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Optimizing resource use efficiency for sustainable paddy production in South India - a regional study

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Introduction: The inefficient use of inputs in paddy production leads to either over-exploitation or under-exploitation of natural resources, thereby minimizing productivity and sustainability. This study investigates Resource Use Efficiency (RUE) in paddy production across South Indian states.
Methods: The study uses secondary data extracted from the Directorate of Economics and Statistics, Department of Agriculture and Farmers' Welfare, Ministry of Agriculture and Farmers Welfare, Government of India for the period 2022-23 for the South Indian states – Andhra Pradesh, Karnataka, Kerala, Tamil Nadu and Telangana. The research employed Cobb–Douglas production function analysis and RUE estimation to compare the RUE among the study states using the variables like paddy yield, labor (human, animal and machine), fertilizer usage, irrigation and seed application.
Results and Discussion: The key findings revealed significant regional disparities in paddy productivity and input efficiency. Telangana has emerged as the most productive state with efficient input–output relationships, whereas Kerala lagged in productivity despite its high input usage. The analysis identifies widespread underutilization of critical inputs, including fertilizers, seeds, and irrigation, across most states, in contrast to the excessive use of labor resources. State-specific interventions for enhancing paddy productivity include optimizing labor and seed rate efficiency in Kerala, fertilizer use efficiency in Tamil Nadu, and capital use (mechanization) efficiency in Andhra Pradesh. The quantitative analysis results reveal the inefficient use of inputs and overuse of labor resources across the states.
Policy Suggestions: The implementation of targeted, region-specific, and state-specific strategies, including investments in irrigation infrastructure, promotion of balanced application of fertilizers, adoption of good quality and high-yielding varieties of seeds, and increase in technology adoption, will optimize the input use and enhance the paddy productivity in South India.

KEYWORDS

resource use efficiency, Cobb–Douglas production function, productivity, sustainability, precision farming

1 Introduction

Paddy cultivation in South India, particularly in Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, and Telangana, is crucial for bolstering the regional economy and ensuring food security (Narayanamoorthy and Jothi, 2018; Jayapradha et al., 2020). Nevertheless, sustainable paddy production faces challenges concerning RUE owing to the overexploitation of natural resources through intensive rice-based cropping systems (Gora et al., 2022). Resource Use Efficiency involves minimizing environmental impacts by optimizing inputs such as water, land, labor, and agrochemicals to maximize output. Given that paddy is a water-intensive crop, efficient water management practices are essential for their sustainability. Numerous studies have emphasized the necessity of technologies such as the System of Rice Intensification (SRI) to enhance water productivity and reduce the per unit water requirement for paddy cultivation (World Bank Report, 2020; Anbumani et al., 2020). Thakur et al. (2014) examined the impact of water management on yield under SRI and conventional (manual) transplanting systems and reported that the SRI technique increased rice yield while consuming less water per unit than traditional transplantation methods. A comprehensive study by Hashim et al. (2024) suggested that continuous growth in rice productivity and Resource Use Efficiency can be achieved by introducing yield-enhancing, smart, and sustainable farming technologies. In addition to water for irrigation, land and labor-use efficiency are critical aspects of paddy cultivation. With decreasing landholdings and increasing urbanization pressures, farmers must adopt strategies such as land consolidation[1] and multiple cropping systems to optimize land use patterns (Lu et al., 2022). To address labor shortages and maximize production efficiency, mechanization and modern farming techniques can significantly enhance farm productivity (Ma et al., 2023). Furthermore, the overuse of chemical inputs, including fertilizers and pesticides, must be curtailed to prevent environmental pollution and ensure long-term soil health (Anjaria and Vaghela, 2024). Integrated Pest Management[2] (IPM) practices can be adopted to reduce pesticide use and conserve natural predators, thereby maintaining ecological balance (Das et al., 2024).

Paddy production is complex and involves the interrelationships between agronomy, hydrology, economics, and sociology for efficient resource use. Policy interventions focusing on incentives for sustainable practices and access to modern technologies are vital for promoting resource-efficient paddy cultivation in Southern India (Felix et al., 2024). This can be achieved by adopting innovative technologies, optimizing input use, and integrating ecological principles into farming practices to enhance productivity while conserving natural resources. Consequently, this study on Optimizing Resource Use Efficiency for Sustainable Paddy Production in South India explores the concept of Resource Use Efficiency in the context of paddy cultivation in the region.

This paper commences with an introduction that delineates the study's primary contributions and underscores the necessity of this research. The literature review section addresses various facets pertinent to paddy cultivation, including water management practices, the influence of mechanization on RUE, the role of IPM in sustainable production, and the economic and policy perspectives affecting RUE. The methodology section elucidates the approaches employed to ascertain RUE, utilizing the production function (Cobb–Douglas) and the estimation procedure for Marginal Value Product (MVP) and Marginal Input Cost (MIC) or Marginal Factor Cost (MFC). The results and discussion section articulates the findings and their interpretation. The paper concludes with a conclusion and policy implications section, which encapsulates the key findings and their significance for policymaking. Additional sections include data availability, ethical approval, informed consent, and funding, which ensure the transparency of the research process and resources. The paper concludes with a reference section that enumerates the sources cited in the study.

1 Land consolidation in Indian agriculture can be achieved through voluntary plot exchanges, government-led consolidation programs, and promotion of collective farming models like FPOs, supported by digital land records and GIS mapping.

2 Integrated Pest Management (IPM) is an eco-friendly approach to crop protection that combines biological, cultural, mechanical, and chemical methods to manage pests sustainably and minimize environmental harm.

2 Review of literature

2.1 Water management practices in paddy cultivation

Given the susceptibility of the study region to water shortages and climate variability, it is pertinent to examine the literature on water management practices for cultivating rice. Datta et al. (2017) elucidated the diverse water management strategies employed in rice production, highlighting efficient irrigation methods to enhance water-use efficiency and crop productivity. This was corroborated by Narayanamoorthy and Jothi (2018), who assessed the water-saving benefits of the rice intensification system in various irrigated settings across South India, emphasizing the necessity of tailored approaches to optimize water resource use. Surendran et al. (2021) critically reviewed various water-saving techniques through the lens of climate change adaptation, underscoring the importance of adopting sustainable practices to bolster the resilience of paddy farming systems against environmental challenges. In addition to water management, the impact of drought on irrigated agriculture in South India is an important area of research. Venot et al. (2010) analyzed farmers' adaptations to cope with drought conditions in the Nagarjuna Sagar region, highlighting the importance of adaptive strategies and efficient resource allocation. Additionally, Deelstra et al. (2018) explored alternative rice-growing practices aimed at enhancing water productivity in Southern India, providing invaluable insights into innovative approaches that could enhance resource efficiency and sustainability in paddy production. These studies underscore the importance of developing tailored water management strategies and innovative farming practices to optimize resource efficiency within paddy production systems in southern India. This could assist stakeholders in identifying context-specific interventions aimed at enhancing the sustainability and resilience of paddy cultivation in water-stressed regions of South India, leveraging research on SRI, an alternative rice-growing practices, and adaptive water management strategies.

2.2 Impact of mechanization on resource use efficiency

Understanding the impact of mechanization on Resource Use Efficiency is essential for sustainable paddy production, particularly given the agricultural landscape and evolving labor dynamics in Southern India. Bhoi et al. (2021) identified an innovative approach that utilized machine learning to manage input-use efficiency in paddy production systems in India. Their study underscores the potential of technology to optimize resource allocation and enhance productivity in paddy cultivation. Reddy (2013) study on farm profitability and labor-use efficiency demonstrated that mechanization could streamline operations, reduce labor demand, and improve overall resource efficiency in rice production. Further examination of rice production efficiency highlights the importance of tailoring interventions to specific contexts in the study area. Insights from the Kpong Irrigation Project in Ghana, as provided by Nimoh et al. (2012), emphasize efficient resource allocation and management practices to enhance productivity and sustainability. Soni et al. (2018) examined the energy use and efficiency of rice-based cropping systems in the Middle Indo Gangetic Plains of India and demonstrated the interconnections between energy inputs and resource utilization in agricultural systems. Additionally, the adoption of management practices, such as Direct-Seeded Rice (DSR), is instrumental in increasing Resource Use Efficiency in paddy production. Joshi et al. (2013) discussed the management of DSR as a strategy to improve resource utilization and productivity, representing a broader trend towards sustainable agricultural practices aimed at optimizing resource allocation with minimal environmental impacts. By integrating findings from studies on mechanization, labor efficiency, and innovative farming practices, including DSR, stakeholders can recognize synergies and harness technologies to achieve sustainable Resource Use Efficiency in paddy production systems in South India.

2.3 Role of integrated pest management (IPM) in sustainable paddy production

Integrated Pest Management (IPM) is an essential element of sustainable paddy production in South India, offering highly effective strategies for mitigating pest effects while minimizing environmental harm. Mishra and Jena (2007) emphasized that IPM in rice cultivation involves innovative and integrated pest control strategies encompassing biological, cultural, and chemical methods. This assertion was reiterated by Hajjar et al. (2023), who discussed integrated insect pest management techniques specifically designed for rice crops and emphasized the importance of holistic approaches to sustainably mitigate pest-related challenges in rice cultivation. Trivedi and Ahuja (2011) elucidated various approaches and implementation strategies for IPM, underlining the necessity of context-specific interventions that align with existing local agricultural practices. Alam et al. (2016) contributed to this discourse through a comparative study analyzing the environmental sustainability of IPM versus conventional farming practices in rice ecosystems, highlighting the ecological benefits of integrated pest management (IPM) approaches. Furthermore, Pretty and Bharucha (2015) provide a broader perspective on the adoption of IPM across Asia and Africa, advocating its role in achieving sustainable agricultural intensification by reducing the use of synthetic pesticides and promoting an ecological balance. Recent studies have reinforced the evolving significance of IPM in promoting sustainable agricultural development. Bothikar and Pagire (2022) highlighted that IPM represents a new dimension in sustainable agriculture, emphasizing its significant potential to enhance productivity while minimizing adverse environmental impacts. Integrating insights from these diverse studies on IPM will enable stakeholders to position integrated pest management as a central element of sustainable paddy production in South India, aligning with the broader goals of environmental stewardship and agricultural resilience.

2.4 Economic and policy perspectives on resource use efficiency

Examining the economic and policy perspectives on RUE is essential for promoting sustainable paddy production in South India, with the ultimate aim of optimizing output with minimal input use and minimum waste generation. Pal et al. (2021) focused on optimizing energy-use efficiency for agricultural sustainability, emphasizing the economic implications of efficient resource management in developing nations. Similarly, Mujeri et al. (2012) addressed the enhancement of fertilizer effectiveness and sustainability in South Asia through policy interventions aimed at improving nutrient utilization efficiency and reducing the environmental impact of excessive fertilizer usage. This area is critical for agricultural sustainability and environmental management. Dass et al. (2015) identified SRI as a pivotal strategy for enhancing productivity and RUE in paddy production. Their review highlighted the economic and agronomic benefits of SRI, emphasizing its potential to optimize resource utilization and promote sustainable agricultural practices in rice cultivation. This approach has gained attention for its ability to increase yields while minimizing inputs such as water and chemical fertilizers.

Ahmad et al. (2018) conducted an economic analysis of RUE in sugarcane cultivation, underscoring the importance of assessing growth and instability factors, alongside resource allocation. This approach is crucial for informed policy formulations aimed at enhancing the agricultural sustainability and productivity of sugarcane farming in Brazil. Their study provides insights into how optimizing resource use can contribute to more stable and productive agricultural outcomes. A holistic perspective on conservation agriculture is key to addressing RUE and sustainability in paddy production systems. Das et al. (2021) offer a comprehensive review of the impacts of conservation agriculture on productivity, RUE, and environmental sustainability, indicating the interrelationship between agronomic practices, economic considerations, and policy frameworks in achieving sustainable intensification. This review underscores the necessity of integrating these elements to promote practices that enhance agricultural productivity while ensuring environmental and economic sustainability. Dey et al. (2023) analyzed the RUE of paddy farmers to optimize input use and minimize Green House Gas (GHG) emissions, thereby increasing yield. They adopted three technologies, including the use of high-yielding seeds, SRI, and SPAD-based Nitrogen Management, and observed a significant increase in paddy yield and a decrease in GHG emissions.

Findings from these studies on the economic and policy dimensions of RUE contribute to the multifaceted strategies that

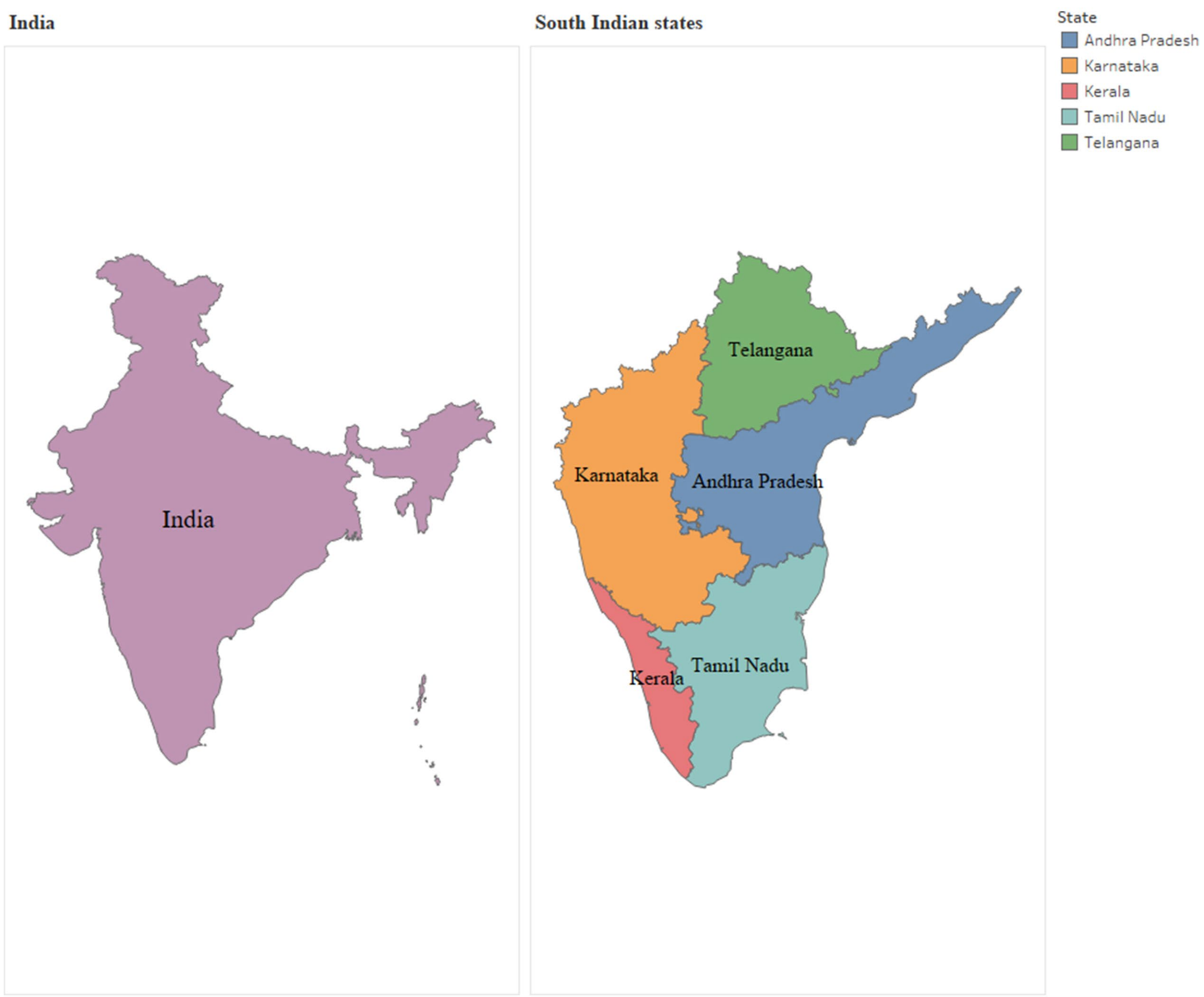

FIGURE 1
Selected South Indian states for the study (Source: Author).

stakeholders can use to advance sustainable paddy production in Southern India. From optimizing energy and fertilizer use to adopting innovative agricultural practices such as SRI, DSR, and conservation agriculture, informed policy interventions can be instrumental in driving positive outcomes for both agricultural productivity and environmental sustainability in the study region.

3 Methodology

3.1 Production function analysis-resource use efficiency of paddy cultivation

3.1.1 Data source

In India, the Directorate of Economics and Statistics, Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare (MoA & FW), Government of India, is actively involved in conducting extensive surveys and publishing agriculture-related data.

This study utilized published data from the Department of Agriculture and Farmers Welfare, available at https://eands.da.gov.in/. Every year, the MoA & FW publish statistical data for all states to assess the performance of agriculture and allied sectors in India.

Our study focuses on the secondary data published during 2022–23,[3] concentrating exclusively on paddy cultivation in South India (Andhra Pradesh, Karnataka, Kerala, Tamil Nadu and Telangana), as depicted in Figure 1.

This study includes six major input variables such as human labor, animal labor, machine labor, irrigation, seed quantity, and fertilizer based on the availability of standardized secondary data from the 2022–23 agricultural survey. Variables such as rainfall, soil type, and market access, while important for understanding agricultural efficiency, were not included as they were not part of the published

3 The data was selected because it is the most recent and comprehensive nationwide agricultural survey available in open access. It provides standardized, state-wise data essential for comparative analysis and reflects the latest trends in input use and productivity across South Indian states. Using this dataset ensures the study's relevance to current policy and practice. The datasets pertaining to the study is attached as a Supplementary file.

dataset. As the analysis is constrained by the scope of available data, these exclusions are acknowledged as limitations.

3.2 Production function methodology

3.2.1 Cobb-Douglas production function approach

The RUE of paddy crops grown in South Indian states was analyzed using the Cobb–Douglas production function, which reflects the marginal productivity of resources/inputs at the mean levels of return. The Cobb–Douglas production function was employed, because of its analytical simplicity and empirical robustness in modelling the relationship between inputs and output. It allows researchers to quantify how efficiently resources such as labor, land, and capital are utilized in production processes by estimating input elasticities directly from observed data (Kadiyala, 1972). This function supports the calculation of marginal physical products and returns to scale, which are critical for evaluating efficiency and identifying under- or overutilization of resources (Lopatin, 2019). Moreover, the Cobb–Douglas model is compatible with diverse datasets (Zhang et al., 2017).

The model specification is as follows:

The output is expressed as a dependent variable.

$$Y = a\, X_1^{\beta_1} X_2^{\beta_2} X_3^{\beta_3} X_4^{\beta_4} X_5^{\beta_5} X_6^{\beta_6} e^U$$

where, Y, Output (q/ha); a, Intercept/ Constant; X_1, Human labor (h/ha); X_2, Animal labor (h/ha); X_3, Machine labor (h/ha); X_4, Irrigation Machine (h/ha); X_5, Seed quantity (kg/ha); X_6, Total Fertiliser[4] (kg/ha); e^U, Multiplicative Error Term; u, error term/ stochastic disturbance term; $\beta_1\ldots, \ldots, \beta_6$ are regression co-efficients.

3.2.2 Estimation procedure

Ordinary least squares (OLS) method was used to estimate the parameters associated with different independent variables. The estimable form of the function is formally expressed as.

$$\begin{aligned} \text{Ln}\, Y &= \ln a + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \beta_3 \ln X_3 \\ &+ \beta_4 \ln X_4 + \beta_5 \ln X_5 + \beta_6 \ln X_6 + U \end{aligned}$$

This function is expressed in the linear form as

$$y = a + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + u$$

where, $y = \ln Y$, $a = \ln a$, $x_j = \ln X_j$ for $j = 1$–6.

3.2.3 Marginal productivity of factors

The estimates of the parameters $\beta_1\ldots\beta_6$ are the elasticity of Y with respect to the jth input. The marginal product of resources is derived from these elasticity coefficients. The marginal value product of the significant inputs was calculated at the geometric mean level using the following formula:

$$MVP_j = \beta_j \frac{\overline{Y}}{\overline{X}_j} P_y$$

where, MVP_j, Marginal value product of jth product; $\overline{Y}$,Geometric mean level of output, Y; $\overline{X}_j$,Geometric mean of input 'j'; β_j,Estimated co-efficient of elasticity; P_y,Price per unit Output.

The Marginal Value Product (MVP) of each input was compared with the marginal input/factor cost (MFC) to estimate efficiency.

Resource Use Efficiency (r) is defined as the ratio of the Marginal Value of the Product (MVP) to the Marginal Factor Cost (MFC). The formula used to estimate RUE is

$$r = \frac{MVP}{MFC}$$

where, r, Resource Use Efficiency; MVP, Marginal Value of the Product; MFC, Marginal Factor Cost (or) Marginal Input Cost.

According to economic theory, an entity maximizes its profit with regard to resource use when the ratio of the marginal return to the opportunity cost is equal to one. As such, if the MVP-to-MFC ratio (r) is less than one, it indicates excessive use of the resource; if r is greater than one, it indicates underutilization; and if r is equal to one, it indicates that resources are optimally utilized and is a point of profit maximization.

Resource efficiency was determined by computing the ratio of the MVP of the resource to its factor cost.[5]

$$\frac{MVP}{MFC} = 1, \text{means Optimum use of resources}$$

$$\frac{MVP}{MFC} < 1, \text{means Excess use of resources (Surpass optimal)}$$

$$\frac{MVP}{MFC} > 1, \text{means Under use of resource (Sub⌊optimal)}$$

4 Results and discussion

4.1 Descriptive statistics of paddy production in South Indian states

The descriptive statistics of paddy production, in terms of both quantity and value, provide interesting comparisons of agricultural practices and efficiencies in each region (Annex A1).

4 Fertilizer cost refers to the expenditure incurred on major nutrient fertilizers, primarily nitrogen (N), phosphorus (P), and potassium (K) compounds used in paddy cultivation.

5 Although r > 1 might suggest high returns, in the context of Resource Use Efficiency (RUE), it specifically indicates that the marginal value of the output exceed its input, meaning the input is under-utilized and increasing its use could improve profitability.

The average yields of the main product (q/ha) varied notably across South Indian states. Telangana had 59 q/ha, reflecting high output efficiency, whereas Andhra Pradesh followed a moderately high yield of 55.79 q/ha. Karnataka recorded 51.85 q/ha, which is slightly above the regional average of 49.36 q/ha. Tamil Nadu, at 46.26 q/ha, aligns closely with the average, whereas Kerala lags behind at 35.97 q/ha, indicating lower productivity. The higher yield in Telangana can be linked to effective irrigation and climate adaptation strategies. Studies have indicated that irrigation is a critical factor in determining yield, particularly in regions with variable rainfall. Telangana is likely to benefit from better irrigation infrastructure and practices that provide a stable water supply for crops, unlike Kerala, where irrigation needs are complicated by changing rainfall patterns (Guntukula and Goyari, 2020; Singh et al., 2019). Additionally, climate variability, such as changes in temperature and rainfall, impacts yield differently across regions. In Telangana, adaptation strategies to manage climatic risks might be more effectively implemented, which would help maintain high crop yields (Guntukula and Goyari, 2020). Conversely, Kerala faces significant challenges related to climate change, such as increased temperatures and altered rainfall patterns, which can negatively affect crop maturity and yield (Saseendran et al., 2000). The implementation of modern farming practices, such as tillage management and the adoption of crop systems resilient to climatic stress, may also contribute to the differences in yields between these states (Ahmed et al., 2019).

The human labor input (h/ha) showed significant variations. Karnataka had the highest average human labor input of 629.88 h/ha, suggesting intensive labor use. Kerala (420.24 h/ha) and Telangana (427.37 h/ha) exceeded the regional average of 414.32 h/ha, whereas Andhra Pradesh (412.85 h/ha) was nearly aligned with it. Tamil Nadu, at 370 h/ha, which was below the average. In Karnataka, higher labor hours, averaging 629.88 h/ha, which may be due to the traditional labor-intensive methods that are still prevalent in regions of the state. These methods may involve manual planting, harvesting, and irrigation activities, which require continuous labor input to manage water levels, control pests, and perform manual transplantation (Tadesse, 1997). In contrast, Tamil Nadu has lower labor hours at 370 h/ha can be attributed to advancements and efficiencies in agricultural practices. The state has adopted strategies such as Alternate Wetting and Drying (AWD) irrigation, which reduces the need for constant water management and, consequently, the labor required for it (Oo et al., 2018). Additionally, Tamil Nadu's focus on organic farming, which often involves fewer inputs and control requirements owing to its sustainable nature, may result in lower labor usage (Panneerselvam et al., 2011).

In terms of animal labor (h/ha), Karnataka again leads with a 41.53 h/ha, far surpassing the regional average of 14.66 h/ha. Kerala (15.95 h/ha) and Telangana (14.00 h/ha) hover around the average, whereas Tamil Nadu (6.70 h/ha) and Andhra Pradesh (5.82 h/ha) show minimal dependence on animal labor. Karnataka's higher usage of animal labor, at 41.53 h/ha may be linked to several regional agricultural practices and socio-economic conditions. The state has a significant tradition of Zero-Budget Natural Farming (ZBNF), which emphasizes low-cost, environmentally friendly agricultural methods that may encourage dependence on traditional practices, including animal labor (Khadse and Rosset, 2019). In contrast, Andhra Pradesh's minimal dependence on animal labor is only 5.82 h/ha, could be influenced by the state's strong institutional support for ZBNF. This state-led initiative aims to reduce costs and boost yields via more efficient natural farming methods that potentially reduce the need for animal labor (Bharucha et al., 2020; Duddigan et al., 2022). Additionally, Andhra Pradesh has experienced a significant expansion of aquaculture, which might divert labor resources from traditional farming methods to more profitable ventures, further decreasing reliance on animal-based labor in agriculture (Nagaraju et al., 2022).

Machine labor (h/ha) was the highest in Karnataka (25.08 h/ha), indicating greater mechanization. Telangana followed at 19.80 h/ha, both above the regional average of 17.20 h/ha. Andhra Pradesh (16.79 h/ha), Kerala (15.83 h/ha), and Tamil Nadu (15.42 h/ha) fall below this benchmark. In Karnataka, the increased adoption of agricultural mechanization has been partly driven by regional government support, including subsidized farm machinery and the establishment of custom-hiring centers (Sarkar, 2020). The pattern of mechanization is significantly influenced by the region's agro-ecological characteristics, which affect the level of machine usage required for efficient farming operations. Additionally, ownership and investment in machinery differ across states, with Karnataka potentially having better access to the necessary financial resources and credit facilities for machinery investments (Sarkar, 2020). In contrast, Tamil Nadu faces challenges such as groundwater depletion and variable climatic conditions that affect its agricultural sector (Chinnasamy and Agoramoorthy, 2015).

Irrigation machine usage (h/ha) is the most intensive in Telangana, which records 374.36 h/ha, which is nearly double the regional average of 208.33 h/ha. Tamil Nadu (125.69 h/ha) and Kerala (124.16 h/ha) showed moderate usage, while Andhra Pradesh (95.03 h/ha) and Karnataka (69.48) were at the lower end. Telangana's intensive irrigation usage was 374.36 h/ha is largely driven by its reliance on traditional water-intensive practices to compensate for erratic rainfall patterns and ensure high paddy yields. The region prioritizes the use of irrigation machines to mitigate climate risks and enhance agricultural productivity, especially in areas that lack sufficient rainfall during critical growth stages (Singh et al., 2019). In contrast, Karnataka had a usage rate of 69.48 h/ha, may benefit from more adaptable water management practices, such as AWD irrigation methods, which can significantly reduce water usage without adversely affecting the yields. This approach not only conserves water but also addresses challenges related to water scarcity and climate change (Bwire et al., 2024). Moreover, the availability and management of groundwater resources in Karnataka, as exemplified by diverse farming typologies, provide a strategic advantage in optimizing water usage and minimizing reliance on machine-intensive irrigation methods (Robert et al., 2017).

Seed quantity (kg/ha) was the highest in Kerala at 100.05 kg/ha, which was significantly above the regional average of 72.22 kg/ha. Tamil Nadu (69.91 kg/ha) and Telangana (66.12 kg/ha) were close to average, whereas Andhra Pradesh (61.85 kg/ha) and Karnataka (59.48 kg/ha) used fewer seeds per hectare. The highest seed quantity used in Kerala for paddy cultivation was 100.05 kg/ha, compared with Karnataka's 59.48 kg/ha can be attributed to several factors. Variations in rainfall patterns in Kerala have significantly influenced agricultural practices. Despite the absence of significant trends in rainfall, irrigation systems are crucial for maintaining crop productivity in Kerala's challenging climate, which could lead to a preference for using more seeds to ensure optimal crop density and yield (Lakshmi et al., 2024). This is in contrast to Karnataka, where different ecological conditions, soil fertility, and possibly different paddy varieties may require less seed input to achieve similar productivity. Furthermore, Karnataka may adopt more efficient nitrogen management practices, reducing the need for high seed density and focusing on environmentally sustainable approaches that optimize yield while minimizing the inputs (Alam et al., 2023).

Fertilizer application (kg/ha) is highest in Karnataka (361.39 kg/ha), followed by Telangana (299.91 kg/ha), and Andhra Pradesh (267.15 kg/ha). Kerala (174.41 kg/ha) and Tamil Nadu (205.37 kg/ha) were below the regional average of 241.36 kg/ha, indicating diverse fertilization practices. The higher fertilizer application rate for paddy cultivation in Karnataka compared to Tamil Nadu can be attributed to several factors. In Karnataka, greater emphasis on nitrogen fertilizers has resulted in greater usage, driven by the perception that increased nitrogen (N) application leads to higher yields, despite low nitrogen-use efficiency in paddy farming (Alam et al., 2023). This belief persists even though a significant portion of nitrogen fertilizer remains unutilized, potentially degrading the environmental quality. Conversely, Tamil Nadu's agricultural practices often integrate advanced strategies, such as AWD irrigation methods, which are effective in reducing both water usage and greenhouse gas emissions while maintaining rice yields (Oo et al., 2018).

Price of the main product was highest in Kerala at INR 2352.37/q, suggesting premium market value or quality. Telangana (INR 2090.62/q) and Tamil Nadu (INR 1906.83/q) followed, while Andhra Pradesh (INR1747.17/q) and Karnataka (INR1341.79/q) received lower prices. In Kerala, the higher price of paddy at INR 2352.37/q is likely due to differences in public procurement systems, land ownership patterns, and the efficiency of the regulated markets. Public procurement and the Minimum Support Price (MSP) play crucial roles in price determination, and they may function more robustly or favorably in Kerala than in Karnataka (Thakur, 2023). Furthermore, the implementation of the Unified Market Platform (UMP) in Karnataka was designed to unify agricultural markets and potentially increase prices; however, its impact varies by commodity and has not uniformly shown a significant effect on all crops (Levi et al., 2020).

Human labor costs (INR/h) are highest in Andhra Pradesh (INR 91.21/h) and Telangana (INR 88.89/h), both above the regional average of INR 75.29/h. Kerala (INR 87.18/h) is close to the average, whereas Tamil Nadu (INR 58.83/h) and Karnataka (INR 37.84/h) are significantly lower. Several factors contribute to the high labor costs in Andhra Pradesh compared to Karnataka among the South Indian states. One prominent reason for this is the different levels of development and economic activity across these regions. Andhra Pradesh has focused on enhancing agricultural productivity through initiatives such as zero-budget natural farming (ZBNF), which has led to significant improvements in yields without the input costs associated with synthetic fertilizers and pesticides. This shift in agricultural practices may contribute to higher labor costs owing to the increased demand for more skilled and labor-intensive farming methods (Bharucha et al., 2020).

Additionally, Andhra Pradesh's investment in replenishing groundwater resources, community-based resource management, and sustainable development practices may enhance agricultural productivity and bolster labor demand (Reddy, 2005). Furthermore, the state has promotions tied to various rural employment guarantees, such as the National Rural Employment Guarantee Scheme, which might elevate labor wages given its impact on consumption and economic well-being, particularly among lower-income communities (Deininger and Liu, 2013). In contrast, Karnataka may have a lower demand for skill-intensive labor or different economic factors influencing labor markets, possibly resulting in comparatively lower costs (Gately, 1974). Additionally, socioeconomic structures and policies specific to each state, such as resource accessibility and labor demand in various sectors, contribute significantly to these differences (Bosher et al., 2007).

Animal labor costs (INR/h) peaks in Telangana at INR 290.99/h, followed by Tamil Nadu (INR 177.85/h) and Andhra Pradesh (INR 165.30/h). Kerala (INR 164.99/h) and Karnataka (INR 100.82/h) are below the regional average of INR 217.25/h. In Telangana, the higher labor cost of INR 290.99/h is likely influenced by a combination of factors, such as the availability of labor, demand for animal labor in agricultural activities, and economic conditions that affect the wage levels. Telangana may have a higher reliance on animal labor for specific agricultural tasks or geographical terrain that necessitates the use of animal power rather than mechanized solutions, thereby driving up the demand and, consequently, the cost (Turner and Hiernaux, 2007). Conversely, in Karnataka, where the cost is significantly lower at ₹100.82/ h., there may be greater access to mechanized farming options, thereby reducing the reliance on animal labor. This could also be due to the different labor market dynamics, where the supply of labor meets or exceeds demand, thereby keeping costs lower. Additionally, differing socioeconomic conditions, such as average income levels and cost of living between these states, could further contribute to discrepancies in animal labor costs (Sinclair et al., 2019).

Machine and irrigation costs (INR/h) were relatively consistent across the states. Telangana incurred the highest cost at INR 1234.71/h, while Kerala had the lowest at INR 1075.48/h. The regional average was INR 1075.64/h, indicating minimal variation.

The seed value (INR /kg) is exceptionally high in Karnataka at INR 193.59/kg, followed by Tamil Nadu (INR 97.88/kg) and Telangana (INR 90.65/kg). Kerala (INR 48.24/kg) and Andhra Pradesh (INR 33.68/kg) are much lower, with the regional average at INR 80.76/kg. The exceptionally high seed value for paddy fields in Karnataka (INR 193.59/kg) compared with Andhra Pradesh (INR 33.68/kg) among South Indian states may be attributed to several factors, including the use of High-Yielding or Hybrid Varieties, Private Sector Involvement, Supply Chain and Distribution Costs, Farmer Preferences and Market Demand, etc. In contrast, Andhra Pradesh has adopted zero-budget natural farming (ZBNF), emphasizing low-cost and sustainable farming practices that reduce input costs, including seed costs, by using locally sourced organic inputs rather than expensive synthetic seeds (Bharucha et al., 2020). Moreover, agricultural policies and support mechanisms in Andhra Pradesh may have further bolstered these practices by keeping seed costs relatively low.

Fertilizer cost (INR /kg) is highest in Kerala at INR 39.30/kg, followed by Telangana (INR 36.85/kg) and Karnataka (INR 32.99/kg). Tamil Nadu (INR 32.02/kg) and Andhra Pradesh (INR 32.17/kg) are close to the regional average of INR 34.36/kg. The high fertilizer costs in Kerala and the average costs in Andhra Pradesh can be attributed to several factors related to market dynamics and logistical challenges. In regions such as Kerala, which are heavily reliant on imports for fertilizer supply, transportation costs significantly influence the overall price of fertilizers. The global fertilizer industry is characterized by high levels of market concentration, which often results in higher prices in regions that are more dependent on imports, such as Kerala (Hernandez and Torero, 2013). This supply chain dependence substantially increases costs, especially when considering transportation logistics from ports to inland agricultural areas. Market pricing strategies and policies can also influence regional fertilizer prices. For instance, countries' protective trade measures and specific subsidy schemes can exacerbate price increases (Khabarov and Obersteiner, 2017). Furthermore, the geographic distribution and local demand variations within these states may also contribute to price disparities. Kerala's diverse agricultural production demands varied fertilizer use, potentially increasing costs owing to nuanced supply requirements. In contrast, agricultural practices and input utilization in Andhra Pradesh might be more streamlined and aligned more closely with regional averages.

The results revealed significant variations in agricultural practices and productivity across South Indian states. Telangana yielded a total of 59 q/ha, while Kerala lags behind at 35.97 q/ha. These differences can be attributed to factors such as irrigation infrastructure, climate adaptation strategies, and farming practices. Labor input varies widely, with Karnataka using the most human and animal labor, while Tamil Nadu shows lower labor usage, possibly because of more efficient practices in Tamil Nadu. The mechanization levels differ, with Karnataka showing higher machine labor hours. Irrigation practices vary significantly, with Telangana using the highest number of irrigation machine hours. Seed and fertilizer usage also differed, with Kerala using the most seeds and Karnataka applying the most fertilizers. Product prices are highest in Kerala, possibly because of quality or market-related factors. Labor costs vary, with Andhra Pradesh and Telangana having the highest human labor costs.

4.2 Estimates of Cobb-Douglas production function of paddy cultivation in South India

The Cobb-Douglas production function estimates for paddy production across South Indian states revealed notable regional variations in the significance and impact of agricultural inputs on paddy production in the study states. The state-wise estimates of the Cobb–Douglas production function for paddy cultivation in South Indian states are provided in Table 1.

Among the five states analyzed, Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, and Telangana. Kerala showed the highest number of statistically significant parameters. In Kerala, human labor exhibits a negative and highly significant relationship with paddy output. The negative impact of human labor on paddy yield in Kerala, where a 1% increase in human labor results in a 0.131% decrease in yield, can be attributed to several factors. One possible explanation is the inefficiency related to over-reliance on manual labor, which can lead to suboptimal farming practices and decision-making. Manual labor may also be less precise than mechanized options, leading to poor resource management, such as water and fertilizer. Additionally, excessive human labor activities can aggravate soil compaction and degradation, hindering root growth and nutrient absorption, and thus lowering yield potential. Furthermore, increased labor costs without corresponding increases in yield could result in the allocation of fewer resources for other yield-enhancing inputs such as quality seeds, optimal fertilizers, or effective pest control strategies (Chhatre et al., 2016; Tomita et al., 2003). There is also consideration of climate-related challenges unique to Kerala, such as rainfall variability, leading

TABLE 1 Estimates of paddy production using Cobb–Douglas production function in South India[a].

$\ln Y^1$	Andhra Pradesh		Karnataka		Kerala		Tamil Nadu		Telangana		South India	
	Co-efficient	$P > t$	Co-efficient	$P > t$	Co-efficient	$P > t$	Co-efficient	$P > t$	Co-efficient	$P > t$	Co-efficient	$P > t$
$\ln a$	4.231^{NS}	0.470	−0.015^{NS}	0.997	3.508***	0.000	2.036^{NS}	0.178	1.320***	0.007	1.085***	0.018
$\ln X_1$	0.192^{NS}	0.558	0.454*	0.082	−0.131***	0.003	0.546^{NS}	0.106	−0.040^{NS}	0.722	0.119^{NS}	0.174
$\ln X_2$	0.151^{NS}	0.377	−0.528^{NS}	0.111	Negligible	NA[2]	−0.250^{NS}	0.273	0.076^{NS}	0.178	−0.021^{NS}	0.708
$\ln X_3$	0.290**	0.023	0.358*	0.068	0.038^{NS}	0.391	−0.233^{NS}	0.450	0.120^{NS}	0.289	0.046^{NS}	0.614
$\ln X_4$	−0.025^{NS}	0.891	−0.110^{NS}	0.519	Negligible	NA[3]	0.025^{NS}	0.826	0.019^{NS}	0.653	0.085**	0.019
$\ln X_5$	−0.466^{NS}	0.659	0.220^{NS}	0.675	−0.164**	0.031	−0.072^{NS}	0.744	0.278***	0.000	0.107*	0.090
$\ln X_6$	−0.162^{NS}	0.593	0.046^{NS}	0.920	0.285***	0.000	−0.042**	0.039	0.208**	0.046	0.194**	0.022
R^2	0.795		0.740		0.577		0.584		0.580		0.779	
Observations	466		134		405		833		484		2,322	

***, **, *, and NS indicate significance at the 1, 5, and 10% levels, and not significant, respectively.

[1]Dependent variable.

[2,3]Because of the low number of observations for the variables "animal labor (X_2)" and "irrigation machine hours (X_4)," these variables were excluded when running the Cobb–Douglas production function for Kerala.

[a]To ensure the robustness of the regression estimates, we tested for multicollinearity using the Variance Inflation Factor (VIF), and for heteroscedasticity using the Breusch–Pagan test. All VIF values were below 5, and the Breusch–Pagan test yielded a p-value greater than 0.05, indicating no evidence of multicollinearity or heteroscedasticity in the model.

to inconsistent irrigation practices that may not be efficiently managed (Lakshmi et al., 2024).

Additionally, seed quantity had a negative and significant effect, which may indicate issues related to seed quality or an inappropriate seeding rate. The negative impact of increasing seed quantity on paddy yields in Kerala can be attributed to several factors. When seed density is too high, it can lead to overcrowding, which affects the growth and development of seedlings. Overcrowded conditions can reduce the availability of sunlight, nutrients, and water for each plant, thereby causing competition among plants and inhibiting their growth. This condition is known as overcrowding stress, which can result in reduced plant height, lower tiller number, and smaller grain size, collectively leading to a diminished yield (Sarwar et al., 2011). Furthermore, dense seeding can exacerbate pest and disease infestations, as plants in close proximity can facilitate the spread of pathogens. This further stresses rice plants, contributing to the observed decrease in yield per unit area with an increase in seed quantity (Sarwar et al., 2011). Additionally, improper nursery management and a lack of nitrogen application can exacerbate these negative effects, leading to reduction in overall productivity in rice-field.

Conversely, fertilizer use in Kerala had a strong, positive, and significant impact, underscoring its critical role in enhancing productivity. Fertilizers supplement essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which are crucial for plant growth and development. In paddy fields, the addition of fertilizers enhances nutrient availability in the soil, thereby promoting better root and shoot development, increasing chlorophyll content, and improving photosynthetic capacity, all of which contribute to higher crop yields (Meirong et al., 2011). Moreover, fertilizers can improve soil properties by increasing soil organic carbon and microbial biomass, which further supports plant growth (Pasley et al., 2019). The observed increase in paddy yield of 0.285% with a 1% increase in fertilizer use is likely due to the efficient uptake of nutrients facilitated by fertilizers, which leads to enhanced plant growth and productivity. Fertilizer application strategies that optimize the balance between nutrient supply and plant demand can significantly boost yield while maintaining soil health (Minami, 1995).

Karnataka presents a more moderate profile, with both human and machine labor showing marginal significance. The positive coefficients for these variables imply that both manual and mechanized labor contribute positively to paddy production, albeit with less statistical certainty. Human labor remains crucial, especially in tasks that require precision and sensitivity, such as manual transplanting and hand weeding, which can significantly affect crop yields (Tomita et al., 2003). Meanwhile, machine labor enhances efficiency and productivity, particularly in tasks such as ploughing, sowing, and harvesting crops. The integration of technologies such as big data, machine learning, and the Internet of Things (IoT) in agriculture has increased the productivity of mechanized operations, facilitating precision farming practices that optimize input use and enhance yield (Alfred et al., 2021).

In Tamil Nadu, the only significant variable is fertilizer, which surprisingly has a negative co-efficient. The decrease in paddy yield in Tamil Nadu as a result of increased fertilizer use can be attributed to several factors, including the overuse or improper application of fertilizers, which can degrade soil quality, reduce soil fertility, and harm surrounding ecosystems (Abdul Khalil et al., 2023). This degradation can disrupt the delicate balance of nutrients required for optimal crop growth, leading to diminished yields despite increased fertilizer input. Increased fertilizer use can also lead to environmental issues, such as nutrient leaching into water bodies, contributing to eutrophication and loss of biodiversity (Arora et al., 2024; Felix and Ramappa, 2023). Additionally, traditional farming methods and the lack of modern fertilizer management practices can exacerbate this problem, highlighting the need for sustainable agricultural practices to enhance yield and environmental health (Zhang et al., 2025).

In contrast, Telangana demonstrated a more favorable input–output relationship. Both seed quantity and fertilizer use were positively and significantly associated with paddy production. In Telangana, increasing seed quantity and fertilizer use positively influenced paddy yield owing to enhanced plant density and nutrient availability. A 1% increase in seed quantity led to a 0.278% increase in yield because more seeds enhanced the plant population and optimized light and space usage for photosynthesis and growth (Luo et al., 2024). A 1% increase in fertilizer use boosts yield by 0.208% owing to improved nutrient supply, which enhances plant growth and grain filling, and is crucial for maximizing yield potential (Kakar et al., 2020; Ning et al., 2022). Furthermore, balanced fertilizer application, including macro-and micronutrients, improves soil fertility and crop productivity (Lu et al., 2021).

Andhra Pradesh shows limited significance among the variables, with only machine labor emerging as a significant contributor to output. The use of machine labor has positively impacted paddy yields in Andhra Pradesh by streamlining agricultural processes, improving efficiency, and reducing the dependency on manual labor. Mechanization saves time and reduces the costs associated with labor and traditional farming methods, leading to enhanced agricultural productivity. As machine labor increases by 1%, its efficient contribution to farming tasks could lead to a notable increase in paddy yields by 0.29%, given that machines can optimize various stages of the farming process. Mechanization also allows for better handling and monitoring of crops, resulting in the precise application of inputs that can enhance crop yields. In addition, by eliminating human error and fatigue, machines can maintain consistent performance levels, further supporting their use (Sarkar, 2020).

At the aggregate level for South India, the analysis revealed that irrigation, seed quantity, and fertilizer were significant contributors to paddy yields. Fertilizer consistently showed a positive and significant effect, reinforcing its importance in all regions. Despite its insignificance in most individual states, the significance of irrigation at the regional level suggests that its impact may be more pronounced when considering broader climatic and infrastructural variations across southern India.

4.3 Estimating the resource use efficiency of paddy cultivation in South Indian states

The Marginal Value of Product (MVP) to Marginal Input Cost (MIC) ratio or Marginal Factor Cost (MFC) and the Resource Use Efficiency (RUE) decision (r) reveal the efficiency of resource utilization in paddy cultivation across South Indian states. If the ratio is one, then there is an optimal utilization of resources; a ratio less than one indicates excessive use of resources, while a ratio greater than one indicates underutilization of resources (Narayanamoorthy and Jothi, 2018; Saravanan, 2022). The results obtained regarding the RUE of paddy cultivation across South Indian states are provided in Table 2.

TABLE 2 Resource use efficiency in paddy cultivation across South India.

State	Factors	Elasticity	APP (Y/X)	MPP	MVP = MPP*PY	MFC or MIC	*r* = MVP/ MIC	RUE decision
Andhra Pradesh	Human labor (hr./ha.)	0.192	0.151	0.029	50.485	86.035	0.587	Excess use of resources
	Animal labor (hr./ha.)	0.151	11.028	1.661	2884.686	149.290	19.323	Under use of resource
	$Machine (hr./ ha.)	0.290	3.463	1.006	1746.865	810.084	2.156	Under use of resource
	Irrigation machine (hr./ ha.)	−0.025	0.799	−0.020	−34.760	10.525	−3.303	Excess use of resources
	Seed Qty. (kg. / ha.)	−0.466	0.905	−0.421	−731.946	32.633	−22.430	Excess use of resources
	Total fertiliser (kg. /ha.)	−0.162	0.216	−0.035	−60.976	31.785	−1.918	Excess use of resources
Karnataka	$Human labor (hr./ha.)	0.454	0.080	0.036	48.708	37.068	1.314	Under use of resource
	Animal labor (hr./ha.)	−0.528	3.094	−1.634	−2190.477	112.948	−19.394	Excess use of resources
	$Machine (hr./ ha.)	0.358	2.114	0.756	1013.659	980.738	1.034	Under use of resource
	Irrigation machine (hr./ ha.)	−0.110	1.244	−0.137	−183.621	122.253	−1.502	Excess use of resources
	Seed Qty. (kg. / ha.)	0.220	0.863	0.190	254.979	162.008	1.574	Under use of resource
	Total fertiliser (kg. /ha.)	0.046	0.155	0.007	9.561	32.962	0.290	Excess use of resources
Kerala	$Human labor (hrs./ha.)	−0.131	0.087	−0.011	−25.837	77.733	−0.332	Excess use of resources
	Machine (hrs./ ha.)	0.038	2.338	0.089	201.617	996.578	0.202	Excess use of resources
	$Seed Qty. (kg. /ha.)	−0.164	0.342	−0.056	−127.298	43.216	−2.946	Excess use of resources
	$Total fertiliser (kg. /ha.)	0.285	0.221	0.063	143.154	37.552	3.812	Under use of resource
Tamil Nadu	Human labor (hrs./ha.)	0.546	0.128	0.070	130.724	58.210	2.246	Under use of resource
	Animal labor (hrs./ha.)	−0.250	7.629	−1.910	−3580.149	164.402	−21.777	Excess use of resources
	Machine (hrs./ ha.)	−0.233	3.033	−0.707	−1325.876	992.919	−1.335	Excess use of resources
	Irrigation machine (hrs./ ha.)	0.025	0.466	0.011	21.548	43.990	0.490	Excess use of resources
	Seed Qty. (kg. / ha.)	−0.072	0.667	−0.048	−90.599	59.131	−1.532	Excess use of resources
	$Total fertiliser (kg. /ha.)	−0.042	0.232	−0.010	−18.237	30.725	−0.594	Excess use of resources

(Continued)

TABLE 2 (Continued)

State	Factors	Elasticity	APP (Y/X)	MPP	MVP = MPP*PY	MFC or MIC	*r* = MVP/ MIC	RUE decision
Telangana	Human labor (hr./ha.)	−0.040	0.145	−0.006	−10.961	85.487	−0.128	Excess use of resources
	Animal labor (hr./ha.)	0.076	5.798	0.438	825.443	256.878	3.213	Under use of resource
	Machine (hr./ ha.)	0.120	3.275	0.394	743.241	1169.804	0.635	Excess use of resources
	Irrigation machine (hr./ ha.)	0.019	0.193	0.004	6.824	11.324	0.603	Excess use of resources
	$Seed Qty. (kg. /ha.)	0.278	0.969	0.269	507.159	66.196	7.661	Under use of resource
	$Total fertiliser (kg. /ha.)	0.208	0.209	0.043	81.875	35.907	2.280	Under use of resource
South India	Human labor (hr./ha.)	0.119	0.124	0.015	26.611	65.801	0.404	Excess use of resources
	Animal labor (hr./ha.)	−0.021	5.675	−0.119	−213.293	161.922	−1.317	Excess use of resources
	Machine (hr./ ha.)	0.046	2.983	0.138	248.131	983.386	0.252	Excess use of resources
	$Irrigation machine (hr./ ha.)	0.085	0.388	0.033	58.914	28.505	2.067	Under use of resource
	$Seed Qty. (kg. /ha.)	0.107	0.687	0.074	132.144	61.702	2.142	Under use of resource
	$Total fertiliser (kg. /ha.)	0.194	0.215	0.042	75.079	33.690	2.229	Under use of resource

$Indicates that the coefficients of the variables are significant.

In Andhra Pradesh, machine labor was the only significant input, with *r*-value of 2.156, indicating its underutilization. The underutilization of machine labor in Andhra Pradesh for paddy cultivation can be attributed to several factors. The *r* value of 2.156, which is greater than 1, indicates that the MVP of machine labor exceeds its MIC or MFC. This suggests that farmers do not fully exploit the potential benefits of mechanization in paddy cultivation in the region. The high MVP of 1746.865 compared with the MIC of 810.084 further emphasizes the economic advantage of increasing machine labor usage. The underutilization of machine labor in Andhra Pradesh's paddy cultivation is influenced by several factors. One key aspect is the existing agricultural practices, such as zero-budget natural farming (ZBNF), which emphasizes minimal use of external inputs, including machinery, favoring traditional and non-mechanized techniques (Bharucha et al., 2020). Additionally, regional variations in agricultural mechanization can be attributed to agro-ecological characteristics, landholding sizes, and access to credit, where some areas might lack the necessary infrastructure and investment in machinery ownership (Sarkar, 2020). Furthermore, the prevailing economic factors might not favor the acquisition or rental of machines, alongside a significant influence from sociocultural aspects, where traditional methods are still preferred or considered more economically viable. Lastly, lack of awareness, hesitancy towards technological interventions, and preference for eco-friendly practices also play a role in this underutilization (Sarkar, 2020). This suggests that increasing machine labor may enhance productivity.

The state-wise RUE Scores of Animal and Human Labor in Paddy Cultivation across South Indian States are depicted in Figure 2. The legend of the graph clearly indicates that the darker shade represents higher RUE or underutilization of resources, and lighter shade denotes lower RUE or overutilization of resources. In this case, Andhra Pradesh represents underutilization and Tamil Nadu represents the overutilization of animal labors. Similarly, human labors were underutilized in Tamil Nadu and over utilized in Kerala.

Karnataka demonstrates significant contributions from human and machine labor. Human labor had a *r* value of 1.314, and machine labor was close to optimal at 1.034, indicating underutilization. Despite positive Resource Use Efficiency (RUE) values, the underutilization of human and machine labor in paddy cultivation in Karnataka may be attributed to several factors. For human labor, with an RUE of 1.314, there is potential for increased utilization as the marginal value product (48.708) exceeds the marginal input cost (37.068). This suggests that farmers could benefit from employing more human laborers. For machine labor, an RUE of 1.034 with an MVP of 1013.659 and MIC of 980.738 indicates near-optimal usage, but slight underutilization persists. In Karnataka's paddy cultivation, the underutilization of both human and machine labor can

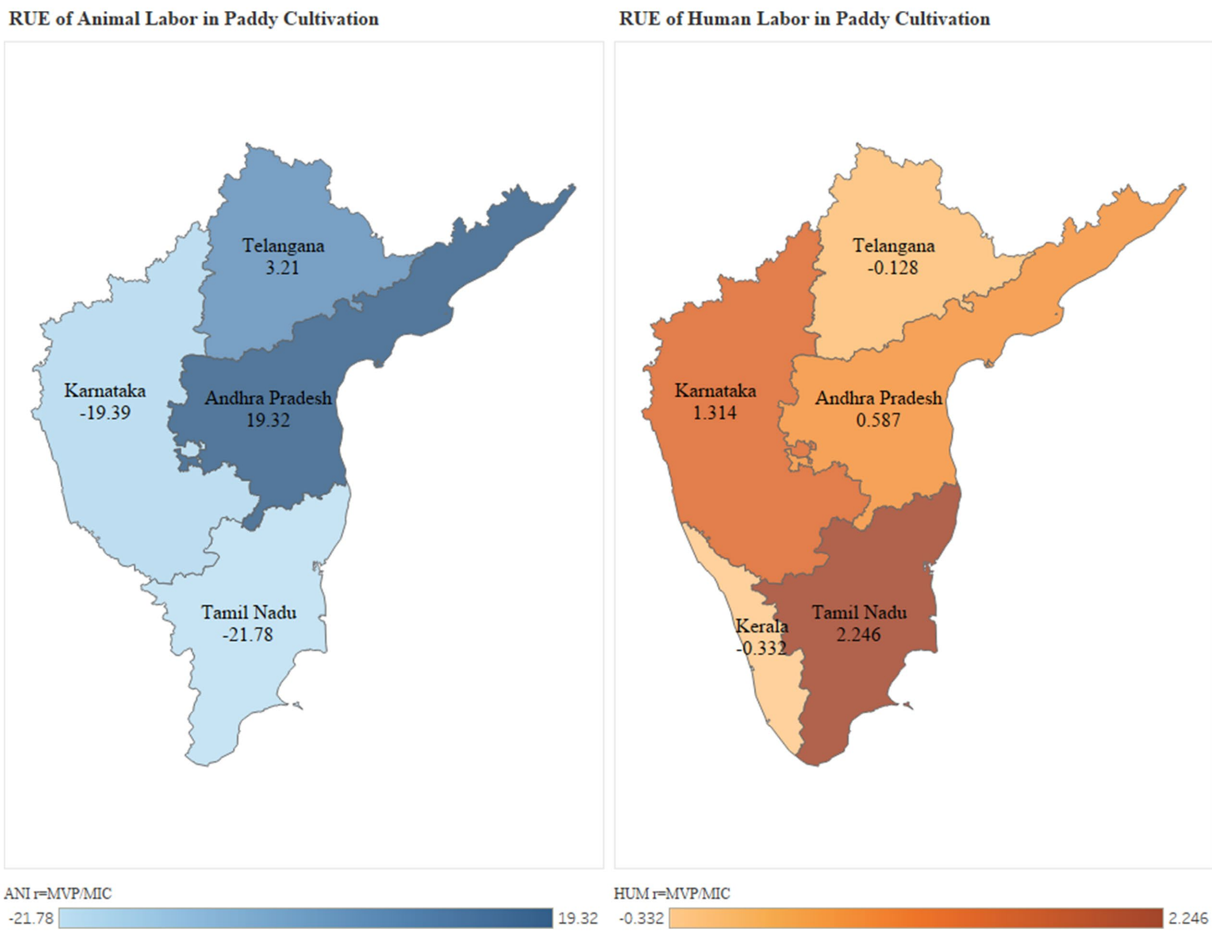

FIGURE 2
Resource use efficiency scores of animal and human labor in paddy cultivation across South Indian states.

be attributed to several factors. One primary issue is the inefficiency arising from labor market imperfections, where there may be mismatches between labor availability and demand for labor during peak agricultural periods.

The state-wise RUE scores of irrigation machine hours and machine labor in Paddy Cultivation across South Indian States are depicted in Figure 3. It clearly indicates that Telangana has highest RUE, while Andhra Pradesh has lowest RUE of irrigation machine hours in the South Indian states. Meanwhile, the RUE is highest in Andhra Pradesh and lowest in Tamil Nadu with regard to machine labor usage.

Additionally, traditional methods of paddy cultivation, which have been less adapted to mechanization, rely on manual labor, limiting the effective use of machines (Bardhan, 1973). Furthermore, technological barriers and a lack of awareness of advanced farming technologies, such as big data, machine learning, and IoT in agriculture, hinder the adoption of smart farming practices that could optimize both labor types (Alfred et al., 2021). These factors collectively contribute to the insufficient utilization of available resources for paddy cultivation in this region. These findings imply that both manual and mechanized labor can be scaled up to improve output. In Karnataka, the coefficients of animal labor, irrigation, and fertilizer were not significant. Animal labor and irrigation were both excessively used, with r values of −19.394 and −1.502, respectively. Fertilizer, although less extreme, also showed inefficiency, with an r of 0.290, suggesting its overuse. These findings highlight the need for improved input management, particularly for animal- and irrigation-based resource management.

In Kerala, the significant variables of human labor and seed usage showed less than one value of RUE, but fertilizer showed a value greater than one. The excessive utilization of human labor and seeds in paddy cultivation in Kerala can be attributed to the negative and low RUE values, respectively. For human labor, an RUE of −0.332 indicates that the marginal value product (−25.837) is significantly lower than the marginal input cost (77.733), suggesting an inefficient resource allocation. Seed usage, with a negative and less than one RUE of −2.946, also shows inefficiency, as its marginal value product (−127.298) is lower than the marginal input cost (43.216). The underutilization of human labor and seeds in Kerala's paddy cultivation can be attributed to several factors, including economic growth and industrial development, which have prompted a shift towards labor-saving techniques such as direct seeding. Although this lowers labor costs, it can increase weed problems and reduce yields under resource-poor conditions (Tomita et al., 2003).

Furthermore, the ineffective use of inputs, such as nitrogen fertilizers, owing to low nitrogen-use efficiency (NUE), contributes to poor yields and soil degradation, further limiting

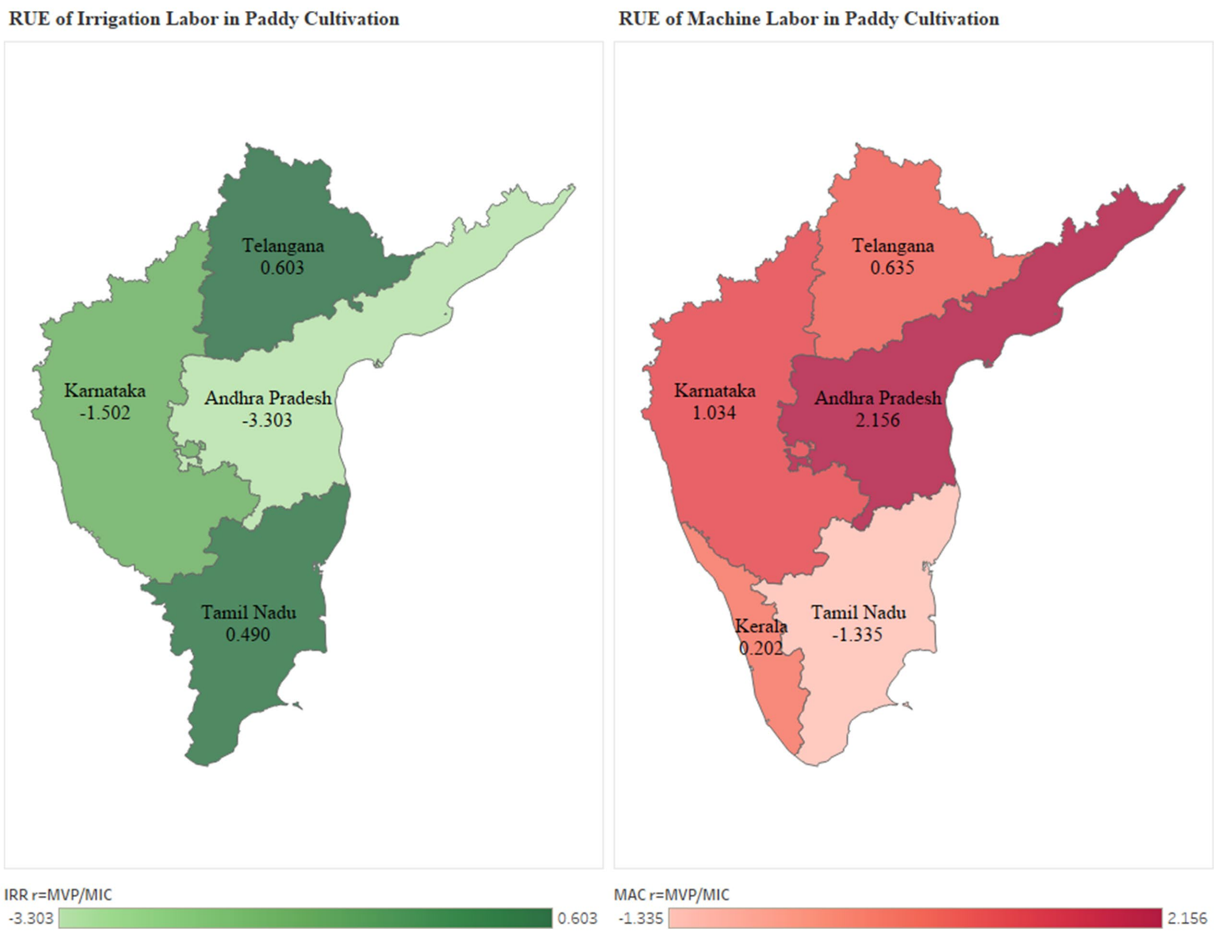

FIGURE 3
Resource use efficiency scores of irrigation machine hours and machine labor in paddy cultivation across South Indian states.

the optimal utilization of human labor and seeds (Alam et al., 2023). Additionally, environmental challenges such as microplastic pollution in paddy fields can affect crop health and productivity, indirectly influencing labor and seed utilization (Amaneesh et al., 2025). Changes in climate patterns and their impacts on water availability and plantation timing could further exacerbate these issues, complicating the management and effective use of these resources (Watanabe and Kume, 2009). In contrast, fertilizer demonstrated a higher *r* value of 3.812, which is greater than one, indicating that the marginal value product (MVP) of fertilizer exceeds its marginal input cost (MIC). This suggests that farmers do not fully exploit the potential benefits of fertilizers in their paddy cultivation practices. The high MVP of 143.154 compared with the MIC of 37.552 further emphasizes the economic advantage of increasing fertilizer usage. The underutilization of fertilizers in Kerala's paddy cultivation can be attributed to several environmental and economic factors, including low nitrogen use efficiency in paddy farming, which typically ranges from 20%–40%, leading to substantial nitrogen loss that deteriorates the soil and water quality (Alam et al., 2023). Additionally, traditional fertilizer application methods often contribute to increased methane emissions, prompting farmers to search for alternative practices to mitigate these environmental impacts (Minami, 1995).

There is also a lack of awareness and misconceptions among farmers who may not fully understand the benefits of optimized fertilizer use, leading to either overuse or underuse. Moreover, factors such as inadequate access to fertilizers, high costs, and limited knowledge of new technologies and management strategies further contribute to the suboptimal use of fertilizers in Kerala's paddy fields. These issues highlight the need for improved awareness, policy interventions, and education to enhance fertilizer use while minimizing the environmental damage. In Kerala, the coefficient of machine labor is insignificant. Despite their statistical insignificance, the RUE analysis revealed that there was excess use of resources in paddy cultivation.

Tamil Nadu presented a scenario where fertilizer is the only significant input, yet it is inefficiently used with an *r* of −0.594, which is less than 1, indicating that the marginal value product (MVP) of fertilizer is less than its marginal input cost (MIC). This suggests that farmers overexploit the potential benefits of fertilizer use in paddy cultivation. The low MVP of −18.237 compared to the MIC of 30.725. The over-utilization of fertilizers in Tamil Nadu's paddy cultivation can be attributed to a combination of factors, including the pressure to enhance agricultural output, inadequate knowledge about optimal fertilizer application, and ecological variations within the region. Studies indicate that significant variations in technical efficiency exist across different farm sizes and ecological zones, influencing the use of inputs such as fertilizers in paddy production (Tadesse, 1997). Additionally, the reliance on groundwater for irrigation, despite its depletion, may drive farmers to use more fertilizers to maintain high yields despite limited water availability (Chinnasamy and Agoramoorthy, 2015).

The lack of widespread adoption of sustainable practices, such as organic farming or precise farming techniques that limit the use of chemical fertilizers, also contributes to this issue (Mariappan and Zhou, 2019; Hussain et al., 2020; Khangar et al., 2025). This highlights the need for better fertilizer management to avoid waste and potential environmental harm. In Tamil Nadu, all inputs, except fertilizer, were non-significant. Human labor, despite being non-significant, showed an *r*-value of 2.246, indicating underutilization. However, animal labor, machine labor, irrigation, and seed quantity exhibited negative MVPs and *r*-values below one, confirming excessive use. This pattern suggests widespread inefficiency in the input applications across the states.

The state-wise RUE scores of seed quantity and total fertilizer usage in Paddy Cultivation across South Indian States are pictorially represented in Figure 4. It is clear that, the efficiency of seed usage is higher in Telangana and lower in Andhra Pradesh. Similarly, the efficiency of fertilizer usage is higher in Kerala and lower in Andhra Pradesh.

Telangana exhibited a more favorable pattern. Seed quantity and fertilizer were both significant and efficiently used, with *r* values of 7.661 and 2.280, respectively, indicating underutilization. This indicates that the marginal value product (MVP) of the seed and fertilizer exceeds its marginal input cost (MIC). This suggests that farmers do not fully exploit the potential benefits of seeds and fertilizers in paddy cultivation. The high MVP of 507.159 and 81.875 compared to the MIC of 66.196 and 35.907 further emphasizes the economic advantage of increasing seed and fertilizer usage. The underutilization of seed quantity and fertilizers in Telangana's paddy cultivation can be attributed to several factors. One major reason for this could be the high reliance on traditional chemical fertilizers, which often results in low nutrient-use efficiency and substantial environmental losses. This inefficient use can discourage farmers from using them optimally, leading to under-application.

Additionally, emerging technologies, such as nano fertilizers, show promise in improving efficiency, but their adoption may be slow because of the lack of awareness or high initial costs (Aljutheri et al., 2020; Basit et al., 2022). Another factor is environmental concerns, such as potential soil and water pollution from excessive fertilizer use, which might lead to reluctance in its application to avoid ecological damage (Das et al., 2018). Therefore, a shift towards more sustainable and efficient

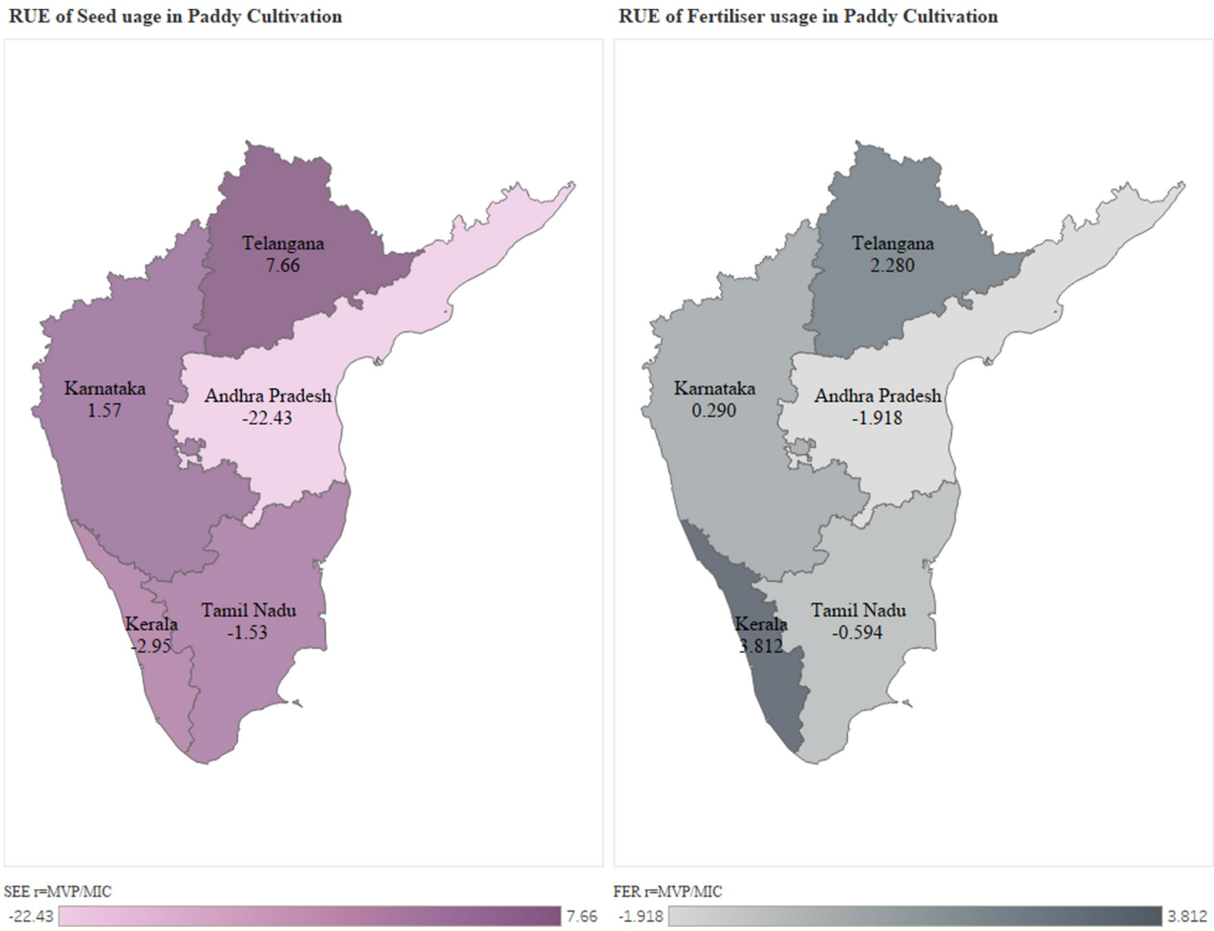

FIGURE 4
Resource use efficiency scores of seed usage and total fertiliser usage in paddy cultivation across South Indian states.

fertilizer-use practices is required to optimize resource utilization in this region. These results suggest that increasing these inputs may substantially improve productivity. Telangana was not significantly different in terms of human, animal, and machine labor, and irrigation. Among these, animal labor is notably underutilized with an r of 3.213, whereas the remaining human labor, machine labor, and irrigation are excessively used with r values of −0.128, 0.635, and 0.603, respectively. These results imply that while animal labor has potential, other inputs may be over-applied without corresponding gains in productivity.

At the regional level in South India, the significant inputs of irrigation, seed quantity, and fertilizer were all underutilized, with r values of 2.067, 2.142, and 2.229, respectively. This suggests that these inputs were not used to their full productive potential across the region. At the regional level in South India, human, animal, and machine labor were not significant. All three inputs showed signs of excessive use, with r values of 0.404, −1.317, and 0.252, respectively. The underutilization of resources such as irrigation, seed quantity, and fertilizer in paddy cultivation in South India can be attributed to several factors. One significant reason for this is the inefficiency of irrigation practices. For instance, traditional flooding methods often result in excess water usage without necessarily enhancing crop yield, whereas adopting water-saving techniques, such as alternate wetting and drying, could improve water productivity and yield (Mboyerwa et al., 2021).

Additionally, farmers' willingness to invest in effective irrigation systems is influenced by economic constraints and perceived water value, highlighting the need for policy incentives to adopt efficient water management practices (Chandrasekaran et al., 2009). Fertilizer underutilization may result from inefficient application, as overuse can lead to nitrogen leaching and environmental concerns without matching productivity benefits (Chen et al., 2024). Economic considerations, including the cost of fertilizers and lack of knowledge regarding their optimal usage, further contribute to their underutilization (Mboyerwa et al., 2021). Consequently, optimizing resource usage requires the adoption of modern agricultural practices and ensuring the availability of the necessary infrastructure and education for farmers. This suggests that these inputs are not used efficiently across the region and may contribute to resource wastage.

The RUE scores of Paddy Cultivation in South India are shown in Figure 5.

The analysis of RUE in paddy cultivation across South Indian states revealed significant variations and opportunities for improvement. Fertilizer and seed quantities are consistently underutilized in most states, particularly in Telangana and Kerala. In contrast, machine labor showed potential for increased use in Andhra Pradesh and Karnataka. Human labor tends to be overused in several states, suggesting the need for more efficient allocation or increased mechanization. Irrigation, despite being a significant input at the regional level, is underutilized across South India, indicating its potential for improving water management. Animal labor, machine labor, and irrigation are generally used excessively in most states, indicating inefficient resource allocation in these states.

State-specific variations highlight the need for tailored strategies, such as focusing on increasing machine labor use in Andhra Pradesh, optimizing both human and machine labor in Karnataka, and addressing inefficient fertilizer use in Tamil Nadu. At the regional level, there is a general trend of underutilization of

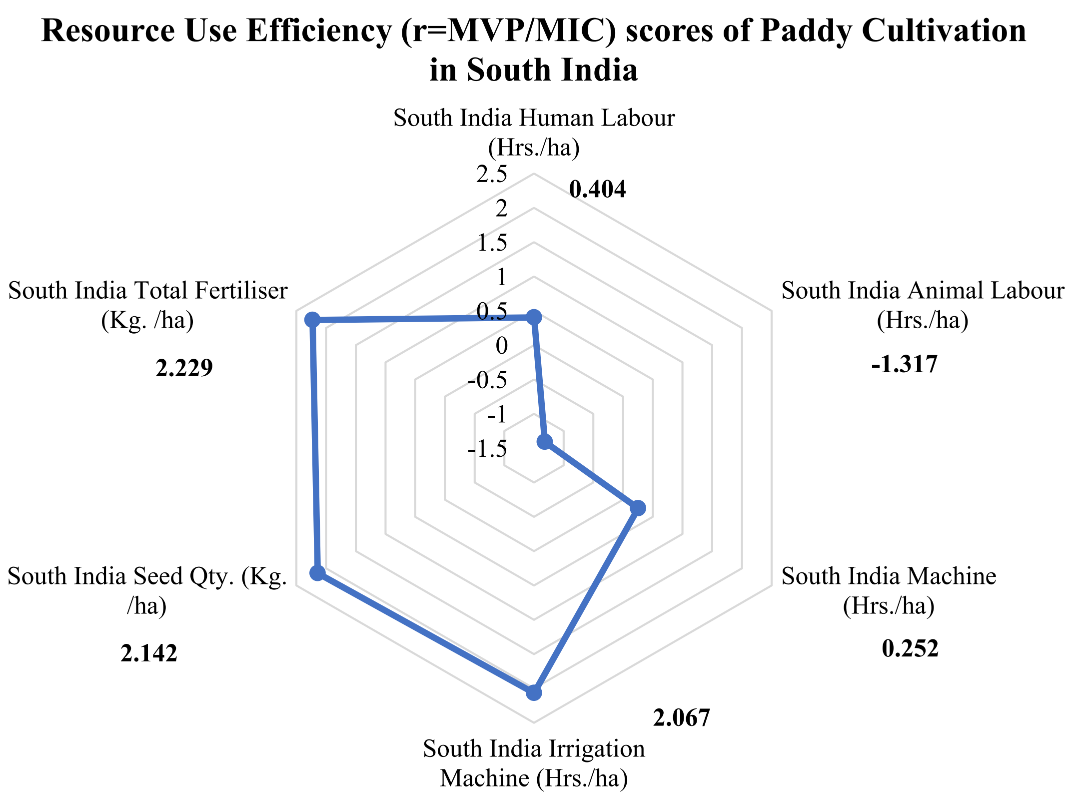

FIGURE 5
Resource use efficiency scores of paddy cultivation in South India.

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significant inputs (irrigation, seed quantity, and fertilizer) and excessive use of non-significant inputs (human, animal, and machine labor). To improve RUE, policymakers and farmers should focus on implementing region-specific input optimization strategies, increasing the use of underutilized resources while reducing the excessive application of inefficient resources, adopting modern agricultural practices, providing education and infrastructure support, encouraging precision farming techniques, and addressing the economic constraints that affect resource allocation.

5 Conclusion and policy implications

From the descriptive statistics, it is evident that Telangana leads in paddy productivity, supported by intensive irrigation practices and favorable adaptation strategies for climate variability. In contrast, Kerala lags in productivity, likely because of environmental challenges and less efficient use of inputs. Labor dynamics also vary significantly, with Karnataka exhibiting the highest human and animal labor input, while Tamil Nadu demonstrates lower labor usage, possibly because of mechanization and sustainable practices such as Alternate Wetting and Drying (AWD). Fertilizer and seed usage patterns further highlight regional disparities, with Karnataka applying the most fertilizer and Kerala using the highest seed quantity, reflecting differing agronomic strategies and ecological conditions.

Cobb–Douglas production function analysis adds depth to these observations by quantifying the impact of specific inputs on paddy output. Kerala showed a negative relationship between yield and both human labor and seed quantity, suggesting inefficiencies and possible overuse. The descriptive statistics also showed that Kerala used a huge quantity of seeds per hectare for cultivating paddy compared to other South Indian states, and its human labor usage was also higher than the average human labor usage in South India. However, fertilizer use in Kerala has a strong positive effect, indicating its critical role in enhancing productivity. The descriptive statistics results also showed that a lower fertilizer quantity per hectare was used for paddy cultivation in South Indian states. Telangana emerged as the most efficient state in input–output relationships, with both seed quantity and fertilizer contributing significantly and positively to yield. Tamil Nadu, on the other hand, presents a counterintuitive negative impact of fertilizer on yield, although it uses comparatively less fertilizer for paddy cultivation among the South Indian states. This indicates potential overuse or mismanagement. Andhra Pradesh and Karnataka showed moderate results, with machine labor being the only significant contributor in Andhra Pradesh, and both human and machine labor showing positive, albeit less significant, effects in Karnataka. Human and machine labor usage per hectare for paddy cultivation is high in the state among South Indian states.

The RUE analysis corroborates and extends these findings by evaluating the economic efficiency of input utilization. This reveals the widespread underutilization of key inputs, such as fertilizers, seed quantity, and irrigation, across most states, particularly in Telangana and Kerala, where increased application could yield substantial productivity gains in these states. Conversely, human, animal, and machine labor are often excessively used, especially in states such as Tamil Nadu and Karnataka, indicating inefficiencies and the need for better resource allocation. Andhra Pradesh shows a significant underutilization of machine labor, suggesting the potential for mechanization to boost output. Tamil Nadu's overuse of fertilizer and other inputs, despite their limited impact on yield, highlights the need for improved input management and adoption of precision agriculture practices.

At the regional level, the convergence of findings from all three analyses points to a common pattern: significant inputs, such as fertilizer, seed quantity, and irrigation, are generally underutilized, whereas non-significant inputs, such as human and animal labor, are overused. This imbalance suggests that improving paddy productivity in South India requires a strategic shift towards optimizing the use of high-impact inputs and minimizing the inefficient application of less productive resources. Policymakers should prioritize investing in irrigation infrastructure, promoting balanced fertilizer applications, and supporting the adoption of high-quality seeds. Simultaneously, efforts should be made to enhance mechanization and reduce dependency on manual labor through training and access to farm machinery.

In conclusion, this study underscores the importance of tailored state-specific interventions to address the unique agricultural, ecological, and socioeconomic contexts of each state in South India. Enhancing paddy productivity and RUE requires a combination of technology adoption, policy support, and farmer education aimed at optimizing input use and achieving sustainable agricultural growth.

Drawing on the insights derived from the comparison of paddy cultivation inputs and outputs, the significantly valued coefficients from the Cobb–Douglas function of production, and the analysis of RUE across states of South India, the following are some important policy implications that can help improve agricultural productivity and sustainability.

1. Telangana: Promote balanced input intensification by aligning with existing schemes such as the PM-KISAN and the Sub-Mission on Agricultural Mechanization (SMAM), which offer financial support for precision farming tools. Encourage optimal seed and fertilizer application through soil health card-based recommendations. Studies show that precision agriculture can increase paddy yields by up to 15% and reduce input costs by 10%–20%. While mechanization may reduce labor demand, this can be mitigated by upskilling rural workers for machinery operation and maintenance roles.
2. Kerala: To address labor inefficiency and excessive seed use, promote mechanization through schemes like SMAM and Rashtriya Krishi Vikas Yojana (RKVY). Introduce targeted fertilizer subsidies and training under the Paramparagat Krishi Vikas Yojana (PKVY). Mechanization in Kerala could improve labor productivity by 20%–30%, but may displace manual labor. This can be mitigated by integrating rural employment programs (e.g., MGNREGS) with agricultural extension services to retrain workers.
3. Tamil Nadu: Implement precision fertilizer management using the Soil Health Card Scheme and integrate it with the National Mission on Sustainable Agriculture (NMSA). Demonstration plots and farmer field schools should be supported under RKVY. Evidence suggests that site-specific nutrient management can increase yields by 12%–18% and reduce fertilizer use by 15%–25%. While adoption may require upfront

investment, cost-sharing models and cooperative-based machinery banks can ease the transition.

Implementing these policies in agricultural development strategies will foster sustainable growth, improve farmers' livelihoods and reinforce food security across South Indian states. A holistic approach that considers both the local context and technological innovation is the vehicle for achieving long-term agricultural sustainability in the region.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for the studies involving humans because the study focuses on the secondary data published during 2022–23. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

KF: Conceptualization, Data curation, Methodology, Validation, Visualization, Writing – original draft. PG: Conceptualization, Formal analysis, Funding acquisition, Methodology, Validation, Writing – review & editing. VPR: Methodology, Software, Visualization, 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.

Generative AI statement

The author(s) declare that Gen AI was used in the creation of this manuscript.

The author(s) declare the use of AI tools (Grammerly, ChatGPT) to improve grammer and language clarity. The authors confirm that all study design, data analysis, interpretation, and conclusions were entirely developed by the authors without AI. assistance. Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1665774/full#supplementary-material

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