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Global Challenges, Local Solutions: Engineering, Science, and Technology in Developing Regions

Evaluation of rice establishment strategies for productivity and water use effectiveness in plains

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Abstract The efficient rice establishment methods are essential to increasing yield and maximizing the use of water, given the increasing water shortages and the importance of sustainable agriculture. In focusing their implications on the agronomic performance and water use efficiency (WUE) in plain areas, the following review examines the agronomic basis, benefits, and drawbacks of the three primary innovations of rice establishment: Transplanted Rice (TPR), System of Rice Intensification (SRI), and Direct Seeded Rice (DSR). The advantages of DSR are faster growing crops and reduced labor and water costs. Some of its disadvantages include inadequate seedling establishment, uneven crop stands, and the presence of weeds in different field conditions. SRI enhances WUE and yield possible through methods such as younger seedlings, broader spacing, and alternate wetting and drying (AWD). Although it has its compensation, it also suffers shortcomings in terms of scalability because of the troubles of mechanization and popularization. TPR remainder the predictable technique because it reliably puts crops in the ground; however, with significant demands on both the water resource and labor resources, the topic of sustainability is problematic given current resource and climatic restrictions. To better improve the efficiency of such methods, there was also the assessment of how technical innovations such as sensor-based irrigation, incorporated nutrient management, and accurate field leveling might be helpful. It accounts significantly on the substance of matching techniques to their nutrient dynamics, plant physiology, irrigation plans and soil structure, to maximize on the results. EVR-SD The research also determines the need to establish models of the agriculture of rice that are local and provide efficiently viable and ecologically sustainable conditions, with consideration to regional agro-ecological factors.

Keywords: rice establishment methods, direct seeded rice (DSR), system of rice intensification (SRI), transplanted rice (TPR), water use efficiency (WUE)

1. Introduction

Rice (*Oryza sativa L.*) is a worldwide essential staple food that plays a mainly significant role in the diets of many Asian populations. In India, rice farming is the cornerstone of agricultural efficiency, especially in fertile plains, where it promotes food security, rural employment, and economic resilience (Santiago-Arenas et al., 2021). The most common process in this region has been Puddled Transplanted Rice (PTR). Although there are certain agronomic benefits to this well-established method, such as enhanced weed control and initial crop vigor, it is also notoriously labor- and water-intensive. The area of agricultural sciences is critically reevaluating these traditional methods in light of the growing strain on water supplies and workforce immigration away from agriculture (Hossain et al., 2021). The WUE needs to be developed immediately and has become a significant topic in agricultural research, particularly on plains where groundwater levels are rapidly decreasing. Agricultural sciences present a key obstacle to long-term sustainability, given that the field uses over 80% fresh water in India (Kong et al., 2021). Owing to great improvements in agricultural research, a number of new methods for growing rice have been introduced and tested in the last few years. The SRI, machine-transplanted rice (MTR) and DSR have demonstrated promise among these techniques. The intention behind an approach is to address the drawbacks of the traditional PTR system through improvements in soil sustainability, reduced manpower, and utility in terms of water consumption (Negi et al., 2024).

The DSR saves an important amount of water and labor by planting seeds straight into the field, which is needed for puddling and transplanting. MTR offers timely planting and precise seedling placement through automatic transplanters. SRIs promote younger seedlings, better plant spacing, and synchronized irrigation to improve plant health and support root development (Ponce de León and Bailey, 2024). Commitment and performance of varied establishment strategies can be influenced by changing local agroecological conditions, i.e., soil conditions, water availability and climate fluctuation. This discussion underscores the need for local studies in plains, which often different field conditions embody considerable energy source for rice agricultural methods (Tamanna et al., 2021). There is a unique setting for evaluating the efficacy of differing rice establishment methods in plains, as the valuable sedimentary alluvial soils, moderate precipitation, availability of large irrigation options are plentiful. These methods balance mechanized and supply capability advanced by agricultural science by research. This research makes an important contribution to an ongoing debate in the agricultural sciences of how to maximize crop yield per unit input and minimize agricultural environmental impact, through computational modeling and experimental design and testing (Flor et al., 2021). The goal of this research is to provide useful information to farmers, academics and policy makers by linking agronomic performance outcome with water management implications.

2. Methodology

In the agricultural sciences rice, utilizes the greatest amount of water in rice wheat greengram systems. DSR decreased water use by 6.8% compared to conventional transplanting. Water use in the system overall decreased with conservation agriculture, while productivity at the system level also increased, especially in the case of greengram integration, which had significantly lower water needs and economic benefits.

2.1. Literature search strategy

Finding pertinent research from reputable academic databases, such as Google Scholar, AGRICOLA, Web of Science, and Scopus, was the methodical approach taken for the literature search in the field of agricultural sciences. Several targeted keywords, including "WUE in Rice," "SIR," "TPR," "Direct Seeded Rice," and "rice productivity plain regions," were employed to guarantee that the subject was fully examined. To refine the findings, Boolean operators and sophisticated search filters were applied. The search was mostly restricted to research published in the last 5–10 years to identify current trends, developments, and comparative assessments of rice establishment processes. Figure 1 shows the preferred reporting items for systematic reviews and meta-analyses (PRISMA) calculations.

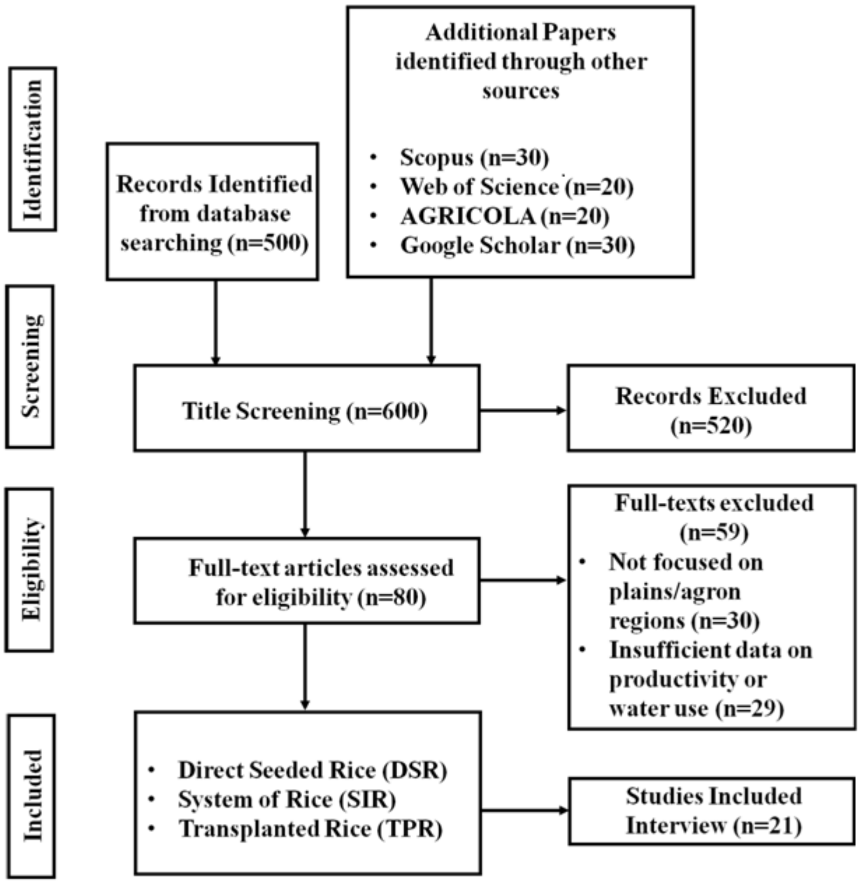

Figure 1 Prisma calculation used in the study.

2.2. Inclusion and exclusion criteria

This review focuses exclusively on rice establishment tactics in plain agro ecological zones within the field of agricultural sciences. The focus is on sources with scientific validation that provide knowledge on the basis of acts. English-language publications are required for uniformity and accessibility. Unpublished theses, conference abstracts, and reports without peer review are examples of gray literature that are eliminated by exclusion criteria. To preserve contextual relevance and spatial focus, investigations that are not carried out in plain regions or that have nothing to do with plain agroecologies are also left out. Because of the possibility of inconsistent translations and restricted accessibility for researchers worldwide, non-English articles were not included.

2.3. Screening & selection process

The screening and selection process followed the PRISMA guidelines to ensure the systematic and transparent inclusion of studies in the field of agricultural sciences. The remaining data were filtered for relevancy via titles and abstracts after duplicates were eliminated. The eligible articles were subsequently subjected to a full-text evaluation to be included on the basis ofpredetermined standards. Excluded studies with stated justifications that did not match the inclusion criteria. All quality and relevance criteria were satisfied by the research that made the final selection. This procedure is graphically summarized in a PRISMA flow diagram, which shows how many records were found, screened, evaluated, and ultimately added for review.

3. Overview of Rice Establishment Techniques

Rice establishment techniques are methods used in the agricultural sciences to initiate rice cultivation in fields. Common approaches include DSR, TPR, and SRI. Each technique varies in terms of labor requirements, water usage, and yield efficiency.

3.1. Direct seeded rice (DSR)

Typically, rice production involves the transplantation of seedlings into puddled soil, an activity that typically occurs between 20 and 25 days after sowing. The previously stated transplanting practice is delayed by 1--3 weeks because of the puddling-based, late monsoon rice sowing practice. As a result, the rice is harvested later, which ultimately delays the wheat aswell. This finding suggests that puddling activity has value because it is associated with greater uptake, yield stability, efficiency of resource utilization with respect to water and nutrients, and weed suppression (Bhandaria et al., 2020) for rice plants than sowing directly into uncultivated soil. Even when accounting for soil resource loss and opportunities for weedy growth with puddling, productivity dynamics favor puddled rice cultivation. The transplantation dynamic of traditional tilled-transplanted rice cultivation is not ecologically friendly and involves voracious labor, energy, and water inputs. As labor demands increase and water scarcity intensifies, the inherently water-intensive nature of rice cultivation compels a shift toward more water-efficient practices. Rice farming, which is often regarded as the most water-wasteful system in production agriculture, necessitates the development of new management approaches as legitimate means to improve water productivity. DSR is increasingly adopted and visible for the reduced input options and at higher resource efficiency (Kaur et al., 2024).

DSR refers to the practice of sowing rice seeds openly in the field instead of transplanting seedlings from a nursery. It can be implemented through three primary methods: Wet planting places sprouted grains on moist soil, water planting disperses them over standing water, while dry planting positions untreated grains in soil before irrigation. Like transplanted rice, DSR fields can be alternately flooded and controlled with regulated water regimes once germination and seedling establishment are attained (Bastola, 2020). Direct seeding of rice contributes approximately 23% of the world's rice production on approximately 29 million hectares, approximately 21%. Throughout the crop seasons, there were between 7.8 and 8.6 hours of sunlight each day, with September having the highest amount of sunlight, since that is the month when all cultivars are in their blooming stages.

3.2. Rice intensification (SRI) system

The SRI has drawn much interest as a cutting-edge water-saving technique to increase rice yield and guarantee food security. Despite the use of fewer seeds and water, proponents assert that the SRI method's combined effects of enhanced soil health, stronger root systems, and more robust rice plants result in significantly higher yields (Deb, 2020). SRI practices involve transplanting young seedlings individually with wider spacing to reduce plant density, managing soil moisture by keeping fields moist but not flooded to prevent hypoxic conditions, regularly removing weeds during early crop stages via a mechanical push-weeder instead of chemical herbicides, and prioritizing the application of organic fertilizers over chemical inputs (Thakur et al., 2023). In contrast, the SRI strategy aims to alter the above-ground and particularly below-ground conditions in which crop plants flourish. Instead of attempting to alter the current potential, crop management adjustments were made to take advantage of the genetic potential that already existed. Since SRI gained international recognition after 2000, it has undergone significant change. To improve smallholder production of irrigated rice, SRI was first conceptualized and introduced in terms of certain, often paradoxical, practices (Uphoff, 2023). Farmers, in collaboration with a growing network of civil society and scientific partners, have refined and expanded upon the original techniques. Supported by advances in agricultural sciences, SRI methods have been validated in more than 60 countries. As a result, much of the initial controversy has faded, and the approach has become an established part of modern agricultural practice. Moreover, larger-scale producers are increasingly adopting it for crops beyond rice.

3.3. Transplanted rice (TPR)

In the agricultural sciences, the TPR consistently records the highest plant height at harvest, primarily due to reduced competition for nutrients, sunlight, and space compared with the DSR and wet-direct seeded methods. The specific plant spacing in the TPR allows optimal solar exposure and improved root development, increasing nutrient uptake efficiency. Furthermore, repetitive tillage and standing floodwater in TPR suppress weeds and inhibit undesirable germination. In the agricultural sciences, many farmers adopt puddled TPRs to minimize water loss through percolation and ensure successful crop establishment. However, this method demands significant energy and water for wet tillage, especially in irrigated systems (Nazir et al., 2022). With mechanized land preparation replacing animal traction in rainfed systems, energy and fuel requirements have increased. Moreover, TPR during the monsoon season often delays subsequent 'rabi' cropping cycles, such as those of maize, due to extended field preparation and transplanting times (Hossain et al., 2020).

4. Overview of Rice Establishment Techniques

The ecological impact, water use efficiency, soil health, and crop performance are all assessed via agronomic and environmental studies. It encourages increased output, protects natural resources and enhances agricultural sustainability in the long term by informing farmers about sustainable agriculture, using their inputs wisely and making their activities less harmful to the environment.

4.1. Water use efficiency (WUE)

Water is valuable and essential in agricultural sciences because it helps with cell turgor and acts as a carrier of nutrients and hormones, as well as cooling water through the evaporation process, among other processes. Increasing the water yield, which is crucial, is one of the strategies to increase the water yield and includes enhancing the harvest index or even the transpiration efficiency. The first parameter of concern is the WUE or shell width of the grain with respect to the amount of water applied to the soil, which is a characteristic used to assess the performance of agricultural cultivars under different levels of soilwater and irrigation. During drought stress, WUE is reduced because transpiration increases and often limits yield (Hussain et al., 2022). To increase WUE in agricultural sciences, conservation tilling, mulching, precision irrigation and the planting of drought-producing cultivars are also methods that should be used. However, studies have shown that the greater the level of WUE is, the more difficult it becomes to maximize both parameters simultaneously, as further increases in yield often require more water inputs (Zhang et al., 2021). Table 1 shows that one of the key challenges in sustainable crop production continues to be generating high WUE values and high yields.

Table 1 Factors influencing water use efficiency (WUE) and associated studies.

Features	Description	Citation
Definition of WUE	Grain yield achieved per unit of water consumed.	(Hussain et al., 2022)
WUE Behavior under Stress	WUE generally decreases under drought due to increased transpiration and lower yield; drought-tolerant genotypes can maintain physiological activity and water use.	(Hussain et al., 2022)
Techniques to Improve WUE	Use of drought-tolerant cultivars, mulching, conservation tillage, and water-saving irrigation practices.	(Zhang et al., 2021)
Trade-off Between WUE and Yield	Higher WUE may limit yield improvement and vice versa; difficult to achieve both simultaneously.	(Zhang et al., 2021)
Critical WUE Limitation	After reaching a certain WUE threshold, further yield increases require disproportionate water inputs, making further WUE improvement challenging.	(Zhang et al., 2021)

4.2. Soil and nutrient dynamics

Soil nutrient dynamics refer to the different ways in which nutrients are available to plants and are attributed to the complex interactions among microbial processes, chemistry, and the physical nature of the soil. Examples of integrated practices that have been identified in recent agricultural science literature as a mechanism to increase nutrient use efficiency and limit environmental impact include precision agriculture, cover crops, and regenerative practices (Das et al., 2022). Farming methods like preservation tillage, crop rotation, and the request of organic amendments improve nutrient retention while minimizing losses caused by leaching or soil erosion. (Blesh et al., 2019). Anticipating nutrient use efficiency and long-term soil health potential through conservation methods (e.g., cover cropping, reduced tillage, biochar amendment) is viable (Lal, 2020). Current research in agricultural science clearly highlights the significance of belowground processes (the ability of deep-rooted plants to uptake underground nitrogen, or root bimodality), particularly as that trait is somehow ignored when it originates from nutrient management.

4.3. Weed and pest dynamics

Pest and weed linkages in agricultural science are determined to a greater extent by the interactions among agronomic, climatic, and ecological factors. Integrated weed and pest management (IWPM) strategies have been developed that incorporate biological control, crop rotation, precision agriculture, and targeted chemical control to manage the challenges of invasive and ephemeral species (Barzman et al., 2016). The primary concern is the use of integrated weed management (IWM), which involves the use of cover crops, mechanical methodsand the application of select herbicides. The use of cover crops reduces the number of weeds both prior to termination and after termination of the cover crops by forming a layer that effectively prevents the transmission of light and the growth of the seedlings. Other examples of rapidly developing digital solutions include ML and multispectral photography with drones (Yaseen & Long, 2024). The ecological maturity of the Push Pull system is illustrated through its ability to decrease scrounging weed-like strikes while simultaneously improving soil fertility and variety. This is accomplished by planting pest-drawing trap crops (such as Napier grass) ("pull") and pest-prevention plants (such as Desmodium) ("push") in between cereals.

4.4. Labor and mechanization needs

In the agricultural sciences, labor shortages and increasing wage charges have intensified the insistence on automation in agricultural operations. Mechanization not only decreases the dependence on manual labor but also enhances competence and appropriateness in farm activities. For example, automatic sowing and harvesting have considerably reduced the requirement for recurring labor and increased efficiency in cereal and horticultural crops (Jat et al., 2016). Mechanization is especially critical in regions facing the continuous outmigration of youth from rural areas to urban areas, leaving an aging populace in charge of physically difficult agricultural tasks (Paudel et al., 2020).

4.5. Aerobic rice system

This method employs aerobic rice varieties (developed for aerobic conditions) and appropriate system inputs and water management systems. Aerobic rice yields of 4 to 6 tonnes per hectare can be cultivated while only 50%-70% of the water used in conventional rice farming is used. This model is mostly recommended for areas where water is limited or expensive, while labor is limited and expensive. Table 2 provides information on the water productivity and WUE of aerobic rice cultivation.

Table 2 Summary of WUE and water savings during rice cultivation.

S.No	Season/Place	WUE/WP/% Water Saving	Reference
1	Hyderabad, India	Aerobic rice: 0.70 kg grain m^{-3} vs transplanted: 0.55 kg m^{-3}; ~50% water savings in sandy loam soils	(Ramulu et al., 2020)
2	UAS, Bangalore	WUE: 3.84 q $acre^{-1}$ inch vs traditional: 1.64; Economic WUE: ₹ 1643.54 vs ₹ 269.41 per acre-inch	(Thejaswi et al., 2021)
3	Chennai–Madurai region, Tamil Nadu (2024)	Under drip-irrigation + fertigation, aerobic rice achieved WUE of 3.84 kg ha^{-1} mm^{-1}	(Mariyappillai and Arumugam, 2024)

4.6. Water use and water productivity

In the field of agricultural sciences, the use of different village and crop establishment (TCE) methods revealed that rice (72%) consumed the highest proportion of water in the rice–wheat-greengram cropping system, followed by wheat (16%) and greengram (12%). Compared with traditional transplanting, the DSR production method results in a 6.8% reduction in water use (Mishra et al., 2021). The total amount of water utilized for rice varied from 10,808 m^3 in systems based on conservation agriculture (CA) to 11,963 m^3 in conventional systems versus SRI-driven practices. There was no discernible difference in water consumption between the TCE methods for summer greengram (1,749–1,994 m^3) and wheat (2,410–2,658 m^3). Interestingly, compared with the rice–wheat system, the system-level water productivity of the rice–wheat greengram sequence was significantly greater. This improvement is attributed to the addition of greengram, a leguminous crop that has high economic value and comparatively low water requirements. This highlights the importance of various cropping systems in sustainable agricultural science.

5. Discussion

While this study offers valuable insights into optimizing nitrogen and water use through integrated management strategies, its findings are limited by the controlled experimental conditions under which they were derived. The applicability of these strategies to variable agroecological zones, such as the diverse plains of India, remains uncertain because of differences in soil structure, irrigation access, and farmer practices (Santiago-Arenas et al., 2021).

The extensive focus on genetic improvements for DSR highlights promising traits for climate resilience and adaptability. However, the study emphasized laboratory-based and breeding-centered outcomes without fully addressing real-world constraints such as inconsistent water availability, weed management challenges, and socioeconomic adoption barriers that influence the feasibility of DSR in diverse field conditions (Negi et al., 2024).

This macrolevel investigation effectively decouples water usage from economic growth in the Yangtze River Economic Belt, offering a broader environmental policy lens. However, its regional specificity and economic modeling approach make direct application to agricultural water management in Indian plains tenuous, as it lacks crop-specific agronomic details and localized assessments of water productivity relevant to rice cultivation (Kong et al., 2021).

Although research on mat-type seedlings for mechanical transplanting presents practical stress-mitigation techniques, it primarily addresses nursery-phase improvements. It does not explore long-term impacts on crop performance posttransplantation or how such innovations integrate with water-saving field practices such as SRI or DSR. Moreover, its narrow scope limits insights into broader system-level sustainability (Tamanna et al., 2021). This study provides a comparative assessment of the DSR, SRI, and TPR methods for enhancing rice productivity and water use efficiency in plain regions. Unlike prior studies that focused on controlled environments, genetic traits, or macrolevel trends, our review emphasized field-level adaptability, site-specific practices, and the integration of technologies such as AWD and mechanization.

6. Conclusion

The review highlights that there is not one optimal rice establishment method applicable for all agricultural sciences. The alternative is a site specific, integrated method that incorporates both technological improvements and appropriate agronomic practices. Notably, DSR and SRI have considerable potential in sustainable systems, with all technologies being enhanced when combined with mechanization, training, and improved management practices. While the traditional TPR method may continue to play an important role, substantial changes will be necessary for its viability under climate change conditions. The review revealed that agroecological divergence, particularly with respect to soil, water availability, social and economic conditions, and the policy environment, can restrict the applicability (generalization) of the findings. Future emphasis should be placed on the development of mechanization, matching technologies with specific field conditions, and providing consumer-targeted extensions.

6.1. Limitations and future research

The process of adopting improved practices may be impeded by sociocultural acceptance, labor availability, and regional infrastructure limitations. For farmers to adopt sustainable rice establishment techniques, priority must be given to increasing the mechanization of practices, incorporating technologies appropriate for site conditions, and providing farmer-focused extension services.

Ethical Considerations

Not applicable.

Conflict of Interest

The authors declare no conflicts of interest.

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