



Growth and Development of Rice as Influenced by Establishment, Residue Retention and Zinc Application

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To investigate the effect of different establishment methods, zinc application and residue retention on the rice plant growth metrics.

Study Design: Split-plot design with three replications.

Place and Duration of Study: Rice and Wheat Research Centre-CSK HPKV, Malan, Kangra, Himachal Pradesh, India. The study was conducted during Fall of 2021 and 2022.

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Methodology: We used six main plot treatments viz., M1: transplanting, M2: wet seeding (line sowing under puddle condition), M3: aerobic rice (dry rice cultivation), M4: transplanting + soil application of ZnSO₄ (12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray) at flowering and early milk stages, M5: wet seeding + soil application of ZnSO₄ (12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray) at flowering and early milk stages, M6: aerobic rice + soil application of ZnSO₄ (12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray) at flowering and early milk stages, and three subplot treatments, S1: no residue, S2: 15 cm height of rice straw from ground and incorporation in soil and S3: 30 cm height of rice straw from ground and incorporation. The variety used in the investigation was HPR 1068 of rice.

Results: The zinc was treatment resulted in significantly better rice plant height, leaf area index, crop growth rate and net assimilation rate when coupled with transplanting establishment method. Conversely, the aerobic rice establishment without zinc application resulted in significantly ($P < 0.05$) lower rice growth attributes. The days to flowering and physiological maturity were not significantly influenced by the treatments during the study.

Conclusion: The transplanting in conjunction with soil application of ZnSO₄ 12.5 kg ha⁻¹ and foliar application of ZnSO₄ 0.5% at flowering and early milk stages resulted in significantly higher and better rice plant growth and hence is encouraged.

Keywords: Absolute growth rate; aerobic rice; crop growth rate; leaf area index; net assimilation; transplanting.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is one of the world's most important staple crops, feeding a large section of the population. As demand for rice increases owing to swelling populations and changing dietary habits, improving rice yield and sustainability has become critical [1]. In this context, optimizing rice establishment techniques, zinc application, and rice residue management are identified as essential aspects for creating sustainable rice production systems. Rice establishment techniques such as direct seeding and transplanting have a substantial impact on rice plant growth and development [2]. Direct sowing, while less labour-intensive, necessitates precise water and weed management. Transplanting, on the other hand, includes the labour-intensive procedure of seedling transplantation but frequently results in more uniform plant stands and less competition from weeds. The establishment method can have an impact on a variety of growth metrics, including plant height, root architecture, and grain output.

Zinc (Zn) is a critical element for rice plants, influencing a variety of physiological processes including enzyme activation, photosynthesis, and hormone regulation [3]. Zinc insufficiency is a prevalent limitation in rice-growing locations worldwide, resulting in slower growth, delayed maturity, and poorer grain yield. Zinc fertilizers have been demonstrated to reduce deficient symptoms and improve rice growth and development [4]. However, the efficacy of zinc application varies according to soil type, pH,

organic matter level, and other environmental parameters. Rice residue retention, which includes integrating crop leftovers into the soil or leaving them on the top as mulch, has received attention for its ability to increase soil health and nutrient cycling. Rice residues can alter soil structure, moisture retention, and nutrient availability, impacting rice growth and development. Residue retention can influence weed control, disease incidence, and greenhouse gas emissions in rice fields, highlighting its importance in sustainable rice production systems [5]. Given the intricacies of these interacting elements, further research is required to assess their combined effects on rice growth and development. Thus, we aimed to investigate the impact of different rice establishing methods (direct seeding, transplanting and wet direct seeding), zinc application rates, and rice residue management strategies on important rice plant growth metrics.

2. MATERIALS AND METHODS

The field experiment was conducted during Fall season of 2021 and 2022 under the mid-hill conditions of Himachal Pradesh at the Experimental farm of Rice and Wheat Research Centre, Malan of CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur, Himachal Pradesh, India. The experimental farm is located at an altitude of 950 m above sea level at latitude 32°06'55.4" N and longitude 76°25'00.4" E. According to agroclimatic zones of Himachal Pradesh, the site falls under the sub-humid mid-hill zone of the North-Western Himalayas in the Palam valley of District Kangra, Himachal

Pradesh, India. A composite soil sample from a depth of 0-15 cm were collected before the start of the field study. The sample was air-dried, grounded and passed through 2 mm sieve. The processed soil sample was analyzed for different physio-chemical properties. The soil at the experimental site was silty clay loam in texture and acidic in reaction. It was medium in organic carbon, and medium in available nitrogen, phosphorus and potassium.

The experiment was laid out in split-plot design and comprised of six main plot treatments viz., M₁: transplanting, M₂: wet seeding (line sowing under puddle condition), M₃: aerobic rice (dry rice cultivation), M₄: transplanting + soil application of ZnSO₄ at rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, M₅: wet seeding + soil application of ZnSO₄ at rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, M₆: aerobic rice + soil application of ZnSO₄ at rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, and three sub plot treatments viz., S₁: no residue, S₂: 15 cm height of rice straw from ground and incorporation in soil and S₃: 30 cm height of rice straw from ground and incorporation with three replications. The variety used in the investigation was HPR 1068 of rice. The soil at the experimental site was silty clay loam in texture, acidic in reaction, medium in

available nitrogen, available phosphorus and available potassium. During the wheat growing period (fall, November to May), the mean weekly maximum temperature ranged from 10.58-36.96 °C and 13.43-28.58 °C during 2021-2022 and 2022-2023, respectively. Mean weekly minimum temperatures ranged from 4.16-23.04 °C and 4.24-15.54 °C during 2021-2022 and 2022-2023, respectively. Variation in the mean weekly relative humidity ranged from 4.57-75.6 per cent and 34.99-78.24 per cent during 2021-2022 and 2022-2023, respectively. The fall season received rainfall of 327.11 and 728.57 mm during 2021-2022 and 2022-2023, respectively. The data was subjected to statistical analysis using RStudio 2023.12.1+402 "Ocean Storm" [6]. The post hoc mean separation test employed was the Least Significant Difference (LSD) using package "agricolae" and graphs were prepared using packages "patchwork" "dplyr", "ggpubr" and "ggplot2".

3. RESULTS AND DISCUSSION

3.1 Growth Attributes

Plant height: The plant height of rice was significantly ($P < 0.05$) influenced by varied rice establishment methods with or without zinc application during both years of study (Table 1 and Fig 1). The transplanted method of rice

Table 1. Effect of different treatments on plant height (cm) in rice crop

Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	2021	2022	2021	2022	2021	2022	2021	2022
Rice establishment methods								
M1	49.44	38.83	80.10	67.39	101.60	92.88	104.10	97.13
M2	41.50	38.17	71.27	64.11	92.30	92.00	103.27	86.78
M3	40.33	34.22	67.30	59.78	92.83	89.40	98.10	83.82
M4	47.76	40.28	85.10	70.00	101.67	94.08	105.60	97.83
M5	41.03	38.17	73.07	66.83	95.20	91.58	101.20	95.06
M6	43.20	36.83	69.57	59.89	95.10	92.70	100.30	93.28
SEm±	0.56	0.49	0.75	0.97	1.07	0.91	1.23	0.97
LSD	1.76	1.54	2.35	3.06	3.37	2.87	3.88	3.05
Rice residue retention the spring season								
S1	43.70	36.17	73.93	63.44	95.95	90.79	100.19	92.78
S2	44.02	38.86	75.00	65.61	96.72	94.31	103.08	96.24
S3	43.90	38.22	74.27	64.94	96.68	91.22	103.02	92.92
SEm±	0.37	0.43	0.53	0.54	0.76	0.72	0.98	0.85
LSD	NS	1.27	NS	1.57	NS	2.09	NS	2.49

M₁: transplanting, M₂: wet seeding (line sowing under puddle condition), M₃: aerobic rice (dry rice cultivation), M₄: transplanting + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, M₅: wet seeding + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, M₆: aerobic rice + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, S₁: no residue, S₂: 15 cm height of rice straw from ground and incorporation in soil and S₃: 30 cm height of rice straw from ground

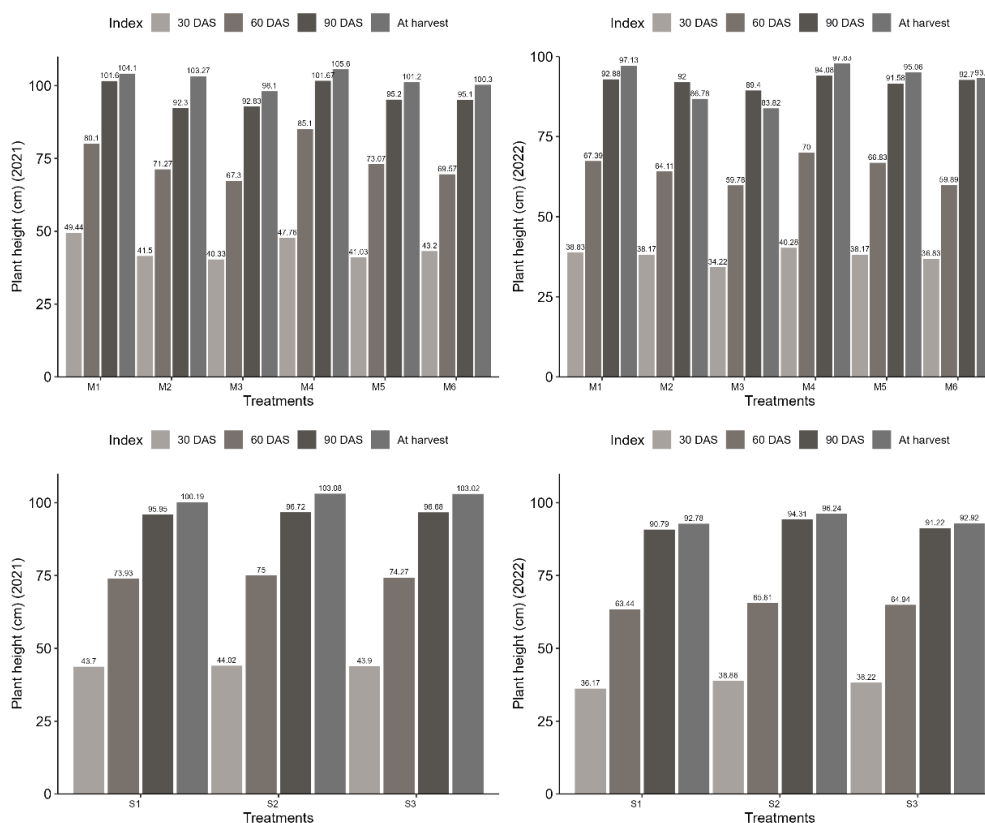


Fig. 1. Plant height as influenced by establishment methods and residue retention

establishment consistently resulted in taller plants, especially in M₄. Conversely, M₃ led to reduced plant height. Residue incorporation showed no significant effect initially but resulted in taller plants during the subsequent year (Fall 2022), with S₂ yielding the best outcomes. At harvest, the transplanted method with zinc application produced the tallest plants, emphasizing the positive impact of zinc on rice growth and the importance of establishment methods. Residue management also played a role, with moderate residue incorporation proving beneficial.

The height of rice plants is a crucial morphological trait influenced by genetic factors, soil conditions, nutrient availability, and environmental factors. Aerobic cultivation methods often result in reduced plant height primarily due to slower initial growth stages compared to transplanting methods [7]. Transplanting from nurseries provides rice with a head start, leading to increased plant height compared to direct seeding [8]. The reduced plant height under aerobic conditions may result from restricted cell elongation due to increased

plant density, intensifying competition for nutrients [9]. Aerobically grown rice plants may allocate more photosynthates to roots, impacting shoot growth. Zinc plays a vital role in rice production, particularly in flooded conditions, with deficiency leading to reduced yield and growth. Zinc enhances plant height by promoting shoot elongation through increased auxin levels. Studies have reported significant increases in plant height with soil zinc applications, indicating its importance in rice cultivation (Saikh et al., [10], Ghoneim, [11]).

Leaf Area Index (LAI): Significant ($P < 0.05$) variations in leaf area index due to varied establishment methods in rice were observed during the rice growing period (Table 2 and Fig 2). Transplanting rice with M₄ resulted in a significantly ($P < 0.05$) higher LAI compared to other methods. Conversely, the aerobic rice system without zinc showed a lower LAI, similar to aerobic rice with zinc application. Incorporating 15 cm of rice residue led to a significantly increased LAI compared to conventional tillage without residue, though LAI was at parity with S₃.

Table 2. Effect of different treatments on Leaf Area Index (LAI) in rice crop

Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	2021	2022	2021	2022	2021	2022	2021	2022
Rice establishment methods								
M1	2.36	2.50	4.10	4.50	3.90	4.34	3.73	4.07
M2	1.98	2.07	4.12	4.41	3.92	4.12	3.69	3.95
M3	1.79	1.88	3.90	4.11	3.44	3.59	3.30	3.43
M4	2.46	2.65	4.24	4.65	4.14	4.39	3.85	4.03
M5	2.24	2.34	4.22	4.45	4.10	4.35	3.77	3.51
M6	1.79	1.90	4.03	4.26	3.58	3.61	3.32	3.06
SEm±	0.02	0.02	0.04	0.05	0.05	0.03	0.04	0.04
LSD	0.08	0.07	0.14	0.17	0.16	0.08	0.13	0.13
Rice residue retention in the spring season								
S1	2.09	2.10	4.09	4.23	3.82	3.90	3.58	3.47
S2	2.10	2.44	4.12	4.51	3.87	4.25	3.65	3.86
S3	2.12	2.13	4.10	4.44	3.85	4.06	3.61	3.70
SEm±	0.02	0.02	0.04	0.04	0.03	0.03	0.03	0.04
LSD	NS	0.07	NS	0.12	NS	0.09	NS	0.11

M₁: transplanting, M₂: wet seeding (line sowing under puddle condition), M₃: aerobic rice (dry rice cultivation), M₄: transplanting + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, M₅: wet seeding + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, M₆: aerobic rice + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, S₁: no residue, S₂: 15 cm height of rice straw from ground and incorporation in soil and S₃: 30 cm height of rice straw from ground

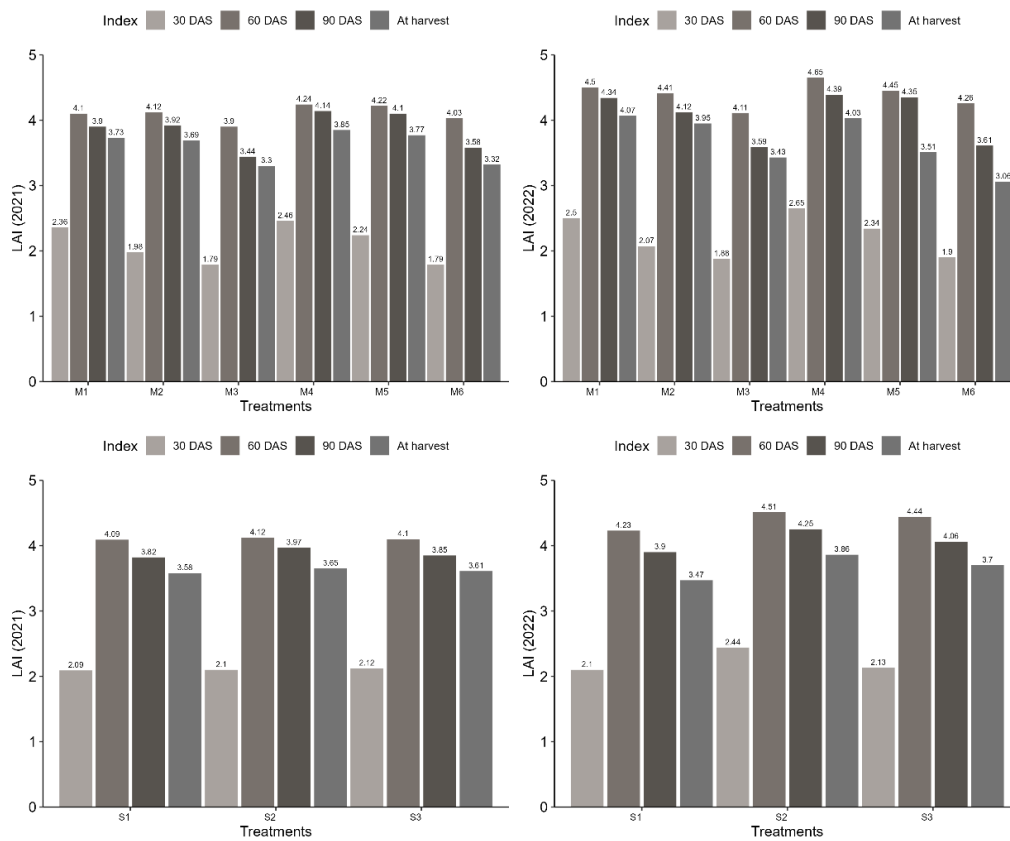


Fig. 2. Leaf area index as influenced by establishment methods and residue retention

The lower leaf area index (LAI) observed under the aerobic method of rice cultivation is likely due to reduced leaf water content and increased electrolyte leakage, indicative of compromised cell membrane stability. This contrasts with the transplanted method, where the inundation of water helps maintain optimal leaf water content, thereby promoting higher LAI during rice establishment, as noted by Zayed et al. [12]. This finding aligns with the results of Kadiyala et al. [13], who similarly reported higher LAI under the transplanted method. Furthermore, studies by Singh et al. [14]. Demonstrated that the application of zinc resulted in increased LAI, suggesting a potential avenue for enhancing leaf area in rice cultivation.

Growth indices: The study investigated the impact of different rice cultivation methods and zinc application on crop growth rates (AGR) and net assimilation rates (NAR) at various stages of growth (Tables 3 and 5). Puddled transplanted rice, when combined with soil and foliar zinc applications, exhibited significantly higher AGR at 30 days after sowing (DAS), highlighting the positive effect of zinc on early growth. A Aerobic rice cultivation without zinc resulted in lower AGR, emphasizing the importance of zinc supplementation. The incorporation of rice residue did not initially affect AGR but showed benefits in subsequent years, indicating a longer-

term impact of residue management. Towards harvest, AGR declined notably in transplanted rice without zinc initially and in aerobic rice without zinc later in the growth cycle, emphasizing the critical role of zinc in sustaining growth throughout the cropping season. At crop growth stages (CGR), wet direct-seeding of rice combined with soil zinc application and foliar zinc spray resulted in notably higher growth rates both at the early stage (30 DAS) and at harvest, highlighting the efficacy of zinc application in promoting sustained growth. Aerobic rice establishment with zinc also exhibited enhanced growth rates compared to methods without zinc, emphasizing the positive impact of zinc across different rice cultivation systems (Table 4). Analysis of net assimilation rates (NAR) revealed similar trends, with wet direct-seeding combined with zinc application showing significantly higher NAR compared to treatments without zinc. Aerobic rice cultivation without zinc consistently exhibited the lowest NAR throughout the study period, underlining the necessity of zinc supplementation for optimal assimilation rates. The study also noted the effects of rice residue incorporation, with positive trends observed with increased residue levels in some instances. Retention of rice straw residue in the Fall season significantly ($P < 0.05$) increased NAR, demonstrating the potential benefits of residue management on crop assimilation rates.

Table 3. Effect of different treatments on absolute growth rate (cm day⁻¹) in rice crop

Treatment	0-30 DAS		30-60 DAS		60-90 DAS		90 DAS-At harvest	
	2021	2022	2021	2022	2021	2022	2021	2022
Rice establishment methods								
M1	1.65	1.29	1.02	0.95	0.72	0.85	0.07	0.12
M2	1.38	1.27	0.99	0.86	0.70	0.93	0.30	0.05
M3	1.34	1.14	0.90	0.85	0.85	0.99	0.14	0.07
M4	1.59	1.34	1.24	0.99	0.55	0.80	0.11	0.10
M5	1.37	1.27	1.07	0.96	0.74	0.82	0.16	0.10
M6	1.44	1.23	0.88	0.77	0.85	1.09	0.14	0.02
SEm±	0.02	0.02	0.02	0.04	0.05	0.05	0.05	0.02
LSD	0.06	0.05	0.07	0.14	0.14	0.15	0.16	0.06
Rice residue retention in the spring season								
S1	1.46	1.21	1.01	0.91	0.73	0.91	0.11	0.06
S2	1.47	1.27	1.03	0.91	0.72	0.96	0.17	0.05
S3	1.46	1.30	1.01	0.87	0.75	0.88	0.17	0.05
SEm±	0.01	0.01	0.02	0.02	0.03	0.04	0.04	0.03
LSD	NS	0.04	NS	NS	NS	NS	NS	NS

*M*₁: transplanting, *M*₂: wet seeding (line sowing under puddle condition), *M*₃: aerobic rice (dry rice cultivation), *M*₄: transplanting + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, *M*₅: wet seeding + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, *M*₆: aerobic rice + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, *S*₁: no residue, *S*₂: 15 cm height of rice straw from ground and incorporation in soil and *S*₃: 30 cm height of rice straw from ground

Table 4. Effect of different treatments on crop growth rate ($\text{g m}^{-2} \text{day}^{-1}$) in rice crop

Treatment	0-30 DAS		30-60 DAS		60-90 DAS		90 DAS-At harvest	
	2021	2022	2021	2022	2021	2022	2021	2022
Rice establishment methods								
M1	2.04	2.02	12.50	12.46	14.91	14.86	3.27	3.30
M2	2.44	2.41	11.44	11.41	9.49	9.39	4.91	5.05
M3	1.76	1.72	11.77	11.73	9.75	9.73	5.03	5.16
M4	2.19	2.14	13.07	13.03	15.25	15.25	3.63	3.69
M5	2.73	2.66	11.83	11.80	10.03	10.06	5.12	5.26
M6	2.01	1.98	11.85	11.80	10.61	10.58	5.26	5.43
SEm\pm	0.03	0.03	0.18	0.13	0.41	0.27	0.39	0.35
LSD	0.10	0.09	0.58	0.41	1.29	0.86	1.22	1.09
Rice residue retention in the spring season								
S1	2.17	2.15	12.08	12.02	11.60	11.35	4.53	4.51
S2	2.18	2.17	12.12	12.30	11.74	11.56	4.56	4.77
S3	2.24	2.15	12.03	11.81	11.69	12.02	4.52	4.67
SEm\pm	0.02	0.02	0.11	0.11	0.27	0.17	0.25	0.28
LSD	NS	NS	NS	0.33	NS	0.51	NS	NS

*M*₁: transplanting, *M*₂: wet seeding (line sowing under puddle condition), *M*₃: aerobic rice (dry rice cultivation), *M*₄: transplanting + soil application of ZnSO_4 at a rate of 12.5 kg ha^{-1} + 0.5% ZnSO_4 spray at flowering and early milk stages, *M*₅: wet seeding + soil application of ZnSO_4 at a rate of 12.5 kg ha^{-1} + 0.5% ZnSO_4 spray at flowering and early milk stages, *M*₆: aerobic rice + soil application of ZnSO_4 at a rate of 12.5 kg ha^{-1} + 0.5% ZnSO_4 spray at flowering and early milk stages, *S*₁: no residue, *S*₂: 15 cm height of rice straw from ground and incorporation in soil and *S*₃: 30 cm height of rice straw from ground

Table 5. Effect of different treatments on Net assimilation rate ($\text{g g}^{-1} \text{day}^{-1}$) in rice crop

Treatment	0-30 DAS		30-60 DAS		60-90 DAS		90 DAS-At harvest	
	2021	2022	2021	2022	2021	2022	2021	2022
Rice establishment methods								
M1	0.74	0.74	4.00	3.72	3.80	3.41	0.87	0.81
M2	0.76	0.73	3.98	3.85	2.39	2.23	1.30	1.26
M3	0.57	0.57	4.37	4.15	2.67	2.56	1.50	1.46
M4	0.80	0.78	4.04	3.67	3.68	3.40	0.92	0.88
M5	0.98	0.96	3.80	3.61	2.42	2.29	1.31	1.34
M6	0.65	0.66	4.38	4.13	2.83	2.73	1.53	1.64
SEm\pm	0.01	0.01	0.06	0.04	0.11	0.07	0.10	0.10
LSD	0.04	0.04	0.20	0.13	0.36	0.23	0.30	0.32
Rice residue retention in the spring season								
S1	0.73	0.75	4.13	3.70	2.99	2.63	1.24	1.22
S2	0.76	0.79	4.08	3.99	2.94	2.84	1.24	1.24
S3	0.76	0.68	4.07	3.87	2.96	2.84	1.23	1.24
SEm\pm	0.01	0.01	0.05	0.05	0.07	0.05	0.07	0.07
LSD	NS	0.02	NS	0.13	NS	0.14	NS	NS

*M*₁: transplanting, *M*₂: wet seeding (line sowing under puddle condition), *M*₃: aerobic rice (dry rice cultivation), *M*₄: transplanting + soil application of ZnSO_4 at a rate of 12.5 kg ha^{-1} + 0.5% ZnSO_4 spray at flowering and early milk stages, *M*₅: wet seeding + soil application of ZnSO_4 at a rate of 12.5 kg ha^{-1} + 0.5% ZnSO_4 spray at flowering and early milk stages, *M*₆: aerobic rice + soil application of ZnSO_4 at a rate of 12.5 kg ha^{-1} + 0.5% ZnSO_4 spray at flowering and early milk stages, *S*₁: no residue, *S*₂: 15 cm height of rice straw from ground and incorporation in soil and *S*₃: 30 cm height of rice straw from ground

Transplanting rice led to higher plant height and leaf area index compared to other establishment methods. This increase in leaf area index suggests a larger surface area available for photosynthesis, while taller plants ensure greater light interception. Additionally, wider spacing and

lower plant density associated with transplanting facilitate enhanced photosynthate production and accumulation of dry matter. Furthermore, the process of water pounding during transplanting serves to suppress weed growth and mitigate the stress of transplanting, promoting rapid

Table 6. Effect of different treatments on developmental studies in rice crop

Treatment	Days to 50% flowering		Days to physiological maturity	
	2021	2022	2021	2022
Rice establishment methods				
M1	82.79	81.79	112.79	111.79
M2	83.12	82.12	113.12	112.12
M3	82.89	81.89	112.89	111.89
M4	83.10	82.10	113.10	112.10
M5	82.79	81.79	112.79	111.79
M6	82.99	81.99	112.99	111.99
SEm±	2.53	1.62	2.53	1.62
LSD	NS	NS	NS	NS
Rice residue retention in the spring season				
S1	82.98	81.98	112.98	111.98
S2	82.93	81.93	112.93	111.93
S3	82.92	81.92	112.92	111.92
SEm±	1.42	1.44	1.42	1.44
LSD	NS	NS	NS	NS

M₁: transplanting, M₂: wet seeding (line sowing under puddle condition), M₃: aerobic rice (dry rice cultivation), M₄: transplanting + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, M₅: wet seeding + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, M₆: aerobic rice + soil application of ZnSO₄ at a rate of 12.5 kg ha⁻¹ + 0.5% ZnSO₄ spray at flowering and early milk stages, S₁: no residue, S₂: 15 cm height of rice straw from ground and incorporation in soil and S₃: 30 cm height of rice straw from ground

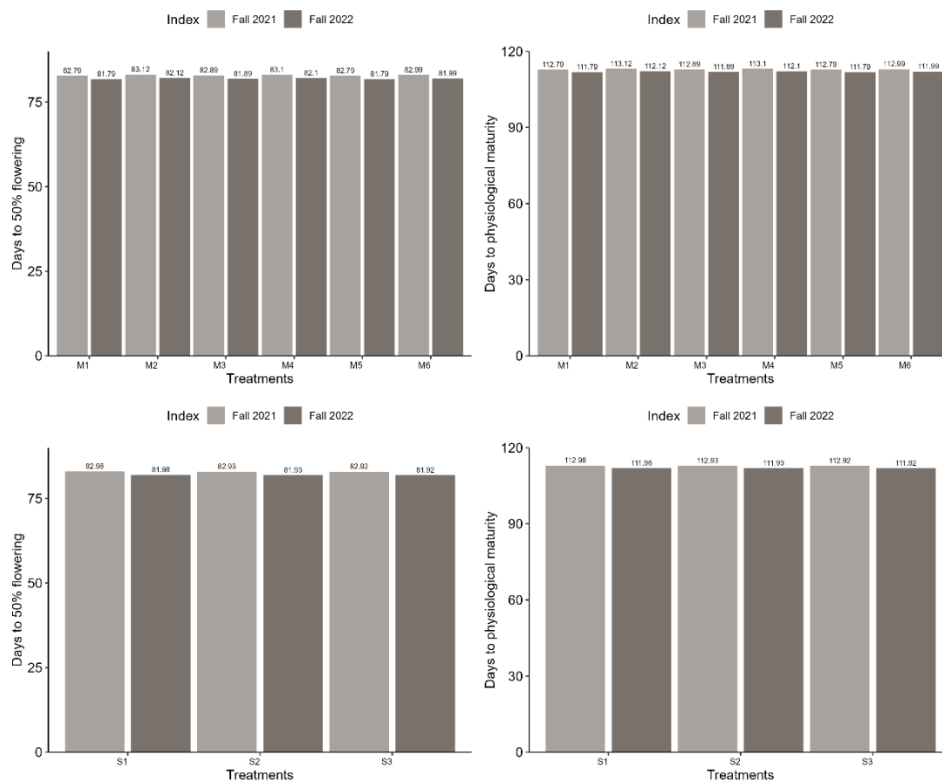


Fig. 3. Leaf area index as influenced by establishment methods and residue retention

seedling growth. Bhandari et al. [15] and Midya et al. [16] also observed significantly higher dry

matter accumulation under conventional puddling and transplanting methods. The application of

zinc, both to the soil and as a foliar spray, was found to enhance rice dry matter accumulation. Zinc plays a crucial role in plant metabolism, regulating enzymes like carbonic anhydrase involved in carbon dioxide fixation and antioxidant enzymes like superoxide dismutase and catalase, which protect against oxidative stress in plant cells. This regulation aids in nutrient distribution towards generative plant organs, ultimately contributing to increased dry matter accumulation. This finding aligns with previous studies by Amanullah and Inamullah [17], Ghoneim [11], and Saikh et al. (2022), which also reported increased dry matter accumulation in rice following zinc application via soil and foliar methods [18].

Developmental studies: The number of days required by a crop to achieve flowering and physiological maturity is a varietal character and depends on weather conditions, mainly temperature varying slightly due to the cultivation practices. It is clear from Table 6 and Fig. 3 that different establishment methods with or without zinc interventions, as well as residue retention treatments, failed to significantly ($P < 0.05$) influence the days to physiological maturity of rice crops.

4. CONCLUSION

Present investigation-based outcomes revealed that integrating the transplanting method of rice establishment with soil application of $ZnSO_4$ at a rate of 12.5 kg ha^{-1} and foliar spray of $ZnSO_4$ at a rate of 0.5% at flowering and early milk stages resulted in significantly higher plant height, leaf area index, absolute crop growth rate, and net assimilation rate. Therefore, this investigation concluded that the transplanting method of rice establishment with soil application of $ZnSO_4$ at a rate of 12.5 kg ha^{-1} and foliar spray of $ZnSO_4$ at a rate of 0.5% at flowering and early milk stages can encourage the stakeholders to promote better growth and development of rice crop plants under the conditions of North-Western Himalayan region of India.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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