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RESEARCH ARTICLE

Comprehensive and comparative analysis of various rice establishment methods: A review

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Abstract

Rice (*Oryza sativa* L.) is the most important staple food crop sustaining nearly two third of the world's population. However, rice cultivation faces several challenges, including the use of uncertified seeds, water scarcity, labor shortages and weed infestations. To address these issues, it is essential to adopt appropriate crop establishment methods that enhance growth and yield attributes of rice. In India rice is commonly grown by transplanting seedlings into the puddled soil. Although this method is widely practiced, it demands substantial labor, water, capital and energy making it less profitable which makes the farmers to shift towards direct-seeded rice (DSR). While DSR offers benefits in terms of labor and water savings, its adoption is hindered by poor seedling establishment and increased weed infestation. Under this situation, System of Rice Intensification (SRI) has emerged as a methodology that achieves higher seedling establishment rate (97.3 %) and also reduces water usage, enhancing weed control and increasing the total production. Despite of its advantages, SRI is laborious, requiring skilled workers for transplanting and it is time-consuming which delays the transplanting process. This situation highlights the need for mechanized rice transplanting, which facilitates timely planting and efficient crop establishment. Mechanization reduces labor, time, energy and production costs, ultimately enabling higher yields at a lower cost.

Keywords: conventional transplanting; dry seeded rice; mechanical transplanting; system of rice intensification

Introduction

Cereals, members of the family Poaceae are grasses cultivated for their edible grain components encompassing the endosperm, germ and bran (1). Among cereals, rice (*Oryza sativa* L.) holds paramount importance as a staple food, satisfying two-thirds of the world's inhabitants (2). According to projections by the Food and Agriculture Organization (FAO), it is anticipated that by 2050, we will need to increase food production by 60 % to adequately feed the global population of 9.3 billion (3). In India, rice is the most widely cultivated crop covering 46.27 million hectares, yielding 129.47 million tons with an average productivity of 2.79 t ha^{-1}. In Tamil Nadu, 2.21 million hectares are devoted to rice cultivation producing 7.90 million tons with a productivity of 3566 kg ha^{-1} (4). A substantial disparity exists between the potential and actual yield of rice in farmer's fields, which is primarily attributed to poor crop establishment methods (5). A variety of biophysical and socioeconomic factors, including climatic conditions, soil quality, social structure, labor availability, access to agricultural inputs and machinery and the economic status of farmers, have been identified as key determinants influencing the choice of crop establishment method in rice (6).

Several methods are employed for rice cultivation which include conventional transplanting (CT) direct seeded rice (DSR), system of rice intensification (SRI) and mechanical transplantation. Rice is predominantly cultivated as a wetland crop in lowland ecosystem by transplanting seedlings into puddled fields (7). Conventional transplanting offers several advantages, including improved soil aeration, enhanced nutrient availability and a favorable environment for optimal crop growth (8). The waterlogged condition associated with puddling help suppress weeds effectively and reduce competition for resources (9). Direct-seeded rice (DSR) involves sowing rice seeds directly into the field, eliminating the need for transplanting and offering several advantages over traditional methods (10). DSR is recognized as water-saving technology because it reduces the water required for puddling. According to the study direct seeded rice provides a resource-efficient and economically viable alternative to traditional transplanting (11). The System of Rice Intensification (SRI) is an innovative agricultural technology designed to maximize yield with minimal inputs (12). SRI has emerged as a valuable technology for economically needy farmers showcasing an almost twofold increase in yield compared to other methods. Moreover, SRI has increased crop resilience to various environmental stresses such as drought and flooding making it a sustainable choice for rice cultivation across diverse agro ecological settings (13).

Taking into account all the approaches despite their benefits, they come with drawbacks such as poor crop establishment, increased labor, costs, energy and time requirements (14). In response to these challenges, mechanized rice transplanting has been implemented with the goal of ensuring timely planting, improved crop establishment and cost -effectiveness in terms of labor, time and energy (15). Ultimately, this initiative aims to enhance rice yield by optimizing resource utilization and minimizing inputs.

Conventional transplanting

The conventional method for establishing rice involves transplanting rice seedlings in nurseries and further replanting into puddled soil. Conventional transplanting is the most common practice in lowland ecosystems. Of India's total land surface, about 44 % (19.6 million ha) is transplanted into the irrigated lowlands (16). Conventional transplanting techniques in puddled land account for 77 % of the world's rice production, especially in South and South East Asia (17). Amongst the diverse establishment methods, conventional transplanting achieved the highest grain yield compared to direct seeding. Furthermore, transplanting offers benefits such as consistent crop stand, enhanced weed control, uniform ripening and decreased lodging (18).

Effect of conventional transplanting on growth and yield attributes of rice

A field experiment conducted in Bangladesh reported that among various establishment methods, conventional transplanted rice recorded higher number of grains per panicle followed by wet seeded rice (19). Transplanted rice has maximum number of productive tillers (302 m^{-2}) following closely with drum seeded rice (294 m^{-2}) (20). It was reported that the yield of transplanted rice (8.54 t ha^{-1}) was nearly twice that of direct-seeded rice (5.78 t ha^{-1}) (21). Transplanted rice was recorded to produce the highest grain and straw yields of 5.54 t ha^{-1} and 6.43 t ha^{-1}, respectively, whereas direct-seeded rice recorded the lowest grain yield and straw yield of 3.13 t ha^{-1} and 4.54 t ha^{-1}, respectively (22). Conventional transplanting was recorded to result in greater grain yield (5.71 t ha^{-1}) compared to direct dry seeding (3.86 t ha^{-1}) and drum seeder direct seeding (4.98 t ha^{-1}) (6).

Advantages of conventional transplanting

Several advantages of transplanted rice in terms of crop management and yield enhancement have been identified (23). The advantages of conventional transplanted rice were asserted to include increased nutrient availability such as iron, zinc and phosphorus, along with effective weed control (24). Additionally, early crop establishment was noted as a significant benefit, as seedlings are pre-grown in nurseries before transplantation, leading to accelerated maturation. Precise water management was facilitated by flooding fields after transplantation, which aided in weed and pest control while optimizing nutrient availability (25). The reduced seed rate required for transplantation was reported to not only lower seed costs but also enhance resource utilization. Conventional transplanting was declared to be the most prevalent method among farmers, as it yielded reasonably higher results than direct seeding despite demanding more labor and energy (26). Although labor-intensive, with labor requirement ranging from 72 to 79 laborers, transplanting remained the predominant method of rice production.

Constraints in adopting conventional transplanting

Conventional transplanting was explicitly stated to remain a viable method for cultivating rice, despite being characterized by its tedious, labor-intensive and time-consuming nature, involving difficult tasks and facing challenges such as labor shortages and high costs during peak agricultural periods (27). Since labor is not readily available in a timely manner it creates higher transplantation expense and delays the transplantation. Transplanting requires approximately 250-300 man-hr per hectare, constituting roughly 25 % of the total labor needed for the crop (28). Of all water present on the planet about 70-80 % is utilized in agriculture primarily for irrigation, due to the high water demands of crop production and livestock management. with increasing water scarcity, efficient practices like drip irrigation and rainwater harvesting have become essential for sustainability. rice accounts for 85 % in total and 30 % specifically in puddling (29). It was reported that the conventional transplanting system requires approximately 2500 L of water to produce 1 kg of rice (23). Repeated puddling has detrimental effects on soil physical properties by disrupting soil aggregates, reducing subsurface permeability and forming shallow hardpans all of which can deleteriously impact subsequent non-rice upland crops in rotation (30). In Asia, manual rice transplanting primarily performed by women, often exposes them to occupational hazards. Challenges such as insufficient irrigation water, shortage of labor during the peak transplanting period and rising labor costs contribute to the increased expense of the transplanting technique leading to delayed and reduced yields ultimately affecting profitability (31).

Direct seeded rice

Global cultivation of traditional rice is expected to decline due to water and labor constraints. Consequently, it is recommended to promote alternative transplanting methods to improve both crop and water productivity (32). Direct seeded rice (DSR) involves initiating a rice crop directly from seeds sown in the field using suitable methods bypassing the transplantation of seedlings from a nursery and is currently practiced in roughly 21 % of the total rice area in Asia (33). There are three primary approaches for implementing the direct seeded rice: dry seeding, wet seeding and water seeding. Wet direct seeded rice is typically adopted in situations of labor scarcity and is currently practiced in countries such as Malaysia, Thailand, Philippines and Sri Lanka (34) Drum seeding involves the direct sowing of pre-germinated paddy seeds in a puddled and leveled field after draining excess water, engaging equipment known as a drum seeder (35). Though wet direct seeded rice is predominantly accepted in many parts due to increasing water shortages, there is a growing impetus to develop and adopt dry direct seeded rice. Dry seeding encompasses sowing seeds into a prepared seed bed under unpuddled and unsaturated soil conditions through methods like broadcasting, drilling or dibbling (36). In the case of water seeding which is suitable for high rainfall areas seeds are sown in standing water on fields with prepared ridges and furrows before submergence and it is extensively practiced in the United States, primarily for weed management especially challenging varieties like weedy rice (37).

Effect of direct seeded rice on growth and yield attributes of rice

Direct-seeded rice was reported to initiate tillering at an earlier stage compared to transplanted rice, as it experienced uninterrupted growth without setbacks caused by uprooting injury to seedling roots (9). Greater growth parameters and a higher number of productive tillers were reported in direct-seeded rice, whereas puddle transplanted rice methods showed higher panicle length and test weight (38). Rice plants grown through drum seeding were specified to demonstrate higher dry matter accumulation, comparable to plants grown by manual and mechanical transplanting (31). The highest number of productive tillers (336 m^{-2}) was attained by direct-seeded rice, surpassing the count in manually transplanted crops (229 m^{-2}) (39). A significantly higher number of productive tillers (271 m^{-2}) was asserted in direct-seeded rice compared to conventional transplanting (247 m^{-2}) (40). Direct-seeded rice was conveyed to produce a significantly greater number of panicles per unit area (429 m^{-2}) compared to transplanted rice (248 m^{-2}) (33). Wet direct-seeded rice using a drum seeder was registered to yield the highest grain and straw yields, comparable to transplanting, with values of 4.2 t ha^{-1} and 6.5 t ha^{-1}, respectively (41). Significantly greater grain yield (5.3 t ha^{-1}) was perceived in direct-seeded rice, showing superiority over transplanted rice (4.1 t ha^{-1}) (19).

Advantages of direct seeded rice

Multiple advantages of direct seeding of rice for both farmers and the environment have been identified compared to traditional puddling and transplanting (42). One notable benefit was the substantial reduction in water consumption by approximately 30 %, achieved by eliminating the need for raising seedlings in a nursery, puddling, transplanting in puddled soil and maintaining a water depth of 4–5 inches at the base of transplanted seedlings (43). Direct-seeded rice was reported to avoid transplanting shock, reducing growth delays and promoting earlier physiological maturity, thereby decreasing vulnerability to late-season drought. Rice established by dry seeding was observed to develop 7–10 days earlier than conventional transplanted rice (44). Additionally, lower methane emissions were exhibited by direct-seeded rice, providing an opportunity for farmers to earn carbon credits compared to the traditional puddling and transplanting system. Direct-seeded rice was expressed to offer higher economic returns, faster and simpler technology, reduced labor and water requirements, shorter crop duration and lower methane emissions (19). Although transplanted rice may yield more than direct-seeded rice, the net return and benefit-cost ratio were reported to be higher for direct-seeded rice (45). A higher benefit-cost ratio was found in dry-seeded rice with a drum seeder (1.70) compared to transplanting after puddling (1.54) (9).

Constraints in adopting direct seeded rice

Although direct-seeded rice (DSR) offers advantages in labor, water, energy and cost savings, its adoption has been limited due to lower yields attributed to challenges such as poor seedling establishment and high weed infestation (38). The primary issues affecting direct-seeded rice and contributing to its low yield were emphasized to include poor crop establishment, weed dominance, pest-related problems and lodging (46). Furthermore, micronutrient deficiencies, particularly in zinc (Zn) and iron (Fe), owing to imbalanced nitrogen fertilization and high infiltration rates in DSR, were reported to pose significant concerns (47). The impact of unchecked weed growth on grain yield loss in direct-sown rice was found to range from 18.2 % to 59.2 %, with this effect being more pronounced when nitrogen fertilizer was applied (48). The yield in DSR was frequently reported to be lower than that of transplanted rice due to factors such as poor crop stand, higher percentage of panicle sterility and increased incidences of weed and root knot nematode infestations (7). The possibility of yield loss in DSR was recorded to be considerably higher, ranging from 50 % to 91 %, compared to conventional transplanted rice (49).

System of rice intensification (SRI)

Various technologies are being accepted to reduce the water requirement for rice cultivation in India. One such method is the System of Rice Intensification (SRI), which holds the potential to enhance water and land productivity by using less water while simultaneously boosting production level (50). SRI was initially developed by Henri de Laulani in Madagascar during 1980's with the aim of establishing sustainable agricultural practices leading to higher productivity, optimal utilization of capital and labor, reduced input costs and decreased water demand (51). Recent studies on rice cultivation highlighted an ongoing increase in the demand for water, particularly in the eastern region (52). In such circumstances, there is an emerging necessity for strategies that can generate higher rice yields with reduced water usage and lower expenses. The System of Rice Intensification has emerged as a favorable option for farmers under these conditions (53). SRI involves the integration of various agronomical cultivation practices such as reducing plant population, transplanting a single young seedling per hill, adopting wider square planting, utilizing mechanical weeding with cono weeder and incorporating the leaf color chart (LCC) for improved nitrogen management resulting in increased yields (54). A key factor contributing to enhanced crop growth and productivity in SRI is the implementation of intermittent irrigation with alternating wet and dry intervals, in this method seedlings are rapidly transplanted within 15-30 min of gently removing them from the nursery and they are delicately planted at a depth of only 1-2 cm (55).

Effect of SRI on growth and yield attributes of rice

Key yield parameters, including the number of productive tillers, spikelets, test weight and total grain yield, were found to exhibit higher values in the system of rice intensification (SRI), making it more productive and economically profitable than the conventional transplanting system (56). A significantly higher number of productive tillers (376 m^{-2}) was recorded under the SRI method of cultivation, followed by the conventional transplanting system (328 m^{-2}) (51). A substantial increase in the number of fertile tillers (167.5 %), filled grains per panicle (29 %), spikelet fertility (6.4 %) and test weight (1.7 %) was documented under SRI in Maruteru, Andhra Pradesh, during the dry season, compared to the conventional transplanting system (57). Crop establishment using SRI was noted to achieve the highest leaf area index (4.17) compared to the traditional transplanting method (3.18) (58). SRI was perceived to result in a grain yield of 6.7 t ha^{-1} and water use efficiency of 6.75 kg ha^{-1} mm^{-1}, compared to the conventional method which had a grain yield of 6.1 t ha^{-1} and similar water use efficiency (59). Higher grain yield under SRI planting (5.76 t ha^{-1}) was revealed compared to conventional transplanting (4.38 t ha^{-1} and drum-seeded rice (4.21 t ha^{-1}) (60). Significantly higher seed yield (2.94 t ha^{-1}) was opined under the SRI method compared to the traditional method (2.37 t ha^{-1}) (61).

Advantages of SRI

SRI method for paddy cultivation offers numerous compensations contrasting to the traditional system. It requires lower seed and water quantities and exhibits a lower incidence of pests and diseases correlate to the conventional approach while also yielding significantly higher results (10). SRI has proven to be a boon for economically needy farmers due to its nearly two-fold increase in yield compare to the traditional transplanting methods, requiring fewer inputs such as water, fertilizers, seeds and labor (54). In SRI a single plant exhibits greater root-pulling resistance (RPR) associated to clumps of multiple rice plants grown through traditional transplanting methods (62). The seed requirement is significantly reduced in SRI, with only 4-10 kg of seeds needed per hectare, as opposed to the minimum of 100 kg in broadcasting and 30-60 kg in transplanting (63). Water savings with SRI have been calculated at 40 % in Indonesia, 67 % in the Philippines and 25 % in Sri Lanka (64). SRI recorded the highest seedling establishment percentage after transplanting at 97.3 %, a significant difference from the conventional methods which is 81.7 %. This improved seedling establishment is primarily due to gentle handling and early-stage transplanting, which minimizes root shock stated that 52.7 % reduction in the use of irrigation water compared to transplanted rice (52). SRI not only increases rice production in a sustainable manner but also enhances crop resilience to climate change and variability (65).

Constraints in adopting SRI

While the System of Rice Intensification (SRI) holds promise in improving water and land productivity in rice cultivation, it comes with certain drawbacks (66). Besides these challenges such as a high labor requirement and issues encountered during the transplanting of young seedlings limit its application (67). SRI necessitates careful and hands- on management of individual plants, including transplanting younger seedlings and frequent weeding, making it more labor-intensive compared to conventional rice cultivation methods (68). A major barrier to widespread adoption of SRI is the lack of skilled labor, particularly for managing cono weeders (69). Moreover, awareness gaps, scarcity of skilled labor and challenges in nursery management pose significant obstacles to SRI production (70). Additionally, the effectiveness of SRI is contingent on specific soil conditions and its applicability may vary across different agroecological contexts (54). These limitations underscore the importance of thoughtful adaptation and consideration of SRI practices based on local farming conditions and available resources (71).

Mechanical transplanting

Rice cultivation necessitated a notable investment of labor, water and energy resources. In India, rice was typically cultivated through the transplantation of seedlings in puddled fields. A delay in transplantation by one month leads to a 25 % reduction in production, while a delay of two months resulted in a 70 % reduction in yield (7). Approximately one-third of the total manpower required for rice production was assigned to land preparation and transplanting (72). Hence, a need was identified for cost-effective, labor-saving rice transplanting methods that maintain grain yield. The adoption of mechanical transplanting was reported to reduce labor needs and ensure the timely completion of crop establishment operations. Mechanical transplanting involved the transplantation of young rice seedlings using a rice transplanter. Favorable outcomes with mechanical transplanters were conveyed, where three man-days were sufficient to transplant one hectare compared to 33 man-days in the traditional transplanting system (73). The efficiency of machine transplanting was influenced by various factors, including the method of cultivation, nursery management, variety selection and seeding density. Among these, seeding density in mat-type nurseries played a crucial role in determining seedling quality, plant establishment and the percentage of missing plants after transplantation (74). Mechanical transplanting was delivered as an encouraging option for achieving maximum yield by ensuring timely planting and achieving the ideal plant population. The implementation of mechanized transplantation was described to have benefits such as reducing seedling age by half, seed requirements by 50 % and labor needs by 60 %, leading to a 27 % reduction in production costs and a 36 % increase in profit per hectare (75).

Effect of mechanical transplanting on growth and yield attributes of rice

The utilization of mechanical transplanters was reported to ensure uniform depth and spacing of seedlings during transplantation, facilitating faster seedling establishment and production of a greater number of tillers (23.0 tillers hill+), which in turn led to a 30–35 % higher yield compared to conventional transplanting (70). Mechanical transplanting resulted in a higher number of tillers (325 m^{-2}) compared to direct seeding (295 m^{-2}) (76). The highest leaf area index (4.14) was recorded in mechanical transplanting, whereas manual transplanting recorded a slightly lower value of 3.78. Mechanical transplanting was perceived to yield greater dry matter production compared to direct seeding and conventional transplanting at harvest stages (77). Employing mechanical rice transplanters for seedling transplantation resulted in a yield increase of 9-14 % compared to the conventional transplanting system (78). The use of CRRI four-row manual transplanters with mat seedlings recorded a grain yield of 4.1 t ha^{-1} and reduced transplanting costs to ₹1570 ha^{-1} compared to manual transplanting. Fields transplanted using an eight-row manual transplanter and VST eight-row self-propelled rice transplanter achieved grain yields of 4.95 t ha+ and 4.62 t ha^{-1}, respectively, compared to 4.18 t ha^{-1} with conventional transplanting. Machine transplanting was asserted to result in a higher rice yield of 5.05 t ha^{-1}, while drum-seeded rice recorded the lowest yield at 4.12 t ha^{-1} (79).

Advantage of mechanical transplanting

Mechanical rice transplanting emerges as a viable and promising alternative, offering labor savings, ensuring timely transplantation and contributing to higher grain yieldswhile a manual laborer can transplant around 700 m^2, a rice transplanter has the capacity to transplant 10000 m^2 per day (70). The requirement for mechanical transplantation is 2-3 man-days per hectare significantly less compared to the 25 man-days per hectare needed for manual transplantation. In comparison to manual transplantation, the mechanical approach can save 61 % in labor and reduce expenses by 18 % (80). Advantages of mechanical transplantation were asserted to include the reduction of time and labor expenses, ensuring consistent plant spacing and maximum plant density by placing two to three seedlings per hill and avoiding shock from seedling movement. Embracing mechanical transplanters was noted to provide a successful alternative to other establishment methods, resulting in savings in cost, energy, time and labor while also offering the advantage of higher grain yield (81).

Constraints in adopting mechanical transplanting

A significant obstacle is the initial investment cost required for obtaining and maintaining the necessary machinery, which may be financially burdensome for small-scale farmers. The adoption of mechanical transplanters was noted to face hindrances due to the time and labor involved in establishing high-quality mat-style nurseries in frames or fields. Although mechanical transplanting offered labor and cost savings, it was identified to be predominantly limited to affluent farmers who could afford such machinery (82). Additionally, the operation and maintenance of such technology demand specialized skills, presenting a barrier activity, including training on agricultural farm machinery further exacerbates the issue, as farmers remain unaware of the benefits offered by rice transplanters (83). Overcoming these challenges entails not only making the technology more accessible but also providing comprehensive training and support to ensure its successful implementation in various agricultural contexts (84).

Conclusion

The adoption of appropriate crop establishment methods is crucial for optimizing rice growth, development and yield. Among the most commonly used methods conventional transplanting, direct seeding and the System of Rice Intensification (SRI) offers advantages, they also present challenges, particularly in terms of labor intensity, water usage, weed management and energy consumption. As agriculture modernizes and shifts toward resource-efficient practices, mechanical transplanting has emerged as a promising alternative, addressing many of the challenges associated with traditional methods. Mechanical transplanting offers several advantages that make it appealing for farmers aiming to increase productivity while lowering input costs. By using machinery to transplant seedlings, farmers can reduce the demand for manual labor, a significant benefit in areas experiencing labor shortages, especially during peak agricultural seasons. Research shows that mechanical transplanting improves energy efficiency and can lead to higher grain yields, with recorded yields reaching up to 5.8 t ha^{-1}. The net return for farmers using this method can be as high as ₹33152 per hectare, making it a financially viable option for small and marginal farmers (SMFs) (Fig. 1, 2 & 3). Additionally, the method ensures uniform plant spacing, which improves weed control, optimizes plant growth and reduces energy consumption (Table 1). However, the adoption of mechanical transplanting is hindered by several challenges, particularly the lack of hands-on training for farmers. Establishing nurseries for mechanical transplanters requires careful planning and management, which can be time-consuming. Despite these hurdles, the benefits of mechanical transplanting in terms of cost savings and increased productivity make it a promising alternative to traditional methods.

To support the adoption of mechanization, especially among SMFs, the government has introduced the Sub-Mission on Agricultural Mechanization (SMAM). This initiative aims to bridge the gap between technology and farming practices by making machinery more accessible and affordable. SMAM focuses on establishing Custom Hiring Centers (CHCs) where farmers can rent machinery, creating specialized hubs for advanced farm equipment and setting up Farm Machinery Banks. These efforts help SMFs access modern agricultural tools without the financial burden of ownership. In addition to providing access to machinery, SMAM promotes skill development and hands-on training, ensuring that farmers can use the equipment effectively. The initiative also provides subsidies for purchasing farm equipment, further easing the financial strain on farmers. By equipping farmers with the necessary skills and tools, SMAM enhances the overall efficiency and sustainability of rice farming practices. In conclusion, mechanical transplanting offers a viable solution to the challenges of conventional rice establishment methods. It delivers significant benefits in terms of cost, labor, energy savings,and increased yields. With initiatives like SMAM, small and marginal farmers are empowered to adopt mechanization, making rice farming more productive, sustainable and economically viable for the future.

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Authors' contributions

VK performed conceptualization and data curation and drafted the original manuscript. RT contributed to conceptualization, provided supervision, acquired funding and participated in writing, reviewing and editing the manuscript. MB assisted in drafting and editing the original manuscript. VA provided resources and contributed to visualization. YR developed the methodology and assisted in writing, reviewing and editing the manuscript. DSK assisted in writing, reviewing and editing the manuscript.

Compliance with ethical standards

Conflict of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

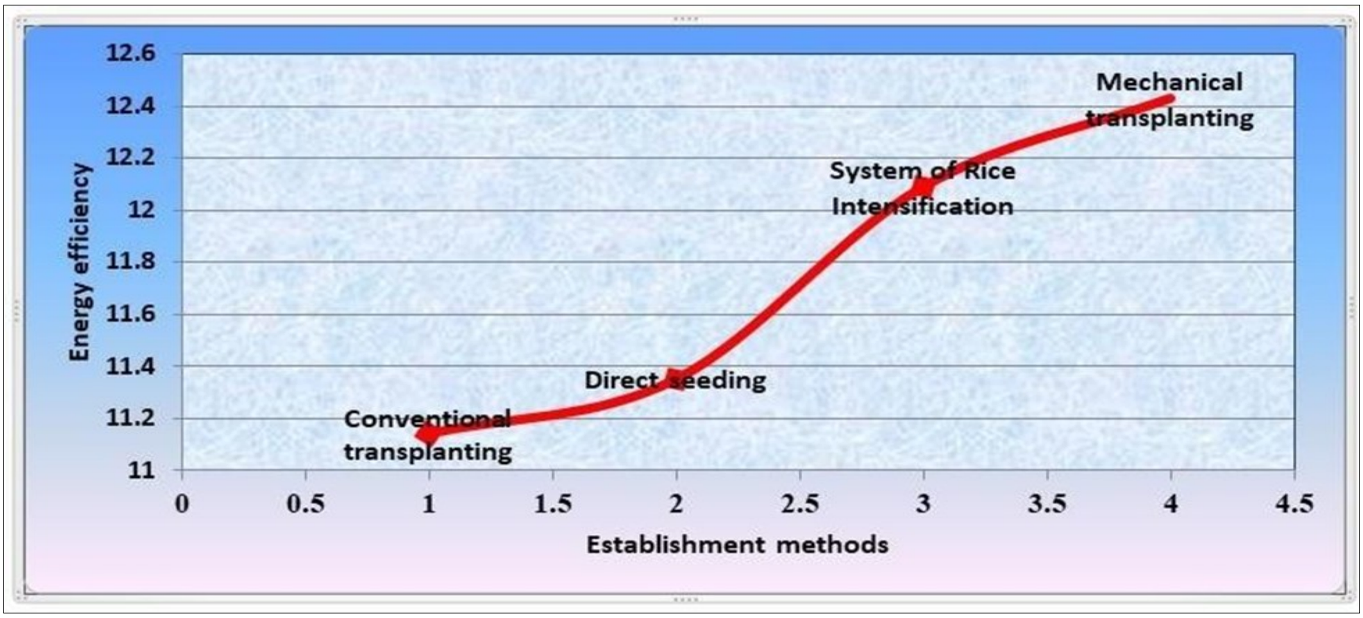

Fig. 1. Effect of different establishment methods on energy efficiency of rice.

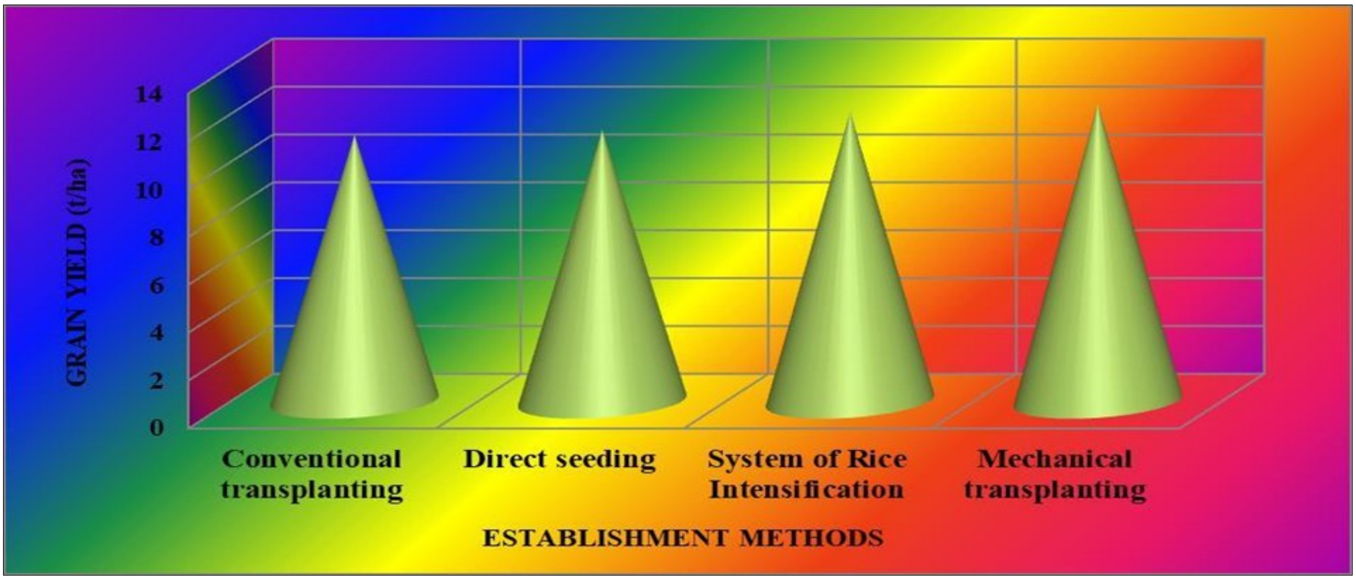

Fig. 2. Effect of different establishment methods on grain yield of rice (kg ha $^{-1}$).

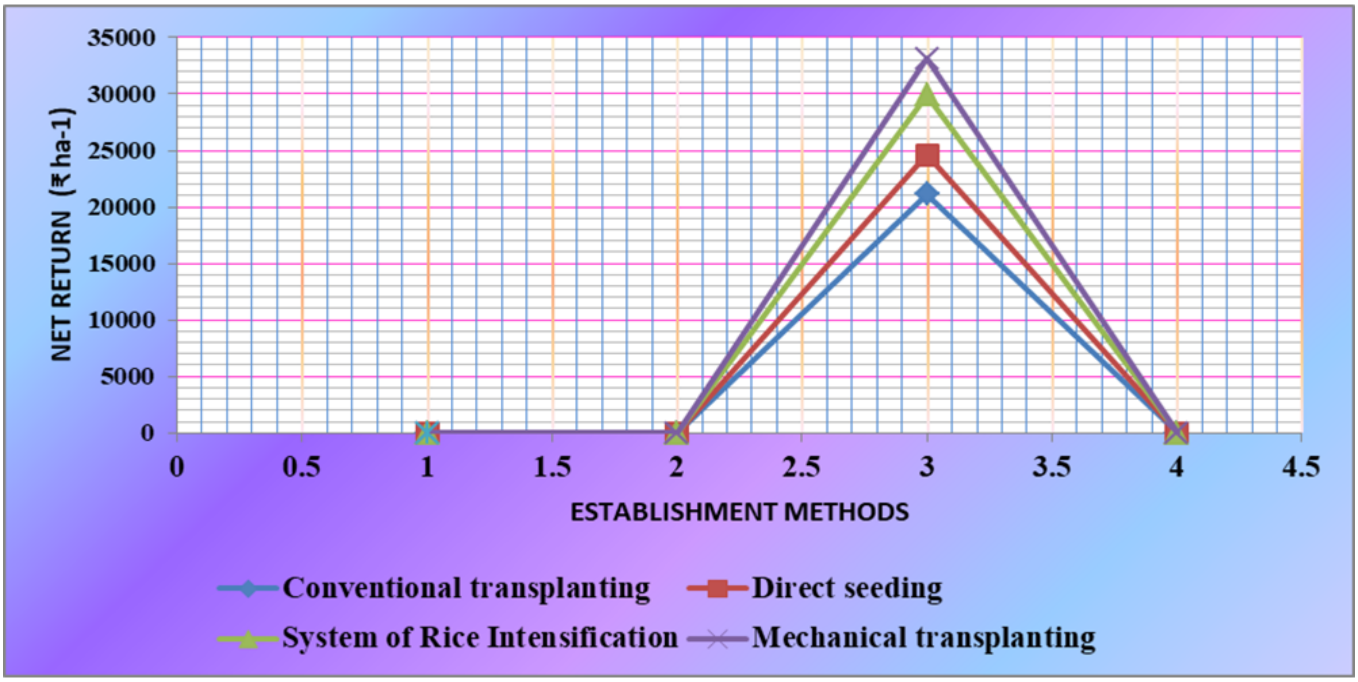

Fig. 3. Effect of different establishment methods on net return of rice (₹ ha $^{-1}$).

Table 1. Comparative analysis of different rice establishment methods

S. No.	Establishment Method	Energy Efficiency (%)	Weed Control Efficiency (%)	Yield Increase (%)	Key Findings	Reference
1	Conventional Transplanting	Baseline	70 %	Baseline	Conventional transplanting is widely practiced but labor-intensive, requiring significant manual effort for planting. Energy inputs are also higher due to repeated puddling and manual labor. While it offers uniform crop growth and good weed control, the cost of labor and energy use can be limiting factors, especially in regions facing labor shortages. Mechanical transplanting is emerging as an alternative to reduce these challenges.	(19)
2	Direct-Seeded Rice (DSR)	20 % reduction	30-40 %	5-8 %	Direct-seeded rice is an efficient method that reduces water and labor requirements compared to conventional transplanting. DSR can achieve moderate yield increases, but weed management is more challenging because the absence of puddling gives weeds a favorable environment. However, the technique is gaining popularity in regions where water availability is a constraint.	(34)
3	Wet Direct Seeding	15 % reduction	35 %	7-9 %	Wet direct seeding offers faster crop establishment compared to conventional methods, with moderate yield increases. Weed control remains a challenge, though slightly better than dry direct seeding. This method is commonly used in areas with timely water availability. Weed management strategies such as herbicide application and the use of specific weed control measures are essential to maximize its benefits.	(19)
4	Dry Direct Seeding	15 % reduction	25-35 %	6-7 %	This method is effective in drought-prone regions where water for puddling may not be available. Dry direct seeding allows early establishment of crops, which can be beneficial under rainfed conditions. However, due to poor weed control, yields are generally lower compared to wet seeding methods. Proper weed management techniques, such as herbicide usage and mechanical weeders, are necessary for better crop productivity.	(52)
5	System of Rice Intensification (SRI)	25 % increase	75 %	15-20 %	The System of Rice Intensification is a widely recognized method that emphasizes planting fewer, younger seedlings and maintaining wider spacing between plants. It leads to reduced water usage, lower energy inputs and increased yields. The system enhances root growth and overall plant vigor, making crops more resistant to stress. The technique is environmentally sustainable but requires precision in water management, weed control and labor input.	(59)
6	Mechanical Transplanting	30 % reduction	65-75 %	20-22 %	Mechanical transplanting significantly reduces labor requirements by utilizing machinery for seedling transplantation. This method achieves better uniformity in plant spacing, which not only enhances weed control but also results in improved crop growth and higher yields. Additionally, the energy savings and reduced labor inputs make this method highly attractive, especially for small and marginal farmers in regions facing labor shortages. Mechanical transplanting is promoted under government initiatives, such as the Sub-Mission on Agricultural Mechanization (SMAM), which facilitates access to farm machinery for small farmers.	(70)

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