Agric Res J **61** (1): 128-133, *February* 2024
DOI: 10.5958/2395-146X.2024.00018.8

COMPARATIVE ANALYSIS OF RICE ESTABLISHMENT METHODS: IMPACT ON PLANT GROWTH, ROOT DEVELOPMENT, AND GRAIN QUALITY

Sayam Padma[1], S Vijayakumar[2,3,*], Varunseelan Murugaiyan[3], R Gobinath[2], Mangal Deep Tuti[2], S Jasudas Gompa[2], K Basavaraj[2] and T Ramesh[4]

[1]*Professor Jayashankar Telangana State Agricultural University, Hyderabad-500 030, India*
[2]*ICAR-Indian Institute of Rice Research, Hyderabad-500 030, India*
[3]*International Rice Research Institute, Los Banos-4031, Philippines*
[4]*TNAU-Anbil Dharmalingam Agricultural College and Research Institute, Trichy-620 027, India*

Rice is of immense significance as one of the world's primary crops, serving as the main staple food for more than half of the world's population. Asia, in particular, leads in rice production, accounting for 92% of the world's output and 90% of global consumption, driven by its sizeable population and agricultural activities. In recent years, climate change, including global warming, has led to noticeable shifts in regular climate patterns. Changes in rainfall patterns, such as delayed monsoon onset and early cessation of rains, have impacted rice cultivation (Vijayakumar *et al.*, 2021; Vijayakumar *et al.*, 2023), disrupting critical growth stages and resulting in unfavorable conditions and reduced yields. These climate-related challenges emphasize the need to sustainably increase rice production to match the needs of the growing population. Moreover, the emission of methane from lowland paddy fields with standing water adds to the global warming potential. Water scarcity is a pressing issue, particularly in regions where rice cultivation requires significant irrigation (Mallareddy *et al.,* 2023). Producing more rice while using less water has become a crucial goal for ensuring food, economic, social, and water security (Vijayakumar *et al.*, 2018).

Conventional methods of rice cultivation are encountering limitations in meeting the increasing demand. Consequently, alternative rice production techniques such as Direct Seeded Rice (DSR), Alternate Wetting and Drying (AWD), and the System of Rice Intensification (SRI) have emerged (Guru *et al.,* 2017). These methods aim to reduce irrigation water requirements and enhance water use efficiency compared to conventional puddled transplanted rice (Vijayakumar *et al.*, 2022a). The root system of rice plants plays a crucial role in nutrient and water absorption, anchoring the plant, and interacting with soil microbes. Assessing the effect of different establishment methods on root parameters, such as length, volume, and dry weight, can offer insights into the vitality and functionality of the root system, thereby influencing plant performance and productivity. Rice quality is a key determinant of consumer preference and market value. Evaluating the influence of different establishment methods on quality parameters, including hulling, milling, amylose content, and head rice recovery, empowers farmers and stakeholders to make informed decisions to meet market demands and ensure consistent quality standards. Rice growth, yield attributes, root parameters, and quality parameters vary across diverse production systems. Understanding how different establishment methods affect growth parameters, yield attributes, and root development aids in identifying strategies to optimize production and maximize yields. In light of these considerations, this study aimed to evaluate the effects of different rice production systems on rice growth, root parameters, and quality.

The field experiment was conducted during the *kharif* season of 2022 in the experimental area of ICAR-Indian Institute of Rice Research, Rajendranagar, Hyderabad. The experimental site is located at 17°19' N latitude and 78°23' E longitude, at an altitude of 542.3 meters above mean sea level. The soil at the experimental site was classified as sandy clay loam with a moderately alkaline pH of 8.15. It had a medium organic carbon content of 0.62% and an electrical conductivity of 0.33 dS/m. Nitrogen availability in the soil was low at 184.5 kg/ha, while phosphorus and potassium were present at medium levels, measuring 23.5 kg/ha and 292.5 kg/ha, respectively.

Throughout the growth period, the crop experienced a total rainfall of 891.6 mm, occurring over 51 rainy days. The cultivar used for the experiment was 'DRR Dhan-42'. The experiment employed a randomized block design with three replications and seven treatments, namely: System of Rice Intensification (T_1), Mechanical Transplanting and Weeding (T_2), Wet Direct Seeded Rice (drum seeding) (T_3), Wet Direct Seeded Rice (broadcasting) (T_4), Conventional Transplanting (T_5), Dry Converted Wet Rice (broadcasting) (T_6), and Dry Converted Wet Rice (line sowing) (T_7). In the dry converted wet rice treatments (T_6, T_7), irrigation was

*Corresponding author: vijayakumar.s@icar.gov.in
Date of receipt: 04.08.2023, Date of acceptance: 20.02.2024

provided for the first 40 days similar to that of dry crops, after which the water level was adjusted to mimic wet direct seeding conditions. For further details on the standard cultural management practices followed during the crop period, please refer to Padma *et al.* (2023).

Five rice plants were randomly selected and individually labeled in the net plot area for biometric measurements. Plant height, measured from the base to the tip of the longest leaf, was recorded using a meter scale at four growth stages: active tillering, panicle initiation, flowering, and physiological maturity. The average height of five plants was calculated and expressed in centimeters. To estimate leaf area, five plants were randomly uprooted from the main plot area at each growth stage. To prevent leaf rolling, the uprooted plants were placed in water. Subsequently, the leaves were carefully detached from the plants and cleaned using de-ionized water. Any excess moisture was gently removed by wiping the leaves with tissue paper. The leaf area meter was then utilized to measure the area of fresh green leaves, expressed in square centimeters per plant (cm^2/plant). The Leaf Area Index (LAI) was calculated using the standard formula given by Watson (1952).

$$LAI = \frac{\text{Leaf area (cm}^2\text{)}}{\text{Ground area (cm}^2\text{)}}$$

Following the LAI measurement, the plant samples underwent shade drying for 5-7 days, followed by oven-drying at 65°C for 24 hours. After the drying process, the dry weights of the five plants were recorded and converted to kilograms per hectare (kg/ha) for subsequent analysis. Within the net plot area, one square meter of land was designated to count the number of tillers and productive tillers in each treatment at 90 days after sowing (DAS). Additionally, the number of days required from sowing to reach the active tillering phase, 50% of the plants starting flowering, physiological maturity, and harvest maturity in each treatment were recorded and reported in terms of days. For the root parameter study, three seedlings per plot were carefully selected and uprooted at the flowering stage. The roots of the seedlings were gently washed with fresh water to remove any soil particles. The length of the roots was measured using a centimeter scale. Subsequently, the roots and shoots were separated, and the root volume was measured using a 1000 ml measuring cylinder. The roots were then dried in an oven at 60°C for 3 days to obtain the root dry weight (RDW).

Standard procedures were followed for the assessment of hulling, milling, and head rice recovery (Vijayakumar *et al.*, 2022b). Additionally, the amylose content, a pivotal determinant of rice quality, was determined following the method outlined by Blakeney *et al.* (1994). Standard formulae were employed to calculate hulling, milling, and head rice recovery. The collected data were subjected to analysis using the ANOVA procedure in OPSTAT (http://14.139.232.166/opstat/) (Gomez and Gomez, 1984). The comparison of treatment means was made using the critical difference (CD) at $p \leq 0.05$.

Significant variations in plant height were observed across different stages among the various rice establishment methods. Wet DSR (drum seeding) consistently displayed the highest plant heights at active tillering, panicle initiation, flowering, and physiological maturity stages (Table 1). On the other hand, conventional transplanting exhibited significantly lower plant heights at active tillering and panicle initiation stages, while dry converted wet rice (broadcasting) showed the lowest plant heights at the flowering and physiological maturity stages. These differences in plant height could be attributed to the initial transplanting stress experienced by the transplanted treatments. Notably, during the flowering and physiological maturity stages, conventional transplanting displayed notably higher plant heights compared to other methods.

Among the direct seeding treatments, wet DSR (drum seeding) and dry converted wet rice (line sowing) demonstrated superior performance over other treatments in terms of plant height. This could be attributed to favorable conditions for seedling establishment, absence of transplanting shock, lower competition for growth resources, improved light penetration, and enhanced aeration. These techniques create favourable environments for seedling development, allowing them to efficiently utilize available resources. In contrast, the lower plant height observed in DSR broadcasted methods can be attributed to the uneven distribution of plants across the field. The inconsistent seed dispersion during broadcasting contributes to this uneven distribution, leading to unequal access to resources and subsequent disparities in plant height.

In the conventional transplanted rice method, stagnant water effectively suppressed weed growth and minimized competition for growth resources between weeds and rice plants. Similarly, the SRI approach, with its wider spacing and cono-weeding practices, successfully suppressed weed growth, resulting in improved plant growth by facilitating root development and enhancing organic matter incorporation into the soil. However, in the case of mechanical transplanting, despite implementing cono-weeding, plant height was relatively lower. This could be attributed to the limited effectiveness of the one-way cono-weeding approach, which primarily targeted spaces between rows while neglecting weed control within rows. Weeds that

Table 1. Effect of rice establishment methods on plant height, leaf area index (LAI) and dry matter accumulation (DMA)

Treatments	Plant height (cm)				LAI			DMA (kg ha^{-1})				Root length (cm)	Root volume (cc/hill)	Root dry weight (g/ hill)
	AT	PI	F	PM	AT	PI	F	AT	PI	F	PM			
T_1	49.4	65.9	102.9	116.5	1.79	3.32	4.46	2698	4274	7087	11970	24.9	48.1	7.4
T_2	48.8	59.0	89.2	100.1	1.35	3.10	4.10	2568	3952	6856	10741	21.8	36.1	5.1
T_3	58.3	78.4	115.8	122.5	1.84	3.4	4.54	2854	4316	7615	12148	24.8	38.9	6.7
T_4	52.3	65.1	92.2	104.6	0.88	2.29	3.11	1956	2985	5962	9470	23.4	26.7	4.1
T_5	47.1	50.1	104.2	111.8	1.08	3.03	4.07	2086	3684	6359	10702	21.9	36.7	5.2
T_6	50.9	64.5	85.5	98.1	0.79	2.02	2.94	1907	2908	5930	9338	23.9	30.6	4.9
T_7	55.3	74.3	102.5	112.8	1.74	3.25	4.23	2756	4251	7240	11413	25.9	49.4	7.2
SEm (±)	2.0	2.7	6.2	5.1	0.07	0.18	0.17	94.88	157.56	263.53	461.1	0.95	1.45	0.34
CD ($p \leq 0.05$)	6.3	8.2	19.1	15.8	0.20	0.55	0.51	292.36	485.49	812.01	1420.7	2.92	4.48	1.06

Note: T_1 – System of Rice Intensification, T_2 - Mechanical transplanting, T_3 - Wet DSR (drum seeding), T_4 - Wet DSR (broadcasting), T_5 - Conventional transplanting, T_6 - Dry converted wet rice (broadcasting) and T_7 - Dry converted wet rice (line sowing), AT - Active tillering, PI - Panicle initiation, F -Flowering, PM - Physiological maturity

escaped control measures within rows were able to compete with the rice crop, consequently affecting plant height.

The Leaf Area Index (LAI) offers valuable insights into the photosynthetic region, which plays a pivotal role in dry matter formation. Our results highlight the variations in LAI among different rice establishment methods across various growth stages (Table 1). During the active tillering stage, wet DSR (drum seeding) exhibited the highest LAI of 1.84, followed by SRI (1.79), and dry converted wet rice (line sowing) (1.74). Conversely, the lowest LAI values were observed in dry converted wet rice (broadcasting) (0.79) and wet DSR (broadcasting) (0.88). At the panicle initiation and flowering stages, the highest LAI was recorded in wet DSR (line sowing), remaining on par with SRI, dry converted wet rice (line sowing), mechanical transplanting, and conventional transplanting. Conversely, the lowest LAI values at these stages were reported in the T_6 and T_4 treatments, indicating relatively smaller photosynthetic areas and potentially lower dry matter production. Wet DSR (drum seeding) and SRI methods demonstrated higher LAI values, suggesting a larger photosynthetic region and potentially higher dry matter production.

The observed higher LAI in wet DSR (drum seeding), SRI, and dry converted wet rice (line sowing) methods at all three stages can be attributed to the optimal plant population adopted in these methods. This equal distribution facilitates efficient resource utilization, leading to increased leaf area and ultimately higher LAI values. In comparison to SRI, conventional transplanting exhibited lower LAI values at the active tillering stage but demonstrated higher LAI values in the remaining stages. This variation in the active tillering stage could be attributed to the longer period of transplanting shock experienced by the plants in conventional transplanting methods compared to SRI. The plants in SRI showed quicker recovery and growth after transplanting, possibly due to the transplanting of young seedlings. The significantly lower LAI in the DSR broadcasted treatments (T_4 and T_6) can be attributed to the uneven distribution of plants, leading to increased competition among the plants for resources.

The higher dry matter accumulation in treatments T_1, T_2, T_3, and T_7 can be attributed to factors such as optimal plant stand, robust root growth, a greater number of tillers per plant, taller plant height, and higher LAI. Conversely, the DSR broadcasted treatments (T_4 and T_6) exhibited the lowest dry matter accumulation. This could be attributed to factors such as an uneven plant stand, a lower number of tillers per plant, shorter plant height, and lower LAI. Dry matter production is influenced by the rate of photosynthesis and crop respiration, which are determined by factors such as plant density, root development, and leaf area. Overall, the results indicate that the choice of rice establishment method can have a significant impact on dry matter production. Wet DSR (drum seeding) demonstrated superior dry matter accumulation compared to DSR broadcasted treatments. Factors such as plant stand, tiller production, plant height, and LAI play crucial roles in determining dry matter production in rice crops.

Root parameters, namely root volume, root length, and root dry weight, exhibited significant differences among the various rice production systems (Table 1). Dry converted wet rice (line sowing) and SRI displayed the highest root length (24.9 cm), remaining comparable to wet DSR (drum seeding) (24.8 cm). In contrast, mechanical transplanting (21.8 cm) and conventional transplanting (21.9 cm) showcased the lowest root lengths. Dry converted wet rice (line sowing) and SRI showcased higher root volume (49.4 cc/hill and 48.1 cc/hill, respectively) and root dry weight (7.2 g/hill and 7.4 g/hill, respectively). Conversely, the wet DSR (broadcasted) treatment exhibited lower root volume (26.7 cc/hill) and root dry weight (4.1 g/hill). The root systems of rice plants play a vital role in nutrient and water uptake, hormone production, plant anchorage, and interaction with soil microorganisms. It is widely recognized that root proliferation and activity have a mutually beneficial relationship with shoot development. These findings highlight significant differences in root characteristics among different rice production systems. The variations in root development can have implications for nutrient and water uptake efficiency, overall plant growth, and crop performance.

The higher root length observed in treatments T_7, T_1, T_3, T_6, and T_4 could be attributed to the favorable conditions provided by non-flooded conditions during the initial growth stages, promoting improved aeration and facilitating better root growth. Conversely, conventional and mechanical transplanting methods, involving continuous flooding, may inhibit root growth, leading to lower root length. The higher root volume and root dry weight observed in dry converted wet rice (line sowing) and SRI could be attributed to their higher root length, better crop establishment, and optimum plant population. Additionally, the square planting in SRI facilitates equal distribution of resources among the plants, minimizing competition and allowing for the development of nodal roots for each newly formed tiller. On the other hand, treatments T_4 and T_6 (DSR broadcasting) exhibited higher root length but lower root volume and dry weight due to the uneven distribution of plants in the field, increasing competition among the plants and resulting in lower overall root development. Overall, the observed variations in root characteristics among the different treatments can be

Table 2. Effect of different rice establishment methods on rice phenology

Treatments	Total number of tillers	Productive tillers	Fertile tillers %	Active tillering (days)	Days to 50% Flowering (days)	Physiological maturity (days)	Harvesting (days)	Hulling (%)	Milling (%)	Head rice recovery (%)	Amylose content (%)
T_1	276	265	96	45	83	108	115	79.0	69.3	61.9	25.3
T_2	363	327	90	45	84	109	116	79.5	69.6	63.1	25.4
T_3	215	203	95	44	78	103	110	79.6	69.5	61.0	24.9
T_4	228	185	81	44	78	103	110	79.2	69.4	58.4	24.9
T_5	287	261	91	45	88	111	118	79.9	71.4	68.7	25.3
T_6	345	276	80	43	75	101	108	80.0	69.6	58.5	25.6
T_7	312	297	95	43	75	101	108	80.4	70.7	60.8	25.5
SEm (±)	10.1	9.0	3.1	-	-	-	-	0.6	1.0	3.0	0.64
CD ($p \leq 0.05$)	31.1	27.8	9.7	-	-	-	-	NS	NS	9.2	NS

Note: T_1 – System of Rice Intensification, T_2 - Mechanical transplanting, T_3 - Wet DSR (drum seeding), T_4 - Wet DSR (broadcasting), T_5 - Conventional transplanting, T_6 - Dry converted wet rice (broadcasting) and T_7 - Dry converted wet rice (line sowing) attributed to factors such as flooding conditions, plant density, spacing, and competition for resources. These factors influence root growth and can have implications for nutrient uptake, plant performance, and ultimately crop yield.

Among the treatments, treatment 2 (Mechanical transplanting) recorded the highest average total tiller count, totaling 363 tillers, followed closely by treatment 6 (Dry converted wet rice - broadcasting) with 345 tillers. Conversely, treatment 3 (Wet DSR - drum seeding) exhibited the lowest total tiller count, averaging 215 tillers. Productive tillers, those contributing to grain formation and yield, were most abundant in treatment 2 (Mechanical transplanting) with 327 tillers on average, closely followed by treatment 7 (Dry converted wet rice-line sowing) with 297 tillers. In contrast, treatment 4 (Wet DSR - broadcasting) displayed the lowest productive tiller count, averaging 185 tillers (Table 2). The findings indicate that mechanical transplanting and dry converted wet rice cultivation through line sowing promote greater tiller numbers and productive tillers compared to alternative methods. The fertile tiller percentage, representing the proportion of productive tillers among the total tillers, offers insights into potential grain yield. Treatment 3 (Wet DSR - drum seeding) and Treatment 7 (Dry converted wet rice - line sowing) both exhibited the highest fertile tiller percentages at 95%, indicating that a significant majority of the tillers produced grain. Conversely, Treatment 6 (Dry converted wet rice - broadcasting) had the lowest fertile tiller percentage at 80%. These differences highlight the efficiency of different cultivation methods in terms of grain-bearing tillers.

The duration to attain various phenophases of rice varied across different establishment methods. Dry converted wet rice treatments (T_6 and T_7) took 108 days to reach the harvest stage, whereas wet DSR treatments (T_3 and T_4) required 110 days. SRI demanded 115 days, mechanical transplanting 116 days, and conventional transplanting the longest at 118 days to reach harvest (Table 2). Compared to conventional transplanting, all other treatments (T_1, T_2, T_3, T_4, T_6, and T_7) achieved harvest earlier by 2-10 days. The period to reach 50% flowering was prolonged in conventional transplanting (88 days), while all other methods achieved flowering earlier by 4-13 days. DSR treatments took 75-78 days to reach 50% flowering, 10-13 days earlier than conventional transplanting. These differences in the duration required for different phenophases and harvesting among the establishment methods can be ascribed to factors such as growth rate, developmental stages, environmental conditions, and management practices associated with each method.

DSR treatments, comprising wet DSR and dry converted wet rice, reached the harvest stage 8-10 days earlier than conventional transplanting. This difference in crop duration can be attributed to the prolonged transplanting shock experienced in conventional transplanting compared to mechanical transplanting and SRI, while DSR treatments were not subjected to transplanting shock. When comparing the two DSR treatments, the difference in days was only 2 for active tillering, physiological maturity, and harvesting, and 3 days for 50% flowering. The early emergence and initial water stress experienced in dry converted wet rice might account for this slight variation in DSR treatments. Similar findings were reported by Guru *et al.* (2017), where the growth duration of manually transplanted rice was 8-10 days longer than that of direct-seeded rice. These results highlight the advantage of direct seeding methods, such as DSR, in reducing crop duration and achieving earlier harvests compared to conventional transplanting.

In the study, hulling, milling, and head rice recovery among the different rice establishment methods did not exhibit significant differences, except for head rice recovery. Dry converted wet rice (line sowing) demonstrated a high hulling percentage of 80.4%, which was comparable to the other methods (Table 2). All treatments, except the DSR broadcasted treatments (T_4 & T_6), showed higher head rice recovery. Uneven resource distribution due to irregular crop geometry may have impacted overall plant health and grain quality, potentially leading to lower head rice recovery. Correlation analysis was conducted to explore relationships between various parameters related to rice establishment methods (Fig. 1). Leaf area at 85

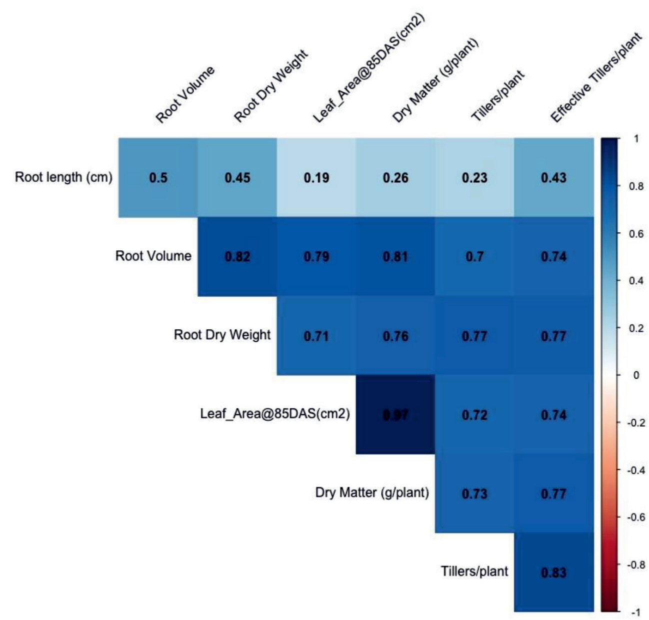

Fig. 1. Correlation between plant growth and root parameters

DAS displayed a strong positive correlation with both dry matter per plant (r = 0.975) and root volume (r = 0.794), suggesting that larger leaf area is associated with higher dry matter accumulation and root development. Effective tillers per plant exhibited positive correlations with leaf area at 85 DAS (r = 0.735), dry matter per plant (r = 0.774), and root dry weight (r = 0.769). These results imply that effective tiller production is influenced by factors such as leaf area, dry matter accumulation, and root biomass. Similarly, dry matter per plant showed a positive correlation with root length (r = 0.256), root volume (r = 0.806), and root dry weight (r = 0.760). This suggests that increased dry matter production generally accompanies longer roots, higher root volume, and greater root dry weight.

The results of this study suggest that wet DSR (drum seeding), SRI, and dry converted wet rice (line sowing) represent viable alternatives to conventional transplanting, offering advantages in terms of growth, yield, and quality parameters. Additionally, these methods were found to have shorter crop duration, which could be advantageous for resource management and overall efficiency.

ACKNOWLEDGMENTS

We extend our heartfelt appreciation to the Director, ICAR-Indian Institute of Rice Research, Hyderabad, for generously providing us the field and laboratory facilities. This article is an excerpt from a section of the M.Sc. Thesis authored by the first author, submitted to Professor Jayashankar Telangana State Agricultural University, Hyderabad, in 2023.

Authors' contribution

Conceptualization and design of experiments (SV); Execution of field experiments and data collection (SP); Data analysis and interpretation (VM, RG, KB); Preparation of manuscript (SP, VK, MDT, SJG, TR).

LITERATURE CITED

Blakeney A B, Welsh L A and Reece J R (1994). Recent developments in rice quality analysis. **In**: E Humphreys, E A Murray, W S Clampett and L G Lewin (eds) *Temperate Rice - Achievments and Potential*, Proceedings of the Temperate Rice Conference, Yanco 1994, Vol. 1, Temperate Rice Conference Organising Committee, Grifith, NSW, Australia.

Gomez K A and Gomez A A 1984. *Statistical procedures for agricultural research.* John Wiley and Sons.

Guru P, Rakesh C, Amit K, Ramesh J and Singh V D 2017. Recent production technologies of rice (*Oryza sativa* L.) for its sustainable cultivation in Haryana. *Int J Agric Sci* **13**(1): 83-92.

Mallareddy M, Thirumalaikumar R, Balasubramanian P, Naseeruddin R, Nithya N, Mariadoss A, Eazhilkrishna N, Choudhary A K, Deiveegan M, Subramanian E, Padmaja B and Vijayakumar S 2023. Maximizing water use efficiency in rice farming: A comprehensive review of innovative irrigation management technologies. *Water* **15**(10): 1802.

Padma S, Vijayakumar S, Venkatanna B, Srinivas D, Kumar R M, Kuchi S, Mahadevappa S G, Sundaram R M, Rekha K B and M Yakadri 2023. Impact of different crop establishment methods on yield attributes, yields and economics of rice: A comparative study. *Oryza* **60**(2): 315-24.

Vijayakumar S, Jinger D, Parthiban P and Lokesh S 2018. Aerobic rice cultivation for enhanced water use efficiency. *Indian Farming* **68**(06): 03-06.

Vijayakumar S, Karunakaran V, Gobinath R, Basavaraj K, Raghavendra Goud B, Sha N, Manasa V and Aravindan S 2022a. Sustainable rice production in India through efficient water saving techniques. *CBM* **6**(1): 32-38.

Vijayakumar S, Kumar D, Ramesh K, Jinger D and Rajpoot S K 2022b. Effect of potassium fertilization on water productivity, irrigation water use efficiency, and grain quality under direct seeded rice-wheat cropping system. *J Plant Nutr* **45**(13): 2023-38.

Vijayakumar S, Nayak A K, Ramaraj A P, Swain C K, Geethalakshmi V, Pazhanivelan S, Tripathi R and Sudarmanian N S 2021. Rainfall and temperature projections and their impact assessment using CMIP5 models under different RCP scenarios for the eastern coastal region of India. *Curr Sci* **121**(2): 222-32.

Vijayakumar S, Rajpoot S K, Manikandan N, Varadan R J, Singh J P, Chatterjee D, Chatterjee S, Santosha R, Choudhary A K and Kumar A 2023. Extreme temperature and rainfall event trends in the Middle Gangetic Plains from 1980 to 2018. *Curr Sci* **124**(11): 1300-07.

Watson D J 1952. The physiological basis of variation in yield. *Adv Agron* **4**: 101-145.