RESEARCH ARTICLE Indian Journal of Agricultural Research, Volume 59 Special Issue: 129-134 (November 2025)

Mitigation of Terminal Heat Stress in Aerobic Rice (*Oryza sativa* L.) by Nitrogen and Potassium Application

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10.18805/IJARe.A-6339

ABSTRACT

Background: Heat stress is one of the major environmental stresses limiting rice productivity. Selecting heat-tolerant rice cultivars and implementing proper nutrient management techniques could result in a high and consistent yield.

Methods: Field experiments were conducted at the Kerala Agricultural University, Thrissur, during the summer (2020 and 2021) to study the response of different rice varieties to elevated temperatures (2 to 3°C) during the flowering to maturity stage, with different N and K levels under aerobic conditions. The experimental treatments comprised of V_1F_0 - Vaishak + 60 kg N and 30 kg K_2O (control), V_1F_1 - Vaishak + 60 kg N and 30 kg K_2O under stress, V_1F_2 - Vaishak + 90 kg N and 45 kg K_2O under stress, V_1F_3 - Vaishak + 120 kg N and 60 kg K_2O under stress, V_2F_0 - Aiswarya + 60 kg N and 30 kg K_2O (control), V_2F_1- Aiswarya + 60 kg N and 30 kg K_2O under stress, V_2F_2- Aiswarya+90 kg N and 45 kg K_2O under stress, V_2F_3- Aiswarya+120 kg N and 60 kg K_2O under stress. These were laid out in a randomized complete block design and replicated three times.

Result: The study revealed that the highest yield (2909 and 2456 kg/ha) and nutrient uptake were observed with application of 120 kg N and 60 kg K_2O from Vaishak. The treatments V_1F_3 and V_2F_3 showed higher NPK uptake than the recommended fertilizer dose in both seasons.

Key words: Aerobic rice, Heat stress, Nitrogen, Potassium, Yield.

INTRODUCTION

Over 60 per cent of the world's population depends on rice as a staple diet, which makes it the most significant and widely cultivated food crop globally (Kaur and Mathpaul, 2025). Millions of rural households rely on rice as their primary source of income and it is vital for our nation's food security. India has the world's largest rice area and ranks second in production behind China (Annamalai and Johnson, 2023). Over 782 million tons of rice were produced in 2018 on 167 million hectares of rice cultivation in India. Due to biotic and abiotic stresses, rice production is facing many problems around the world (Radha *et al*., 2023). It is projected that in India, by the end of the 21st century, the rice yield is expected to reduce by 41% with an increase in the mean annual temperature of 3-5°C (Krishnan *et al*., 2020). High temperatures have an impact on rice growth at several stages of development, particularly at the heading stage (Zhang *et al*., 2021). The ideal temperature for rice is between 21.7°C and 26.7°C during the grain-filling phase and 28.4°C during the vegetative growth phase. The daily average maximum temperature should not be more than 35°C. Grain yield will be reduced if the temperature rises over 27°C during the grain-filling phase, resulting in a decrease in the percentage of seed set and 1,000-grain weight (Zhang *et al*., 2023).

As a result of global warming, adopting suitable nutrient management techniques could be a crucial step in achieving high and stable yields at high temperatures. Nitrogen is essential for tolerance to temperature stress, as plants' photosynthetic capacity is closely linked to leaf nitrogen content. Nitrogen fertilization alleviates abiotic stresses and research demonstrates that plants with sufficient nitrogen can endure excessive light by maintaining high photosynthesis rates and establishing defense mechanisms (Al-Menaie *et al*., 2024). It is essential to supply an adequate amount of nitrogen throughout the reproductive stage to minimize the risk of heat stress (Padhan *et al*., 2023). Potassium also plays a vital role in the survival of crop plants under environmental

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How to cite this article: Murugesan, S.K., Prabhakaran, P., Arunagirinathan, I., Sivalingam, R., Arumugam, R., Perumaland, C. and Manivelu, R. (2025). Mitigation of Terminal Heat Stress in Aerobic Rice (*Oryza sativa* L.) by Nitrogen and Potassium Application. *Indian Journal of Agricultural Research.* **59 (Special Isuue):** 129-134. doi: 10.18805/IJARe.A-6339.

Submitted: 08-11-2024 **Accepted:** 05-11-2025 **Online:** 25-11-2025

stress, aside from its function in growth and yield. Potassium is essential for many physiological processes, such as photosynthesis, turgidity, nutrient uptake, assimilate transport and enzyme activation for protein synthesis under abiotic stress conditions (Sarwar *et al*., 2022). However, there has been very little research on how to alleviate high-temperature stress through fertilizer application. The aim of the present study is to evaluate the effects of nitrogen and potassium nutrition on yield and NPK uptake of aerobic rice under heat stress.

MATERIALS AND METHODS

Study area

Field experiment was conducted during the summer (January to April) of 2020 and 2021 at Kerala Agricultural University, Vellanikkara, Thrissur. The experimental site is geographically situated at 10.55°N latitude and 76.28°E longitude and at an altitude of 18 m above mean sea level (MSL). The objective of the study is to yield and nutrient uptake of the rice varieties (Vaishak and Aiswarya) at different doses of nitrogen and potassium levels under terminal heat stress conditions. The experiment is conducted for two years (2020 and 2021).

Treatments and experimental design

The experimental treatments comprised of V_1F_0 - Vaishak + 60 kg N and 30 kg K_2O (control), V_1F_1 - Vaishak + 60 kg N and 30 kg K_2O under stress, V_1F_2 - Vaishak + 90 kg N and 45 kg K_2O under stress, V_1F_3 - Vaishak + 120 kg N and 60 kg K_2O under stress, V_2F_0 - Aiswarya + 60 kg N and 30 kg K_2O (control), V_2F_1- Aiswarya + 60 kg N and 30 kg K_2O under stress, V_2F_2- Aiswarya+90 kg N and 45 kg K_2O under stress, V_2F_3- Aiswarya+120 kg N and 60 kg K_2O under stress. These were laid out in a randomized complete block design and replicated three times. To impose temperature stress, portable transparent polythene chambers were kept in each plot from the flowering stage up to the maturity stage. These varieties were selected based on their better performance under elevated temperatures from previous pot culture experiments. The temperature inside the chambers was monitored and was observed to be 2-3°C above ambient conditions (28 to 33°C) [Fig 1]. The heat stress was imposed by portable transparent polythene chambers with dimensions of 2×2×1.5 m were fabricated. The top of the chamber was covered with UV-stabilized polythene sheet and the sides were covered with transparent polythene sheet, leaving a gap of 15 cm from the ground level at the base for free air passage (Singh *et al*., 2010). The plot size was 5 m × 4 m and the growth chambers were kept in the field during the flowering to maturity phase of rice. Observations were taken from sample plants inside the chamber.

Cultural practices

The field was ploughed twice, levelled and laid out as per the randomized block design with three replications. The seeds were dibbled in each plot at a spacing of 20×15 cm. Sowing was done on January 1, 2020 and 2021. Farmyard manure at 5 t/ha was applied uniformly to all plots and mixed well with the soil. Nitrogen and potassium were applied equally in three split doses. The full dose of phosphorus (30 kg/ha) was applied at the time of land preparation. Two hand weeding were carried out, the first at 30 days after sowing (DAS) and the second at 60 DAS. The crop was irrigated daily and irrigation was withheld one week before harvest. The crop was harvested at maturity. The plants outside the chamber were harvested first and the plants inside the chamber from each plot were harvested separately. The grain and straw were separately dried and weighed and yields were recorded.

Data collection and analysis

The observations on total number of productive tillers, panicle, total number of spikelets per panicle, filled and unfilled grains per panicle, 1000-grain weight, were recorded from each plot of each replication separately. The yield attributes were recorded at physiological maturity. The grain and straw yield was recorded from net plot area of each treatment and mean values were computed.

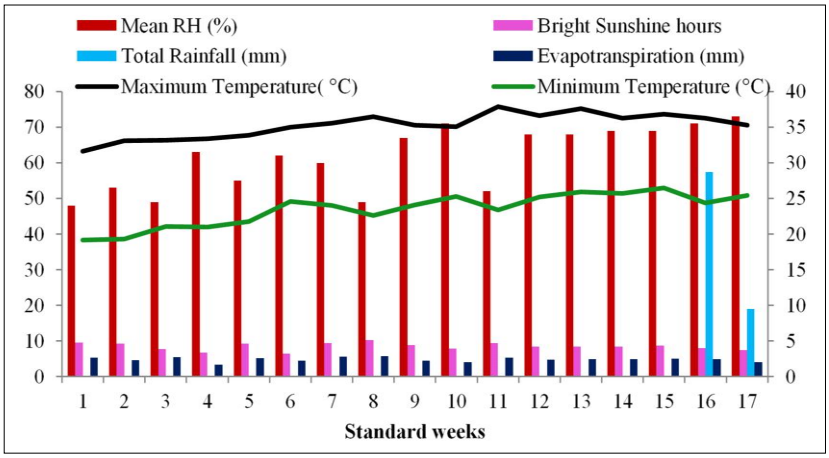


Fig 1: Average weather parameters during the summer season of the year 2020 and 2021.

The uptake of N, P and K nutrients was determined by multiplying the sample's nutrient content and the respective dry weight of plant samples was expressed in g/hill. N, P and K content was estimated in plant samples by Kjeldahl method (Kjeldahl,1883), colorimetric method (Jackson, 1973) and flame photometer method (Stanford, 1949). Data collected were subjected to analysis of variance using SPSS 16.0 (SPSS Inc., Chicago, USA),. Significant treatment means were compared using Duncan's multiple range test (DMRT).

RESULTS AND DISCUSSION

Yield attributes

The response of rice varieties to different nitrogen and potassium levels under high-temperature stress revealed distinct variations in yield-attributing traits (Table 1). The number of panicles per hill was significantly enhanced by higher nutrient inputs, with Aiswarya supplied with 120 kg N and 60 kg K_2O (V_2F_3) recorded the highest values in both 2020 and 2021. This advantage was comparable to Aiswarya with 90 kg N and 45 kg K_2O (V_2F_2) in 2021, indicates sufficient nutrient supply supported tiller emergence and survival even under stress conditions. In contrast, lower nutrient levels restricted panicle formation, suggesting that adequate nitrogen availability was critical to maintain vegetative vigor during the panicle initiation phase (Parthiban and Vijayaragavan 2020).

Filled grains per panicle showed a different varietal response, Vaishak applied with 120 kg N and 60 kg K_2O (V_1F_3) produced the maximum values across both years (Fig 2). However, this treatment was statistically on par with Vaishak + 90 kg N and 45 kg K_2O under stress (V_1F_2), Aiswarya+120 kg N and 60 kg K_2O under stress (V_2F_3) and Aiswarya supplied with 90 kg N and 45 kg K, O (V_2F_2), suggesting that both medium and high nutrient doses improved grain setting under stress. The role of potassium in maintaining pollen viability and reducing spikelet sterility under high temperature has been emphasized in maize by Waqas *et al*. (2021) and a similar mechanism may be attributed in the present study.

Chaff percentage exhibited an inverse relationship with filled grains. Aiswarya applied with 60:30 kg N:K/ha (V_2F_1) and Aiswarya applied with 90:45 kg N:K/ha (V_2F_2) recorded the highest proportion of chaff, indicates poor pollination and incomplete fertilization (Table 1). On the other hand, Vaishak supplied with 120 kg N and 60 kg K, O (V_1F_3) had the lowest chaff percentage, shown that higher nutrient inputs enhanced reproductive efficiency under stress. These results highlight the importance of balanced nutrition not only in improving panicle number but also in ensuring proper seed set (Sharma and Singh, 2021).

The total grain number per panicle was greatest in Vaishak (V_1F_3) and Aiswarya (V_2F_3), both receiving 120 kg N and 60 kg K, O. This increase suggests that higher nitrogen rates enhanced sink capacity by supporting panicle branching, while potassium promoted seed set, ensuring a higher grain count. Similarly, 1000-grain weight was maximum in Aiswarya with 120 kg N and 60 kg K, O (V_2F_3). By contrast, the lowest values were observed in Aiswarya (V_2F_1) and Vaishak (V_1F_1) under low nutrient supply, reflecting inadequate assimilate partitioning during the grain-filling phase. Reports by and Adhikari *et al*. (2021) support the role of potassium in improving grain weight by facilitating assimilate translocation and enhancing grain filling.

Panicle length also followed this nutrient-driven trend, with the longest panicles observed in Vaishak applied with 120 kg N and 60 kg K_2O (V_1F_3), whereas the shortest were recorded in Aiswarya applied with 60 kg N and 30 kg K_2O (V_2F_1). Longer panicles under higher N and K supply likely

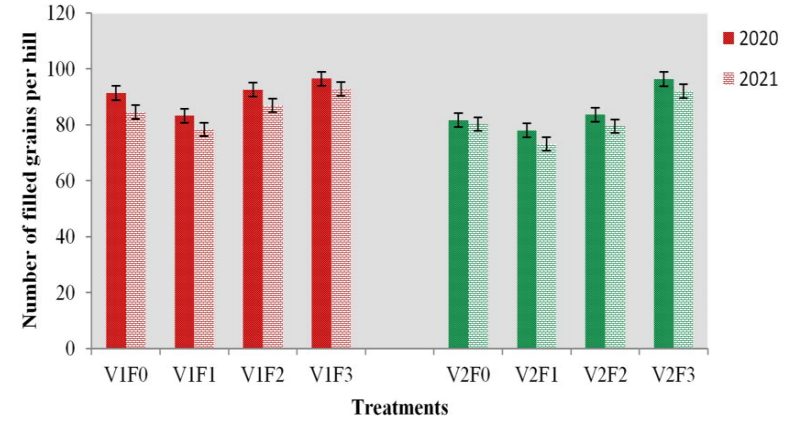
Table 1: Effect of N and K nutrition on number of panicles per hill, panicle length, total number of grains per panicles, chaff per cent and 1000 grain weight under terminal heat stress.

Treatment	Number of panicles per hill		Panicle length (cm)		Total number of grains per panicle (g)		Chaff per cent (%)		1000 grain weight	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
V_1F_0	10.60	9.32	8.56	9.12	100.23	99.25	8.56	9.12	28.50	27.90
V_1F_1	10.50	9.30	14.75	13.19	97.60	90.20	14.75	13.19	28.20	27.60
V_1F_2	11.80	9.40	9.76	11.51	102.50	98.20	9.76	11.51	29.10	28.00
V_1F_3	12.10	10.30	9.23	8.30	116.20	119.20	9.23	8.30	29.00	28.90
V_2F_0	10.50	9.50	18.30	20.40	98.46	94.67	18.30	20.40	27.30	26.10
V_2F_1	10.70	9.40	16.67	18.49	93.60	89.80	16.67	18.49	27.30	26.00
V_2F_2	12.50	10.80	15.56	15.96	99.00	94.60	15.56	15.96	27.40	26.20
V_2F_3	13.50	12.20	9.58	10.68	106.50	103.00	9.58	10.68	27.20	26.94
SEd ±	0.65	0.56	0.72	0.76	5.73	5.60	0.72	0.76	1.56	1.52
CD (p=0.05)	1.39	1.21	1.54	1.63	12.30	12.01	1.54	1.63	NS	NS

Note: V_1F_0 - Vaishak + 60 kg N and 30 kg K_2O (Control - No stress), V_1F_1- Vaishak + 60 kg N and 30 kg K_2O under stress, V_1F_2- Vaishak + 90 kg N and 45 kg K_2O under stress, V_1F_3- Vaishak + 120 kg N and 60 kg K_2O under stress, V_2F_0 - Aiswarya + 60 kg N and 30 kg K_2O (Control - No stress), V_2F_1- Aiswarya + 60 kg N and 30 kg K_2O under stress, V_2F_2- Aiswarya + 90 kg N and 45 kg K_2O under stress, V_2F_3- Aiswarya + 120 kg N and 60 kg K_2O under stress.

contributed to higher spikelet numbers, which were further realized as filled grains. Overall, the study establishes that nitrogen and potassium exert complementary effects under high temperature stress. Higher doses improved both structural traits (panicle number and length) and functional attributes (grain filling, grain weight and reduced chaff), thereby sustaining yield potential. These findings confirm the importance of balanced N and K nutrition as an adaptive strategy to mitigate yield penalties in rice under rising temperature regimes (Raghunath and Beena, 2024).

Under high-temperature stress, nitrogen and potassium fertilization significantly influenced grain and straw yields of rice (Table 2). Grain yield exhibited a linear increase with increasing nutrient levels, indicating that higher N and K supply mitigated the adverse effects of stress. The maximum grain yield of 2906 kg ha^{-1} in 2020 and 2546 kg ha^{-1} in 2021 was recorded in Vaishak treated with 120 kg N and 60 kg K_2O (V_1F_3). This was statistically on par with Aiswarya under the same dose (V_2F_3) and both were markedly superior to other treatments. The next best performance was observed in Vaishak (V_1F_2) and Aiswarya (V_2F_2) supplied with 90 kg N and 45 kg K_2O under stress, highlighting the positive response of both varieties to medium and higher nutrient inputs. Straw yield followed a



The analysis of variance was carried out and comparison was done by Duncan's multiple range test (DMRT) at 5% level of significance. Note: V_1F_0 - Vaishak + 60 kg N and 30 kg K_2O (Control - No stress), V_1F_1- Vaishak + 60 kg N and 30 kg K_2O under stress, V_1F_2- Vaishak + 90 kg N and 45 kg K_2O under stress, V_1F_3- Vaishak + 120 kg N and 60 kg K_2O under stress, V_2F_0 - Aiswarya + 60 kg N and 30 kg K_2O (Control - No stress), V_1F_1- Aiswarya + 60 kg N and 30 kg K_2O under stress, V_1F_2- Aiswarya + 90 kg N and 45 kg K_2O under stress, V_1F_3- Aiswarya + 120 kg N and 60 kg K_2O under stress.

Fig 2: Effect of N and K nutrition on number of filled grains per hill under terminal heat stress.

Table 2: Effect of N and K nutrition on grain yield, straw yield and N, P and K uptake (kg/ha) at harvest under terminal heat stress.

Treatments	Grain yield (kg/ha)		Straw yield (kg/ha)		Uptake of N (kg/ha)		Uptake of P (kg/ha)		Uptake of K (kg/ha)	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
V_1F_0	2103	1937	2946	2701	25.36	24.2	4.75	4.52	53.26	52.96
V_1F_1	2365	2186	3108	2854	20.84	26.47	3.41	2.90	50.32	47.10
V_1F_2	2906	2546	3602	3256	26.54	27.2	5.10	4.62	56.24	54.70
V_1F_3	2001	1788	2836	2454	36.12	33.74	8.20	6.20	72.80	67.84
V_2F_0	2395	2104	3010	2684	25.49	21.7	6.42	5.67	56.32	51.89
V_2F_1	2783	2358	3208	2874	22.45	18.9	5.02	4.12	47.10	44.20
V_2F_2	2103	1937	2946	2701	26.87	22.98	6.90	5.84	58.62	54.80
V_2F_3	2365	2186	3108	2854	34.21	31.22	9.30	8.10	63.00	58.96
SEd ±	131.00	117.27	171.39	154.52	1.59	1.49	0.37	0.31	3.30	3.11
CD (p=0.05)	280.96	251.52	367.58	331.40	3.41	3.19	0.79	0.67	7.08	6.67

Note: V_1F_0 - Vaishak + 60 kg N and 30 kg K_2O (Control - No stress), V_1F_1- Vaishak + 60 kg N and 30 kg K_2O under stress, V_1F_2- Vaishak + 90 kg N and 45 kg K_2O under stress, V_1F_3- Vaishak + 120 kg N and 60 kg K_2O under stress, V_2F_0 - Aiswarya + 60 kg N and 30 kg K_2O (Control - No stress), V_2F_1- Aiswarya + 60 kg N and 30 kg K_2O under stress, V_2F_2- Aiswarya + 90 kg N and 45 kg K_2O under stress, V_2F_3- Aiswarya + 120 kg N and 60 kg K_2O under stress.

similar trend, with higher nutrient doses supported greater biomass accumulation. Vaishak at 120 kg N and 60 kg K_2O (V_1F_3) registered the highest straw yield of 3602 kg ha^{-1} in 2020 and 3256 kg ha^{-1} in 2021, significantly outperforming other treatments. Conversely, the lowest straw yield was recorded in Aiswarya supplied with 60 kg N and 30 kg K, O (V_2F_1) and Vaishak with the same nutrient dose (V_1F_1) across both years. On average, straw yield increased by 21% in Vaishak and 14% in Aiswarya, reflected varietal differences in nutrient utilization efficiency.

The observed increase in grain and straw yield can be explained by the role of nitrogen in enhancing tiller production and spikelet number per panicle, thereby reducing yield losses during flowering under heat stress (Liu *et al*., 2019). Similarly, nitrate fertilization has been reported to alleviate heat-induced damage in rice by supporting reproductive development (Zhang *et al*., 2023). The increase in straw yield at higher nutrient doses also indicates that N and K facilitated greater vegetative growth and dry matter accumulation. However, this was associated with a relatively lower harvest index, as a greater proportion of assimilates were partitioned to straw rather than grain (Kaur *et al*., 2022 and Radha *et al*., 2023). The results suggest that balanced N and K fertilization not only improves sink traits such as grain yield but also enhances biomass production, enabling rice to withstand high-temperature stress more effectively. Varietal differences indicate that Vaishak was more responsive than Aiswarya in terms of both grain and straw yield, although both varieties benefited from higher nutrient inputs.

NPK uptake

Significant differences were observed among treatments for nitrogen, phosphorus and potassium uptake by rice under high-temperature stress (Table 2). The maximum nitrogen uptake was recorded in Vaishak supplied with 120 kg N and 60 kg K_2O (V_1F_3) and Aiswarya at the same nutrient level (V_2F_3), both of which were significantly superior to other treatments in both years. Phosphorus uptake was highest in Aiswarya with 120:60 kg NK/ha (V_2F_3), which consistently outperformed all other treatments, while the greatest potassium uptake was obtained in Vaishak (V_1F_3). These results emphasize the varietal differences in nutrient absorption efficiency, with Aiswarya being more responsive to phosphorus and Vaishak to potassium. Enhanced nutrient uptake under higher N and K fertilization may be attributed to improved root development, greater root activity and expanded leaf area, which collectively promote dry matter production and higher yield potential (Ram *et al*., 2020). Adequate nutrient supply not only ensured better vegetative growth but also supported reproductive processes under stress by sustaining assimilate partitioning to grains. The close relationship between nutrient uptake and biomass accumulation observed in this study is consistent with earlier report by Samant *et al*. (2023). Thus, balanced fertilization plays a pivotal role in improving nutrient uptake efficiency, enabling rice to withstand high-temperature stress conditions.

CONCLUSION

The present study demonstrates that the rice varieties Aiswarya and Vaishak responded positively to nitrogen and potassium fertilization under terminal heat stress, with notable improvements in panicle number, filled grains per panicle, yield, 1000-grain weight and nutrient uptake. Application of 120:60 kg N and K^2O ha^{-1} significantly reduced the adverse effects of heat stress, with Vaishak showing superior performance across yield attributes, grain yield and NPK uptake. These findings highlight the importance of balanced nutrient management in sustaining productivity under climate-induced stress. Future research should focus on integrating nutrient management with physiological, molecular and breeding approaches to develop resilient rice varieties adaptable to high-temperature environments.

ACKNOWLEDGEMENT

The present study was supported by Kerala Agricultural University, Thrissur for the facilities provided.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

All animal procedures for experiments were approved by the Committee of Experimental Animal care. and handling techniques were approved by the University of Animal Care Committee.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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