a weight of 0.121 (12.1%), with entropy and divergence values of 0.928 and 0.072, respectively, indicating a moderate contribution from the environmental dimension. The growth rate of the minimum support price (MSP) and area under rice cultivation receive weights of 0.116 (11.6%) and 0.114 (11.4%), respectively, with divergence values of 0.069 and 0.068. Their closely comparable weights indicate similar levels of discriminatory information within the dataset, although their economic and agronomic implications differ. Monsoon rainfall receives a weight of 0.087 (8.7%), with entropy of 0.948 and divergence of 0.052, whereas rice area intensity records the lowest weight of 0.062 (6.2%), accompanied by the highest entropy (0.963) and lowest divergence (0.037). These results suggest that rainfall and rice area intensity provide comparatively less discriminatory information than the higher-weighted indicators, although both remain relevant to rice production and sustainability. The overall distribution of weights demonstrates that the composite index is more responsive, in informational terms, to variations in irrigation intensity, fertilizer use and monsoon temperature than to variations in rice area intensity and monsoon rainfall weighted contributions of individual indicators with the observed RSI trajectory. Moreover, higher irrigation intensity and fertilizer use cannot automatically be interpreted as improvements in sustainability, since their implications depend on resource-use efficiency, production benefits and environmental costs. Thus, the entropy results should be interpreted as evidence of the relative discriminatory information of the selected indicators rather than as a direct ranking of their causal influence or normative importance in determining the sustainability of rice production in India.

Temporal Dynamics of Rice Sustainability Performance in India

The temporal evolution of the Rice Sustainability Index (SI) provides important insights into the changing composite sustainability profile of rice production in India over the period 2007–08 to 2022–23.

Table 4. Annual Rice sustainability Index(SI) and Rank in India

Year	Sustainability Index(SI)	Rank
2007-08	0.466	7
2008-09	0.452	9
2009-10	0.276	16
2010-11	0.354	14
2011-12	0.427	11
2012-13	0.440	10
2013-14	0.484	6
2014-15	0.330	15
2015-16	0.395	13
2016-17	0.419	12
2017-18	0.464	8
2018-19	0.505	5

2019-20	0.526	4
2020-21	0.573	3
2021-22	0.587	2
2022-23	0.621	1

Source: Calculated by author

The temporal evolution of the Rice Sustainability Index (SI) reveals a considerable improvement in the composite sustainability performance of rice production in India during 2007–08 to 2022–23, despite substantial year-to-year variability. The index increased from 0.466 to 0.621, representing a 33.26% improvement over the study period. However, the observed fluctuations indicate that this progress was not uniform throughout the series. The SI reached its minimum of 0.276 in 2009–10, followed by a recovery to 0.484 in 2013–14 and a subsequent decline to 0.330 in 2014–15. From 2015–16 onwards, the index increased consistently from 0.395 to 0.621, suggesting a sustained improvement in the aggregate performance of the selected sustainability indicators. The highest SI and first-place ranking in 2022–23 further indicate that this year exhibited the strongest relative sustainability performance within the observed period. The entropy-based weights provide additional insight into the information structure of the composite index. Irrigation intensity received the highest weight (0.196), followed by fertilizer use (0.163), mean monsoon temperature (0.141), and methane emissions from rice cultivation (0.121). Together, these four indicators accounted for 62.1% of the total weight, indicating that they contributed a comparatively larger share of the discriminatory information used in constructing the SI. Their influence on the composite score is determined by the interaction between their assigned weights and annual normalized values, taking into account the specified direction of sustainability. Consequently, the upward movement in SI reflects an improvement in the weighted aggregate of the selected indicators, rather than necessarily indicating uniform progress across all sustainability dimensions. Overall, the findings suggest that India's measured rice sustainability performance strengthened over the study period, particularly in the later years, while indicator-level analysis remains necessary to establish the specific contributions underlying this improvement.

CONCLUSION AND POLICY IMPLICATIONS

This study develops an entropy-weighted Rice Sustainability Index (RSI) to examine the temporal dynamics of rice-production sustainability in India during 2007–08 to 2022–23. The findings reveal a fluctuating but overall improving sustainability profile, with the RSI increasing from 0.466 in 2007–08 to 0.621 in 2022–23, representing a 33.26% rise. However, this improvement was not continuous: the index declined to 0.276 in 2009–10 before recovering unevenly and reaching its highest value in the final year. This pattern indicates that progress in the composite sustainability profile occurred alongside substantial inter annual instability. The entropy results further demonstrate differences in the informational contribution of the eight indicators. Irrigation intensity received the highest weight (0.196; divergence 0.117), followed by fertilizer use (0.163; divergence 0.097) and mean monsoon temperature (0.141; divergence 0.084). In contrast, rice area intensity recorded the lowest weight (0.062; divergence 0.037). These estimates indicate the relative capacity of indicators to differentiate observations within the study period; they should not be interpreted as direct measures of causal influence or intrinsic policy importance.The findings highlight the need to assess rice sustainability through an integrated framework that considers resource use, environmental pressures, climatic conditions, and economic incentives. Improving irrigation efficiency, promoting balanced fertilizer application, reducing methane emissions, and strengthening climate-responsive production practices may support more sustainable rice cultivation. Nevertheless, the composite index should complement, rather than replace, indicator-specific analysis. Future research could incorporate groundwater depletion, soil health, farm profitability, and regional disparities, alongside sensitivity testing of alternative weighting and normalization methods. Such extensions would strengthen the robustness and policy relevance of sustainability assessment in India’s rice sector.

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