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Moisture stress at critical stages of rice (*Oryza sativa*) hampers grain yield and economics by inhibiting the growth and yield-forming traits

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ABSTRACT

A field experiment was conducted during rainy (*kharif*) (July–November) 2019 and late winter (*rabi*) (December–March) 2019–20 seasons at Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu to evaluate the effect of moisture stress (MS) at critical stages on the production and economics of rice (*Oryza sativa* L.). Eight MS treatments, viz. MS for 10 days from panicle initiation (PI) stage (T_1); MS for 15 days from PI stage (T_2); MS for 20 days from PI stage (T_3); MS for 25 days from PI stage (T_4); MS for 10 days from flowering stage (T_5); MS for 15 days from flowering stage (T_6); MS for 20 days from flowering stage (T_7); and MS for 25 days from flowering stage (T_8) were compared with the irrigated control (SRI method, T_9) in a randomized complete block design (RCBD) with three replications. Two-season pooled mean results revealed that MS imposed at the PI stage had a more detrimental effect on rice growth, yield attributes, yield, and economic parameters than the flowering stage. Specifically, MS for 20 and 25 days at PI stage (T_3 and T_4) resulted in a higher penalty of grain yield (56.2 and 58.0%, respectively) and straw yield (33.2 and 36.4%, respectively) and economic parameters (gross return, net return, and benefit-cost ratio) due to hampered growth and subsequent deterioration in yield attributes of rice. Hence, the study concludes that moisture stress at the panicle initiation stage generally, and more precisely, for 20–25 days at the panicle initiation stage is highly detrimental to rice causing growth, yield attributes, yield, and economic parameters.

Keywords: Flowering stage, Moisture stress in rice, Panicle initiation stage, Yield penalty

Rice (*Oryza sativa* L.) is a critical component of the global food supply, cultivated on 167.3 Mha worldwide, yielding 495.9 million tonnes (FAOSTAT 2024). Although rice is grown globally, over 50% of its production is concentrated in Asian countries. India is the second-largest producer of rice (136.7 Mt), produced in a 45.1 Mha area, with a productivity of 2.83 tonnes/ha (Indiastat 2023). However, rice production faces significant challenges due to various biotic and abiotic stresses, with moisture stress being one of the most critical threats to global food security (Pathak *et al.* 2021). The increasing demands of urbanization, industrialization, and population growth have led to the depletion of freshwater resources used in agriculture, aggravating the effects of moisture stress on rice production (Mallareddy *et al.* 2023). Projections indicate that by 2025, 15 Mha of Asia's 130 Mha of irrigated rice fields could face 'physical water stress,' while 22 Mha of irrigated dry-season rice may experience 'economic water scarcity' (Silalertruksa *et al.* 2017). Climate change further intensifies the vulnerability of rice crops to seasonal moisture stress, as rainfall patterns and water availability become increasingly unpredictable. Given the looming scarcity of natural resources, particularly water, innovative water-saving strategies are urgently needed in rice cultivation.

The System of Rice Intensification (SRI) has emerged as a promising method for water conservation. The alternate wetting and drying irrigation method is commonly practised in SRI cultivation, saving 29.2–37.1% of water in Tamil Nadu (Paramasivan and Selvarani 2017, Lokanadhan *et al.* 2021). Yet, there is potential to save even more water by strategically withholding it and imposing moisture stress without compromising yield. However, research on the effects of moisture stress, especially under the SRI method, remains limited. Though there is evidence that panicle initiation and flowering stages are sensitive to rice growth and production, the duration of moisture stress is not fully understood. Since the saturation of soil is focused in the SRI method of rice cultivation, withholding water for a few days not only gives soil aeration to the crop but also, saves water. Therefore, this research was conceptualized to explore the impact of moisture stress within the reproductive stage (panicle initiation and flowering stages) on growth, yield traits, yield, and economic parameters of rice.

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MATERIALS AND METHODS

The field experiment was conducted during two growing seasons: rainty (*kharif*) (July–November 2019) and late winter (*rabi*) (December 2019–March 2020) at Tamil Nadu Agricultural University, Coimbatore (11°N, 77°E; at an elevation of 426.7 m amsl), Tamil Nadu. Coimbatore receives an annual average rainfall of 673 mm in 42 rainy days. The soil at the site during both seasons of experimentation was clay loam in texture with an alkaline *p*H (7.8–8.2). It had a medium organic carbon content (0.67–0.70 g/kg), low available nitrogen (213–238 kg/ha), and high levels of both available phosphorus (42.0–47.2 kg/ha) and potassium (643–1045 kg/ha).

The experiment was laid out in a randomized complete block design (RCBD) with nine treatments; each replicated three times. The treatments included varying durations of moisture stress (MS) imposed at two critical stages (panicle initiation and flowering stages) of rice growth, viz. T_1, Moisture stress (MS) for 10 days from panicle initiation (PI) stage; T_2, MS for 15 days from PI stage; T_3, MS for 20 days from PI stage; T_4, MS for 25 days from PI stage; T_5, MS for 10 days from the flowering stage; T_6, MS for 15 days from flowering stage; T_7, MS for 20 days from flowering stage; and T_8, MS for 25 days from flowering stage and were compared with irrigated control (Maintaining saturation as in SRI method, T_9). The test variety used was Rice CO 51, with a field duration of 105–110 days and an average grain yield of 6623 kg/ha released by Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu. The rice seedlings were raised in a mat nursery, and all other cultivation practices were followed according to the Crop Production Guide (CPG 2018). The MS was imposed by withholding irrigation for the specified durations in the respective treatments. For the PI stage treatments, such as T_1, T_2, T_3, and T_4, water was withdrawn and not re-applied for 10, 15, 20, and 25 days, respectively. Similarly, for the flowering stage treatments, viz. T_5, T_6, T_7, and T_8, initially, water was drained and not provided for 10, 15, 20, and 25 days, respectively. After the stress period, irrigation was resumed to relieve the MS. Field seepage was controlled using a buffer channel and a one-foot polythene sheet inserted around the plots. Irrigation according to the SRI method was given to the control treatment (T_9).

The plant height (cm) was measured from five tagged plants. It was measured from the base of the plant to the tip of the panicle at harvest. The leaf area index was calculated as suggested by Palaniswamy and Gomez (1974). Five plants from sampling rows were uprooted with the utmost care, cleaned, shade-dried, and oven-dried at 70±5°C until a constant weight was obtained, and drymatter production (kg/ha) was recorded. Total tiller numbers/m^2 were counted at harvest. The number of panicle-bearing tillers leaving the chaffy tillers was counted in five randomly chosen hills in each plot, the average was taken and expressed in number/m^2. The tagged plants were harvested with care and 10 panicles were selected, hand threshed and the average total grains/panicle, and filled grains/panicle were recorded. 1000-grains were counted and weighed for 1000-seed weight (g). The grain and straw yields were recorded from the produce obtained from the net plot at a 14% moisture level as per the standard procedure. Two-season data were in similar trends and hence data were pooled and performed analysis using the Least Significant difference (LSD) to compare and group the treatment means at a 5% confidence level (Gomez and Gomez 2010). The box plots and correlation panel graphs were drawn using the GGally package of R-software version 4.3.1.

RESULTS AND DISCUSSION

Growth traits: The moisture stress (MS) at critical stages (panicle initiation and flowering stage) had a significant effect on the growth traits, viz. plant height, leaf area index (LAI), tiller numbers, and total drymatter production (DMP) of rice (Table 1). Irrespective of the stages, the MS-imposed treatments showed a significant reduction of all the growth traits of rice compared to the irrigated control. Soil moisture is the most critical input for any crop, specifically, water-loving crops like rice and so, moisture stress influences negatively. The MS is known to inhibit cell division, cell enlargement, and the photosynthetic mechanism. The direct hamper on the growth traits such as plant height, LAI, and tillers, and further on the drymatter was evident in the present study due to the imposing of MS. Similarly, abridged plant height and subsequent growth of plants under MS was reported earlier due to the reduction of cell division and cell elongation (Farooq *et al.* 2010) supports the study results.

Compared to the flowering stage of rice, growth reduction was more pronounced in the PI stage. Plant height decreased by 15.4–31.9% during the PI stage, whereas, only by 13.1–24.1% during the flowering stage because of MS. Similarly, the LAI, tiller numbers, and the DMP of rice were also recorded lower values due to the MS at the PI stage than the flowering stage. This was mainly due to the growth of rice being active and vigour at the PI stage, hence the lack

Table 1 Effect of moisture stress at critical stages on growth characters of rice (pooled over two seasons)

Treatments	Plant height (cm)	LAI[#]	Total tillers/ m^2 at harvest	DMP (kg/ha) at harvest
T_1	90.6^e	2.26^{cd}	317.9^b	12699^{ab}
T_2	87.0^f	2.21^d	240.1^{cd}	8222^e
T_3	81.6^g	2.24^d	235.1^d	7390^{ef}
T_4	79.5^h	1.94^e	230.5^d	6706^f
T_5	94.7^b	2.67^b	337.6^b	12497^{bc}
T_6	93.7^{bc}	2.61^b	330.3^b	11878^{bc}
T_7	93.1^c	2.71^b	312.0^b	11218^c
T_8	91.9^d	2.38^c	267.2^c	9785^d
T_9	96.7^a	3.11^a	378.1^a	14080^a

DMP, Dry matter production; [#]Leaf area index (LAI) at grain filling stage. Values followed by a common letter are not significantly different at the 5% level using LSD (Least significant difference). Treatment details are given under Materials and Methods.

of moisture reduced the growth. Whereas, the rice plant has attained its full vegetative growth and started to produce reproductive organs during the initiation of the flowering stage, hence, the reduction of growth was only marginal due to the withdrawal of moisture. The experimental findings fall in line with the findings of Patnaik *et al.* (2020) and (2023) and Kumar *et al.* (2024).

Among MS-imposed treatments, T_4 (MS for 25 days during the PI stage) followed by T_3 (MS for 25 days during the PI stage) showed significantly lower plant height compared to all other MS-imposed treatments and the irrigated control. The deprived LAI, tiller numbers, and DMP were also observed in these treatments compared to others. The percentage reduction of plant height (15.6 and 17.8 cm), LAI (28.0 and 37.6), tiller numbers (37.8 and 39.0), and the DMP (47.5 and 52.4) due to the treatments T_3 and T_4, respectively over the irrigated control. Prolonged MS (25 or 20 days), at the active young stage (PI) of rice produced shorter plants and lowered the tillers due to the poor uptake of nutrients as seen in the present study. The lack of the two most important critical inputs for rice such as moisture, and nutrients, obviously reduced the growth especially, plant height and tillers. Production of a smaller leaf area is the sole way of reducing the water loss during MS conditions. Inhibition of meristem tissue cell division under water-famished conditions and decreased the metabolism in plants, in due course, might have reduced the LAI of rice. The effect of MS was directly proportional to the duration of stress (Zain *et al.* 2014). Prolonged MS (20–25 days) inhibited the production of leaves and leaf area which would reduce photosynthesis. Tillers are a crucial feature of rice grain production and, as such, essential to growth (Saju and Thavaprakaash 2020). The reduction of tillers' production under MS conditions might be the fact that plants were not able to produce enough assimilates and inhibited photosynthesis. Insufficient water uptake which falls short for preparing food and subsequent inhibition of cell division of meristem tissue might be another reason for reduced tiller production. Similar results were validated by Salsinha *et al.* (2020). Reduced plant height, LAI, and tiller numbers in turn, diminished the DMP of rice in the prolonged MS-imposed treatment at the PI stage (T_4 and T_3). The current study provided strong evidence that the amount of drymatter that accumulated, had positively and significantly depended on plant height (r=0.89***), LAI (r=0.78***), and the number of tillers (r=0.89***) (Fig. 1).

However, irrigated control treatment (T_9) resulted in the maximum growth (plant height, LAI, tiller numbers, and DMP) of rice (Table 1). Continuous supply of moisture helped the plants for better uptake of nutrients from the soil and maintaining good turgor in the plant, ultimately better growth of rice. The results are in line with the findings of Panigrahi and Das (2021).

Yield attributing traits: Yield attributes (panicle-bearing tillers, total number of grains and filled grains, and 1000-seed weight) of rice were significantly influenced by the MS treatments (Table 2). Generally, all the MS treatments produced significantly lesser yield contributing traits

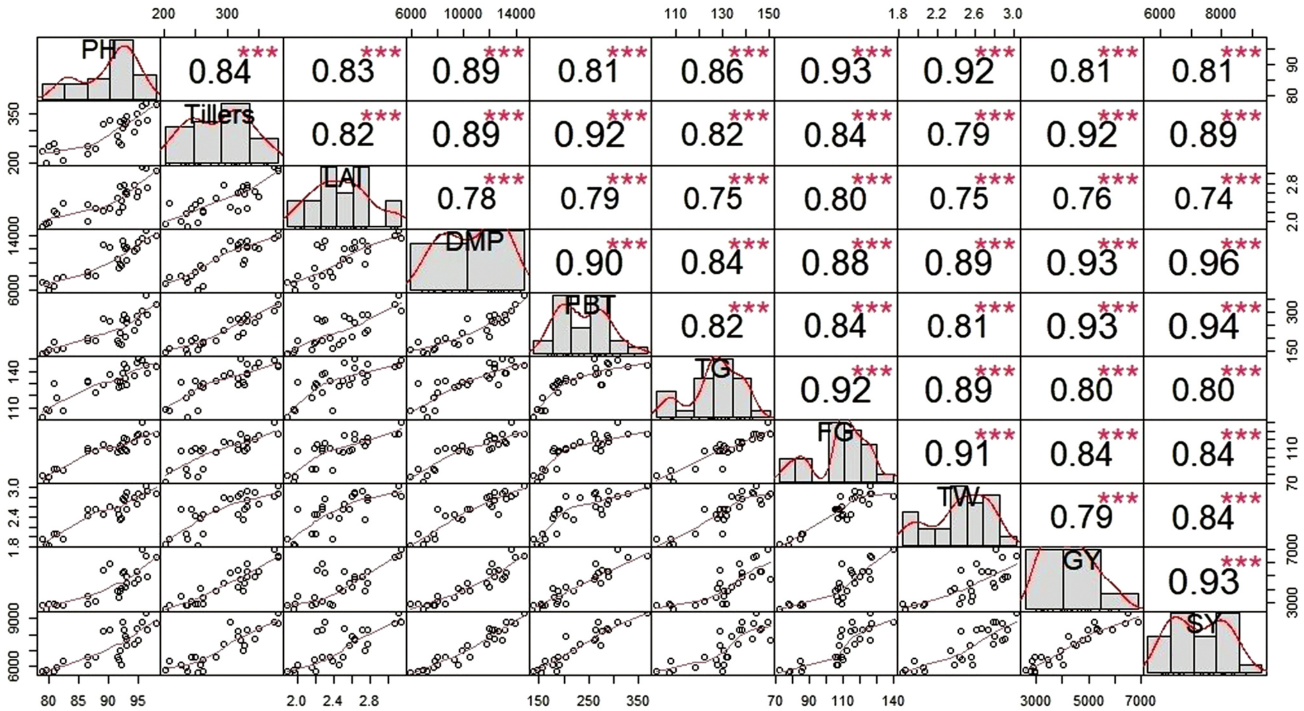

Fig. 1 Correlation panel matrix of various traits of rice subjected to moisture stress at critical stages (pooled over two seasons). PH, Plant height; Tillers, Number of tillers/m^2; LAI, Leaf area index; DMP, Dry matter production (kg/ha); PBT, Panicle bearing tillers/m^2; TG, Total number of grains/panicles; FG, Filled grains/panicle; TW, 1000-seed weight; GY, Grain yield; SY, Straw yield.

compared to the irrigated control which supplied moisture continuously. As proved in the growth of rice, MS is a crucial input that directly influences yield attributes. Hence, the reduced growth had parallelly inhibited all the yield attributes of rice. Panicle-bearing tillers form as a base to produce grains and finally, yield rice. The number of tillers produced in rice is the foundation for producing panicle-bearing tillers (Thavaprakaash 2019). Hence, the reduced number of tillers in the MS treatments in the present study reliably influenced the panicle-bearing tillers of rice. The reduction was more pronounced due to the prolonged MS (25 and 20 days) at the PI stage (T_4 and T_3) compared to other MS-imposed treatments. The treatments T_4 and T_3 reduced 49.9 and 56.4% of productive tillers compared to the irrigated control (334.8/m^2). The reduced number of tillers produced in these treatments was the main reason for the reduced panicle-bearing tillers. Research report by Patnaik *et al.* (2023) was supported strongly by the present results.

Significant reduction of grain characters such as total grains, filled grains, and 1000-seed weight in rice when MS was imposed generally, and PI stage, specifically. It was also evidenced from the current study that MS at the flowering stage had not reduced the sink capacity (grains) significantly (Table 2) compared to the stress at the PI stage. Inactive pollen grain, imperfect growth, and development of pollen tube; insufficient assimilate production and subsequent distribution to grains (Singh *et al.* 2020) are a few of the probable reasons for the poor grain characteristics in these treatments.

The MS for the prolonged period (20 and 25 days) during the PI stage (T_3 and T_4) exhibited a more severe impact on the reduction of grain characteristics than other treatments. More percentage decrease of grains (10.8 and 48.7%), filled grains (38.4 and 41.8%), and 1000-seed weight (30.2 and 35.0%) due to T_3 and T_4 treatments, respectively would mainly be due to the inhibited translocation of assimilate to the grains. From the current study, it was clear that the rice plants undergoing stress at the PI stage for 20 and 25 days could not produce enough source size which could have been used for forming the sinks later, which was the major reason for lowered grain traits. Sarvestani *et al.* (2008) also observed the same outcomes.

Table 2 Effect of moisture stress at critical stages on the yield attributes of rice (pooled over two seasons)

Treatments	Panicle bearing tillers/m^2	Total grains/ panicle	Filled grains/ panicle	1000-seed weight (g)
T_1	269.9^b	134.9^{bc}	113.4^{bc}	2.61^{bc}
T_2	193.9^{cd}	128.3^{cd}	107.7^c	2.52^c
T_3	167.7^{ef}	118.8^d	85.5^d	2.03^d
T_4	146.1^f	106.2^e	76.3^e	1.89^d
T_5	288.5^b	143.8^{ab}	121.5^b	2.78^{ab}
T_6	265.6^b	140.7^{ab}	117.9^b	2.75^{ab}
T_7	217.7^c	133.8^{bc}	112.8^{bc}	2.65^{bc}
T_8	181.4^{de}	129.1^c	107.7^c	2.47^c
T_9	334.8^a	145.8^a	131.2^a	2.91^a

Values followed by a common letter are not significantly different at the 5% level using LSD. Treatment details are given under Materials and Methods.

In the present study, a positive relationship between growth traits and yield-attributing characters in rice was noted (Fig. 2). All the growth traits (plant height, LAI, tiller numbers, and DMP) had significant and strong positive correlations with the yield contributing characters such as panicle-bearing tillers, grain, and filled grain numbers, and the 1000-seed weight indicated that MS not only reduced the growth of rice but equally, the yield attributes.

The irrigated control that was given with continuous moisture produced the highest yield attributes of rice. Continuous irrigation enabled better characteristics on growth, drymatter, pollination, development of the embryo, and subsequent better grain production. The correlation relationship between growth and yield characters as evidenced (Fig. 1) confirmed the direct relationship.

Yield: The impact of MS on grain and straw yields of rice was significant (Fig. 2). The period and stage of MS were related to the grain yield reduction of treatments. When compared to the flowering stage, the PI stage had a greater impact on grain and straw yields of rice due to MS. The percentage reduction of grain yield at the PI stage was up to 58.0% but up to 42.6% at the flowering stage. This could be because the early development was hampered by a lack of moisture, which prevented the growth of the rice plants further, the sink sizes were too reduced at a later stage. Almost similar results were obtained for straw yield too.

The grain yield was significantly reduced in treatments that underwent MS at the PI stage for 25 days (T_4) and 20 days (T_3). The grain yield penalty was 57.9% and 56.1% respectively with T_4 and T_3 treatments. Severe reduction of growth characters in these treatments equally impaired the yield attributes as evidenced by the present study finally, impacted on the grain yield of rice. This was strongly supported by the correlation analysis which indicated that in the present study, different yield attributes such as the number of productive tillers (r=0.93***), number of grains (r=0.80***), filled grains (r=0.84***) and 1000-seed weight (r=0.79***) showed very positive and significant association with grain yield. A remarkable reduction in straw yield was noticed in rice plants under a stress period of 20 and 25 days of MS at the PI stage. The discussion made for grain yield is equally applicable to straw yield too. The DMP of the rice is the main character influence directly to the straw yield (Thavaprakaash 2019). Reduced DMP in these treatments eventually, deprived the straw yield. Results obtained by Patnaik *et al.* (2023) were also similar and strongly supports the current study results.

In the treatment that received a constant water supply (T_9), grain output was noticeably higher (6,607 kg/ha). Continuous water supply increased the LAI and greater accumulation of photosynthates in the form of drymatter,

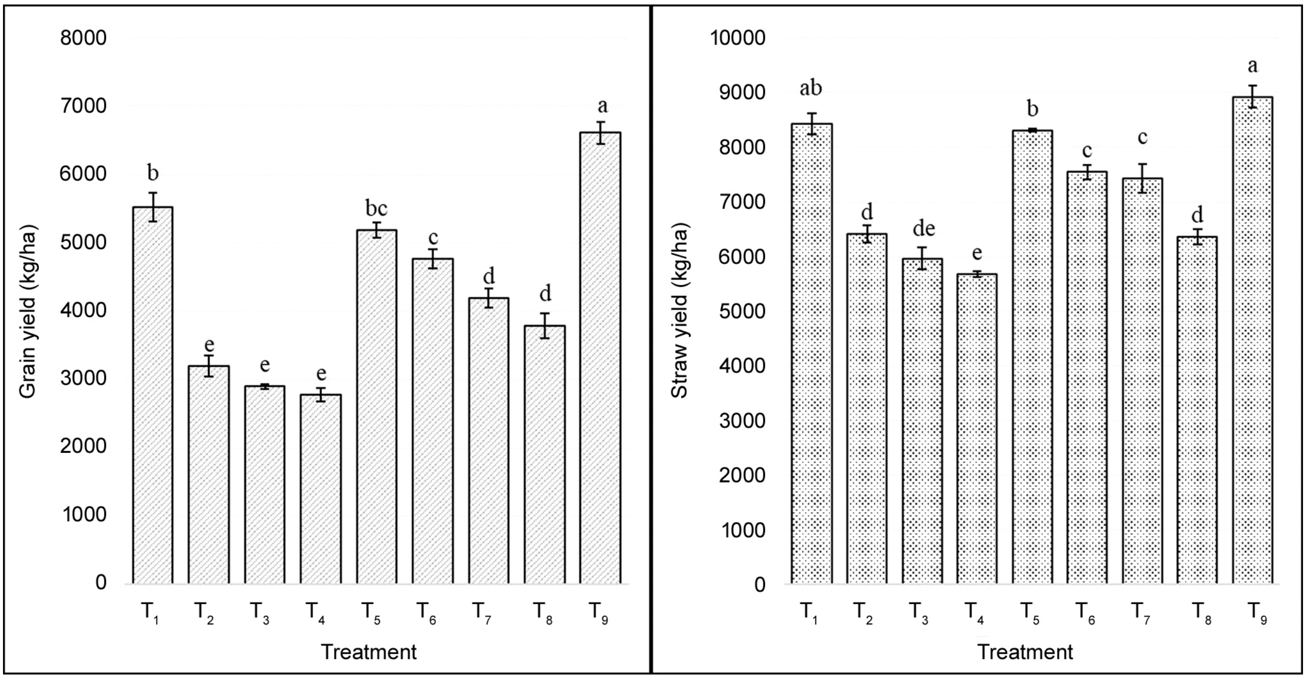

Fig. 2 Rice grain and straw yield as influenced by moisture stress at critical stages (pooled over two seasons). Values followed by a common letter are not significantly different at the 5% level using LSD. Treatments details are given under Materials and Methods.

resulting in improved yield. The straw yield was higher (8,926 kg/ha) in the treatment T_9, which was mainly due to higher drymatter production under an unhindered supply of moisture. There was a strong and positive correlation between straw yield with DMP evidenced in the present investigation (Fig. 1) confirms the relationship.

Economic parameters: The highest cost of cultivation (₹39,663/ha) was recorded in T_9 (maintaining saturation throughout the crop period), attributed to the greater number of irrigations required to maintain continuous moisture. On the other hand, the lowest cost of spending (₹38,269/ha) was observed in the treatment T_8 (MS for 25 days from the flowering stage), primarily due to fewer irrigations, especially towards the crop's maturity (Table 3). Despite the higher cultivation costs, the treatment T_9 resulted in greater gross income, net income, and benefit-cost ratio due to the higher grain and straw yields.

In contrast, lower gross income (₹46,692 and 44,696/ha) recorded in T_3 and T_4 treatments (MS for 20 and 25 days at the PI stage, respectively) was due to the prolonged MS, which negatively impacted grain and straw yields, thereby reducing the gross return. The net return was also lower in the same treatments due to reduced gross return with a constant cost of spending. The deprived benefit-cost ratio (1.21 and 1.16) was also evident from the treatments T_4 and T_3, respectively. Reduced gross income in these treatments caused the reduction of the benefit-cost ratio.

From the two-season experiment, it can be concluded that moisture stress in general, and stress at the panicle initiation stage is more detrimental to the growth and yield of rice. Imposing moisture stress from the panicle initiation stage for 20–25 days, proved more detrimental in terms of growth, yield parameters, yield, and finally, the economic parameters. However, the moisture stress period of 10–15 days at the panicle initiation stage and moisture stress of any period (10–25 days) at the flowering stage were less harmful to the growth and yield of rice.

Table 3 Effect of moisture stress at different critical stages on the economics of rice

Treatments	Total cost of cultivation (₹/ha)	Gross return (₹/ha)	Net return (₹/ha)	Net Benefit-cost ratio
T_1	39219	83085^{b}	43865^{b}	2.12
T_2	38903	51252^{f}	12349^{f}	1.31
T_3	38839	46692^{f}	7852^{f}	1.21
T_4	38523	44696^{f}	6173^{f}	1.16
T_5	39283	78881^{c}	39598^{c}	2.01
T_6	38966	72237^{cd}	33270^{cd}	1.85
T_7	38586	65157^{e}	26570^{e}	1.68
T_8	38269	58203^{ef}	19933^{ef}	1.52
T_9	39663	97138^{a}	57475^{a}	2.45

Values followed by a common letter are not significantly different at the 5% level using LSD. Treatment details are given under Materials and Methods.

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