MANAGEMENT OF HIGH TEMPERATURE STRESS IN AEROBIC RICE (*Oryza sativa* L.)

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THESIS

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2020

DECLARATION

I, hereby declare that this thesis entitled **"Management of high temperature stress in aerobic rice (*Oryza sativa* L.)"** is a bona-fide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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Certified that this thesis, entitled **"Management of high temperature stress in aerobic rice (*Oryza sativa* L.)"** is a record of research work done independently by **Mr. M. Saravana Kumar** (2016-21-028) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

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We, the undersigned members of the Advisory Committee of **Mr. M. Saravana Kumar (2016-21-028)**, a candidate for the degree of **Doctor of Philosophy in Agriculture** with major field in **Agronomy**, agree that the thesis entitled **"Management of high temperature stress in aerobic rice (*Oryza sativa* L.)"** may be submitted by Mr. M. Saravana Kumar in partial fulfilment of the requirements for the degree.

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(M. Saravana Kumar)

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Symbols / Notations and Abbreviations

µg/g	-	Microgram per gram
µ mol/g		Micro moles per gram
µ mol CO_2 /m^2/s	-	Micro moles CO_2 per metre square per second
%	-	Percentage
℃	-	Degree Celsius
℃ day		Degree day
℃ day h		Degree day hour
B:C	-	Benefit cost ratio
cal /cm^2/d		Calories per centimeter square per day
CATD		Canopy air temperature
cm	-	Centi metre
CD	-	Critical difference
CRD	-	Completely Randomized Design
CSI		Chlorophyll stability index
dS m^{-1}	-	Deci Siemen per meter
DAS	-	Days after sowing
DMP	-	Dry matter production
DHY	-	Dehydrogenase activity
EC	-	Electrical conductivity
et al.	-	Co-workers
Fig.	-	Figure
g/cm^3	-	Gram per centimeter cube
g/hill	-	Gram per hill
g/min	-	Gram per minute
gsm		Gram per meter square
ha	-	Hectare
h	-	Hours
KAU		Kerala Agricultural University
kg/ha	-	Kilo gram per hectare

l	-	Litre
m	-	Metre
ml	-	Milli litre
mg/g	-	Milli gram per gram
m mol $H_2O/m^2/s$	-	Milli moles per H_2O per metre per second
MSI		Membrane stability index
MDA	-	Malondialdehyde
n mol/g	-	Nano mole per gram
NO_3-N	-	Nitrate nitrogen
NH_4-N	-	Ammoniacal nitrogen
NS	-	Non-significant
POP	-	Package of practices
RBD		Randomized Block Design
₹/ha	-	Rupees per hectare
SOD	-	Superoxide dismutase
t/ha	-	Tonnes per hectare

Introduction

1. INTRODUCTION

Rice is the most important and extensively grown food crop in the world providing staple food to more than 60 per cent of the global population. Rice plays a vital role in our national food security and is a means of livelihood for millions of rural households. India has the largest area under rice in the world and ranks second in production after China. The area under rice cultivation in India is 43.99 million hectares with a production of 109.70 million tonnes and productivity of 2.49 t/ha (GOI, 2018).

Increase in population is likely to increase the pressure on Indian agriculture, in addition to limitations with respect to land-use, water availability and other resources and globalization. There is an urgent need to raise the rice production to 137.3 million tonnes by 2050 to feed the projected population of 1824 million people in India (Kumar *et al*., 2014). Khush (2005) has estimated that 40 per cent more rice needs to be produced by 2030 to satisfy the growing demand without affecting the resource base adversely.

With respect to Kerala, the rice production was 7.04 lakh tonnes from an area of 3.22 lakh hectares during 2001-02, and during 2017-18, the production declined to 5.21 lakh tonnes from an area of 1.94 lakh hectares (GOK, 2018). The state has witnessed 38 per cent reduction in rice area and 47 per cent reduction in production during these years.

Rice production is facing many problems around the world due to many biotic and abiotic stresses (Sabouri *et al*., 2011). Low land rice has relatively high water requirement and hence the sustainability of rice production is threatened by increasing water shortage. Aerobic rice production method can address the problem of water scarcity to some extent. Global mean surface air temperature increased by about 0.5ºC in the 20th century and may further increase by 1.5 to 4.5ºC in this century (IPCC, 2001). It is reported that the grain yield will decline by 10 per cent with an increase of 1ºC in minimum temperature (Peng *et al*., 2004). It is projected that by the end of the 21st century, in India the mean annual temperature will rise by 3-5°C and rice yields have been estimated to be reduced by 41 per cent due to temperature stress (Matsui *et* *al*., 2001). The mean maximum temperature over Kerala has risen by 0.8°C, the minimum by 0.2℃ and the average by 0.5℃, indicating that the temperature trend in Kerala followed the trend of the west coast (Mohan, 2018). February and March are the hot months of Kerala with a mean maximum temperature of 33℃.

In the current scenario rice is grown mostly in the regions where temperature is already close to optimum for rice production. The further increases in mean temperature during sensitive stages might be harmful and could drastically reduce grain yield. It is reported that the unusual rise in atmospheric temperature during different growth phases causes detrimental effects on growth, yield, and quality of rice by affecting its phenology, physiology and yield components. Since, rice plants can tolerate only narrow temperature range, especially during the flowering phase, fertilization and grain production are affected, resulting in reduced yield. Different phenological stages of plant growth differ in sensitivity to high temperature. Even a short period of heat stress during flowering period can cause significant increases in the abortion of floral buds and opened flowers. Significant reductions had been reported in different rice varieties in total dry weight, root dry weight, total root length, leaf area and specific leaf area in response to increased daily mean temperature from 28ºC to 32ºC (Rankoth and Cost, 2013). High temperatures will damage photosynthetic membranes and cause chlorophyll loss, decrease leaf photosynthetic rate, increase embryo abortion, lower grain number, and decrease grain filling duration and rates, resulting in lower grain yield.

Cultivation of high temperature-tolerant cultivars is one of the most effective counter measures to maintain high productivity and stability of rice under anticipated climate change (Horie *et al*., 1996). Selection of high temperature resistant varieties and adopting proper nutrient management practices could be an important step towards realization of high and stable yield under high temperature conditions expected in the future due to global warming.

Nitrogen plays a very crucial role in temperature stress tolerance as photosynthetic capacity of plants is closely associated with leaf nitrogen content. Nitrogen fertilization has been reported to mitigate the adverse effects of abiotic stresses and studies revealed that N-adequate plants are able to tolerate excess light by maintaining photosynthesis at high rates and developing protective mechanisms. Application of sufficient nitrogen during the reproductive stage is important to reduce the occurrence of heat damage (Morita *et al*., 2016).

Potassium also plays a crucial role in survival of crop plants under environmental stress apart from its role 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 heat stress condition (Mengel and Kirkby, 2001). It also regulates cellular turgor pressure to avoid wilt, in turn controlling the regulation of stomatal opening and closing and greatly enhancing drought and heat tolerance in plants. Potassium deficiency causes severe reduction in photosynthetic CO_2 fixation, impairment in portioning and utilization of photosynthates, stimulation of reactive oxygen species (ROS) production during both electron transport and NADPH – oxidizing enzyme reactions involved in membrane damage and chlorophyll degradation (Kemmler and Krauss, 1987).

However, very little research has been conducted on alleviation of high temperature stress through fertilizer application. Hence, the research programme entitled "Management of high temperature stress in aerobic rice (*Oryza sativa* L.)" was conducted with the following objectives

1. To assess the effect of high temperature stress at different growth phases of rice with respect to growth, physiological parameters, yield attributes and yield.
2. To study the response of aerobic and wetland rice varieties to high temperature stress and
3. To study the effect of nitrogen and potassium nutrition on mitigation of high temperature stress.

Review of Literature

2. REVIEW OF LITERATURE

Most of the world's rice is grown in tropics and the critical determining factor for growing rice appears to be temperature. Plant growth and development is closely related to various biotic factors and change will directly affect crop production. The projected rise in global warming is expected to have a tremendous negative impact on rice production. Review indicated that high temperature stress can damage photosynthetic membranes and cause chlorophyll loss, decrease leaf photosynthetic rate, increase embryo abortion, lower grain number, and decrease grain filling duration and rates, resulting in lower grain yield. Tropical crops exhibit immediate yield decline with even the slightest warming because they are currently grown under conditions close to maximum temperature tolerance. Siqueira *et al*. (1994) reported that an increase in the mean air temperature between 3 to 5°C in Central South region of throughout the year would cause a reduction of 30 and 16 per cent in wheat and corn production by 2050. Research works on the effect of high temperature stress on growth, yield and physiological parameters of rice as well as other cereal crops are reviewed here.

2.1 EFFECT OF HIGH TEMPERATURE STRESS ON GROWTH CHARACTERS

2.1.1 Plant height

Rice can tolerate relatively high temperature during vegetative stage (35°C day temperature and 25°C night temperature) and increase in temperature beyond this reduced plant height, tiller number and total dry matter production (Yoshida, 1973). High day and night temperature enhanced internode elongation in rice due to increased cell elongation in the internodal region (Singh, 2010). Johnson *et al*. (2011) found that plant height at maturity was higher under heat stress imposed along with low light intensity (+3°C than ambient and 20 % reduced light) when compared to control and the maximum plant height was observed when stress given from tillering to maturity (23.8 %). Similarly Aghamolki *et al.* (2014) stated that the increase in plant height was rapid under high temperature (30-35°C) than under ambient condition. Rice plants were taller when exposed to high night temperature of 25°C than at 21°C (Laza *et al*., 2015). Samol *et al*. (2015) found that the tallest rice plants were produced under high temperature (above 2-4°C at daytime and 1-2°C at night time) compared to ambient condition. Amjath, (2018) and Mohan (2018) also found that rice plants under heat stress were taller. However according to Prasad *et al*. (2005), heat stress decreased growth rate resulting in decreased plant height in rice.

Venkatramanan and Singh (2009) revealed that irrespective of the variety, plants subjected to high day and night temperature showed increase in plant height and the early maturing variety Pusa Sugandh 2 was found to be more sensitive to high temperature than Pusa 44. In heat tolerant rice varieties N22 and mutant NH219 height increased even when exposed to 44°C (Poli *et al*., 2013). Sailaja *et al*. (2015) also found that tallest plants in variety N22 and shortest plants in Varadhan under elevated temperature among 11 rice cultivars tried.

2.1.2 Number of tillers

In rice, tillering increased with rise in temperature in the range of 15-33°C (Sato, 1972). Increase in day temperature from 29°C to 37°C reduced tiller number by 10 per cent (Manalo *et al*., 1994). The number of tillers was found to be lower under high temperature (Oh-e *et al*., 2007). Kumar *et al*. (2011) stated that when wheat plants were exposed to heat stress, number of tillers per hill tend to decrease with promoted shoot elongation. Samol *et al*. (2015) reported that number of tillers reduced under high temperature stress. Lower number of tillers were observed when rice plants were exposed to high temperature stress from panicle initiation stage to harvest as well as from seedling to active tillering phase (Amjath, 2018). Maity *et al*. (2019) stated that tillering in rice decreased under elevated temperature (2°C than ambient).

The differential response of rice varieties to temperature stress during tillering phase is also reported. The detrimental effect of high temperature on tiller numbers was more in Pusa Sugandh and it was more thermosensitive than Pusa 44 (Venkatramanan and Singh, 2009). Sailaja *et al*. (2015) also found higher number of tillers per hill was observed in Krishna Hamsa, whereas lowest number of tillers per hill was observed in Jaya and BPT5204 among 11 rice cultivars under elevated temperature (5.5°C above mean maximum temperature). Whereas, Jumiatun *et al*. (2016) observed that the tiller number increased with increase in temperature in all varieties.

The higher day and night temperature greatly reduced the tiller production and development, due to shorter crop growth duration and respiratory loss which in turn reduced the biomass production.

2.1.3 Leaf area

The high temperature has positive impact on biomass production at early stages of growth due to enhanced tillering, leaf expansion and nutrient uptake. Heat stress also resulted in significant increase in leaf number without any decrease in photosynthetic rate (Prasad *et al*., 2008). Venkatramanan and Singh (2009) reported that plants grown at higher temperature (2.7 °C above ambient) showed greater specific leaf area. Vysakh (2015) attributed reduction in LAI in late planted rice to increase in maximum temperature during flowering period in rice. Laza *et al*. (2015) found that high night temperature (25°C) increased leaf area by 3-16 per cent as compared to low night temperature (21°C).

Amareshkumar *et al*. (2017) evaluated response of different rice genotypes to high temperature regimes and observed that the highest LAI was for genotype EC792176 (3.95) under normal sown condition (December) but lowest LAI was for genotype EC792234 (1.86) under late sown condition (January) at 85 DAS. Kumar *et al*. (2017) evaluated different indica rice genotypes under terminal heat stress condition and reported that the maximum reduction in flag leaf area observed in IET 20944 (15 % and 19 %) on 10^{th} and 25^{th} days after treatment. Beena *et al*. (2018) found that many rice genotypes showed an increase in specific leaf area under high temperature stress (6-8°C above the ambient) from panicle initiation to maturity and range in increase was 4-30 per cent among different varieties. The highest reduction in leaf area was observed in the plants which were exposed to combined drought and heat stress followed by heat stress alone and among varieties, the higher leaf area was recorded in Swarnaprabha (Ptb-15) and Vaishak (Ptb-60) (Mohan, 2018).

2.1.4 Days to flowering

In case of photo-insensitive cultivar IR26, temperature above 26°C was found to decrease the number of days to heading (Yoshida, 1981). High day and night temperature (2.7°C above ambient temperature) showed maximum reduction in the days to flowering and days to maturity which was due to increase in temperature, increases rate of growth and metabolism (Venkatramanan and Singh, 2009). Singh *et al*. (2010) also reported that high temperature stress (above 2.5°C than ambient) during vegetative phase results in early maturity (125 days) of Pusa 44 variety compared to ambient temperature (135 days). Similarly, Rani and Maragatham (2013) reported that high temperature stress shortened crop duration of rice, where the heat stress treatment (4°C above ambient) reduced crop duration from 108 to 96 days and heat stress (2°C above ambient) reduced crop duration from 108 to 102 days.

Johnson *et al*. (2011) studied the response of five basmati rice varieties to high temperature at different growth stages and early flowering when stress was given from tillering to maturity and tillering to flowering (67 days) as compared to control (72 days). Thus heat stress showed greater influence on days to flowering than on days to ripening and resulted in shortening of crop duration. Among the varieties, minimum crop duration was recorded in Taraori Basmati followed by Basmati 370 and Pusa sugandh 2. The variety Basmati 386 had showed stability to thermal stress. Lakshmiprasanna *et al*. (2014) evaluated four rice cultivars to temperature stress (ambient + 5°C) throughout the growing period and found that increased temperature reduced crop duration by 5 days in N22 and ADT 43 whereas in TKM 9 and CORH 3 reduced by 4 days. Sailaja *et al*. (2015) observed a significant reduction in number of days to 50 per cent flowering and number of days to maturity under high temperature stress (5.5°C higher than ambient maximum temperature) in 11 Popular and mega rice cultivars widely grown in India. High temperature tolerant variety N22 matures at 97 days under control while at high temperature it matures at 90 days. Beena *et al*. (2018) conducted an experiment to study the response of rice cultivars to high temperature (6-8°C above ambient condition) from panicle initiation to maturity and observed earliness in flowering in most of the varieties but a few cultivars IET23275, IET23297 and IET23300 showed delayed flowering under high temperature.

2.1.5 Dry matter production

The total dry matter production is also affected by high temperature stress. The total dry weight of cultivar IR747B2-6 at 35/25°C (day/night temperature) was only one sixth of that at 30/25°C (Yoshida, 1981). Exposure of wheat during reproductive stage to heat stress resulted in decline in photosynthesis, leaf area, and shoot weight (Shah and Paulsen, 2003). High temperature reduce plant growth and total dry weight by affecting the net assimilation rate (Wahid *et al*., 2007). The biomass of wheat varieties decreased in response to heat stress (35/20°C: day/night temperature) in all three phases such as shooting, early grain development and grain filling. Biomass of variety 'Mv Magma' decreased to a greater extent than 'Plainsman V' when heat stress was imposed (Balla *et al*., 2012). Samol *et al*. (2015) found that plant dry matter was reduced under elevated temperature (2-4°C at daytime and 1-2°C at nighttime above ambient). Also, high temperature stress increased the shoot dry weight in different rice cultivars due to increase in number of tillers per hill. The maximum shoot dry weight was recorded by cultivar Menthik Wangl of 91.2 g per plant at 33.1°C than 43.9 g per plant at 28.3°C (control) was studied by (Jumiatun *et al*., 2016). However, Thuy and Saitoh (2017) found that shoot dry weight of rice cultivars decreased drastically, under high temperature stress. The maximum reduction in shoot dry weight was observed in OM4900 and OM5451 out of 14 cultivars and the mean difference in dry mass between control and high temperature was about 0.08–0.58 kg/m. Kumar *et al*. (2017) observed a minimum drymatter production in rice cultivar IET 20894 under terminal heat stress compared to IET 20734.

2.1.6 Root weight

Root growth may be affected more severely than shoot growth at high temperature because roots have a lower optimum temperature requirement (Nielsen, 1974). In bentgrass, shoot growth increased with temperature from 12 to 36°C, but weight of roots grown at 36°C were only 70 per cent of those grown at 24°C and 54 per cent of those grown at 12°C (Schmidt and Blaser, 1967). According to Huang and Xu (2000), fresh root weights of two bentgrass cultivars reduced significantly when shoots (35/20°C), roots (20/35°C) or both shoots and roots (35/35°C) were exposed to high temperature stress compared to control (20/20°C). Under elevated temperature condition there was lesser dry matter portioning towards root and grain whereas more partitioning towards shoot was reported by Raj and Chakrabarti (2016). Similar result was reported by Kim and You (2010). The highest reduction in root dry weight was observed under combined heat and moisture stress in all the rice genotypes except for N22 and Apo (Mohan, 2018).

2.2 EFFECT OF HIGH TEMPERATURE STRESS ON YIELD AND YIELD ATTRIBUTES

2.2.1 Number of panicles

Number of panicles per unit area is an important yield determinant in rice. A reduction in productive tillers per hill under high temperature stress (30/25°C, day/night temperature) was observed by Djanaguiraman *et al*. (2010). Plants grown under high night temperature (5°C higher than ambient) showed more tillers per hill compared to ambient temperature during first three weeks after heat treatment (Mohammed and Tarpley, 2010). Singh *et al*. (2010) reported that high-temperature stress (2.5°C than ambient) during vegetative phase showed maximum reduction (24%) in the number of panicles per m^2 compared to ambient temperature, followed by stress during reproductive (12 %) and ripening phase (1 %). But, Liu *et al*. (2013) could not observe any significant difference in effective panicles per m^2 between heat stress condition and normal condition. The number of total and effective tillers per plant was the highest under heat stress (36°C) at tillering stage and at flowering stages (Hazra *et al*. 2016). When heat stress was given from 56 days after sowing to harvest, the number of productive panicles decreased significantly in all eight rice cultivars. At 32.1°C, there was 1-5 productive panicles, while at 33.1°C all panicles produced unfilled grains (Jumiatun *et al*. 2016). Mohan (2018) stated that stress conditions reduced number of panicles in all the genotypes and the reduction was more under combined heat and drought stress and genotype Ptb-7 produced more number of panicles.

2.2.2 Total number of grains per panicle

The reproductive phase of rice was the most sensitive stage to high temperature stress because during this period the spikelet differentiation occurs and the potential number of spikelets in rice is determined (Kato *et al*., 2008). A reduction in number of grains per panicle was observed in rice plants when high temperature stress (2.5°C above ambient) was imposed during reproductive phase (Singh *et al*., 2010). Johnson (2011) revealed that exposure of high temperature and low light intensity (3°C than ambient and 20 % reduced light) during various growth stages of basmati rice varieties caused marked reduction in the number of spikelets per panicle compared to control and the lowest number of spikelets per panicle was recorded when plants experienced stress from tillering to flowering stage. A reduction in spikelet number per panicle during dry season was recorded by Zhang *et al*. (2013), which was due to mild increase in night temperature during reprodutive growth. Laza *et al*. (2015) stated that rice cultivars exposed to high night time temperature (25°C) during early reproductive stage showed the lowest number of spikelets per panicle with 36 per cent of degenerated spikelets, significantly higher than other treatments and among cultivars, IR72 was moderately affected. Samol *et al*. (2015) reported that length of panicle, number of grains per panicle under temperature stress (2-4°C above ambient) were significantly greater than ambient temperature. Jumiatun *et al*. (2016) studied the response of eight rice cultivars to high temperature stress from 56 days after sowing to harvest and concluded that at 33.1°C, number of spikelets per panicle decreased in Ciherang and Hipa 14 whereas increased in Menthik Wangl, IPB 3S, IR 64 and Wat Apo Buru compared to 28.3°C.

Temperature affects percentage of filled grains and the length of ripening period, which are inversely correlated with the mean daily temperature (Yoshida, 1983). Number of filled grains per panicle decreased by 26 per cent when plants were exposed to high air temperature compared to normal air temperature (Liu *et al*., 2013). The percent reduction of filled grains of eleven rice cultivars under high temperature stress from 11-66 per cent and among the cultivars IET 21404 and IET 21577 recorded higher number of filled grains (Kumar *et al*., 2015). Exposure of rice cultivars to elevated temperature (5.5°C higher) significantly reduced number of filled grains compared to control and BPT5204 was found sensitive to temperature stress with more number of chaffy grains and N22 was found resistant to temperature stress (Sailaja *et al*., 2015). Higher percentage of unfilled grains under elevated temperature was also reported by Samol *et al*. (2015) and Thuy and Saitoh (2017). The spikelet sterility increased drastically in OM1490, OM 598, AS996, and OM6162 where least affected in OM8923. High temperature decreased filled grains per panicle, grain weight and weight of 1000 grains in eight rice varieties. The lowest filled grain was recorded by HIPA 14 followed by Menthik Wangl at 32.1℃ and all rice varieties produced unfilled grains, when plants were exposed to 33.1℃ (Jumiatun *et al*., 2016). Kumar *et al.* (2017) reported that lowest spikelet fertility was obtained in genotype IET 20915 and highest in IET 20734 under terminal heat stress in rice. High temperature stress imposed from panicle initiation to maturity, most of the genotypes showed 70-80 per cent spikelet sterility. The genotypes IET23324, IET23300, Jyothi and N-22 showed higher spikelet fertility (Beena *et al*., 2018).

2.2.4 Thousand grain weight

When rice plants were grown under high night temperature (ambient + 5℃) decline in 1000 grain weight was observed (Mohammed and Tarpley, 2010). According to Singh *et al*. (2010), the extent of decline in 1000 grain weight was more when temperature stress was during ripening phase. Liu *et al*. (2013) reported that 1000 grain weight decreased by 5 per cent under high temperature stress (2℃ and 0.3℃ above ambient day and night temperature) compared to normal air temperature. Among different rice genotypes, the higher 1000 grain weight was for cultivars IET 21404 and IET 21577 under heat treatment and about 12 per cent reduction in 1000 grain weight was observed in other inbred and hybrids (Kumar *et al*., 2015). Sailaja *et al*. (2015) reported that 1000 grain weight significantly reduced by 5 per cent under high temperature stress (5.5℃ above maximum temperature) compared to control. Hazra *et al*. (2016) observed minimum 1000-grain weight under high temperature (36℃) at booting stage (23.20g). There was significant reduction in thousand grain weight in different rice genotypes during late sown conditions due to coincidence of high temperature during peak anthesis stages compared to normal sowing (Amareshkumar *et al*., 2017). Kumar *et al*. (2017) opined that terminal heat stress drastically reduced the thousand grain weight in rice genotypes and IET 20923 genotype recorded the lowest thousand grain weight of 7.67 g under heat stress compared to control (21.35 g). Amjath (2018) observed that high temperature stress (ambient + 2°C) during early reproductive phase to maturity registered minimum thousand grain weight of 21.30 g in rice in rice variety Jyothi. Similarly, Mohan (2018) found that combined drought and heat stress lead to the lowest 1000 grain weight in all rice varieties tried.

2.2.5 Grain yield

It is reported that the grain yield will decline by 10 percent with 1ºC increase in minimum temperature (Peng *et al*., 2004). Mohammed and Tarpley (2010) observed 10 per cent yield reduction under high night temperature (ambient + 5°C) from 20 days after emergence to harvest compared to ambient condition. Singh *et al*. (2010) concluded that high-temperature stress (2.5°C above ambient) during the vegetative and reproductive growth phases caused greater reduction in grain yield (23% and 27%) as compared with during the ripening phase, which showed 7 per cent reduction in grain yield. Grain yield per plant declined by 33 per cent in N22 cultivar and 23 per cent in NH219 under elevated temperature (44°C) than ambient (38°C) (Poli *et al*., 2013). Aghalmolki *et al*. (2014) revealed that grain yield reduced when heat stress was imposed from booting and flowering stage and the heat stress during ripening stage did not affect yield. Rani and Maragatham (2013) conducted an experiment to study the effect of elevated temperature (ambient + 2°C and +4°C) on rice. The results revealed that under elevated temperature, grain yield was 23 and 13.3 per cent. The highest grain yield of 6.2 t/ha was recorded at ambient temperature followed by 5.3 t/ha under 2°C level and 4.7 t/ha at 4°C level.

Increasing mean temperature by 12°C at full flowering was found to severely affect the spikelets and the net reduction in grain yield was 27 per cent in eleven rice genotypes. They also inferred that hybrids showed a yield loss of above 30 per cent whereas for the inbred decline in yield was only 15 per cent. The genotypes IET 21404 and IET 21577 was considered as heat tolerant (Kumar *et al*., 2015). Sailaja *et al*. (2015) studied the response of 11 rice cultivars to high temperature stress (5.5°C above maximum temperature), grain yield decreased by 29 per cent under elevated temperature. According to Hazra *et al*. (2016), the lowest grain yield per plant (16.87 g) was observed when heat stress (36°C) was imposed at booting stage. Amareshkumar *et al*. (2017) attributed the yield reduction in late sown rice to high temperature stress experienced during flowering and grain filling stages. Kumar *et al.* (2017) observed grain yield drastically declined under terminal heat stress and vary with rice genotypes. The maximum reduction in grain yield was obtained in IET 20923 (33.89 %) and minimum reduction was obtained in IET 20734 (4.29 %). Similar findings were reported by Amjath (2018).

2.2.6 Straw yield

Venkatramanan and Singh (2009) found that high temperature (2.7°C higher than ambient) resulted in 18% reduction in biomass production compared to control. According to Zakaria *et al*. (2002), high respiratory demand and higher tiller mortality under high temperature resulted in lower biomass accumulation. Johnson *et al*. (2011) found that the straw yield of basmati rice varieties decreased significantly when subjected to high temperature and low radiation (ambient + 3°C and 20 % reduced light) compared to normal condition irrespective of the variety and increase in straw yield was record highest when stress given from tillering to maturity (49%) followed by tillering to flowering (42%). This may be due to the longer stem caused by increased plant height when subjected to hyper thermal and low light stress in glass house. High night temperature (25°C) during reproductive phase significantly reduced above ground mass by 10 per cent (Laza *et al*., 2015). Maity *et al*. (2019) concluded that straw yield decreased under high temperature stress (ambient + 2°C). Mohan (2018) observed 38 per cent reduction in shoot dry weight in Ptb-15 exposed to combined heat and drought stress.

2.2.7 Harvest index

Prasad *et al*. (2005) revealed that harvest index significantly decreased in all cultivars and decrease in HI was less in cultivars N-22 and WAB-16 (42%) compared to all cultivars where decrease in HI ranged between 45 and 88 per cent. The lowest value of harvest index was recorded when temperature stress was given during reproductive phase (Singh *et al*., 2010). Johnson *et al*. (2011) stated that lowest harvest index (20 %) was observed when high temperature stress (3°C above ambient) during tillering to maturity and highest HI (37%) was recorded under control. Poor grain development due to non-diversion of photosynthates from vegetative shoot to panicle may possibly be one of the reason for poor harvest index in plants subjected to high temperature stress. Balla *et al*. (2013) observed the greatest reduction of harvest index in two wheat varieties when heat stress (30-35°C) was imposed at early stage of embryo development. Heat stress during grain filling had little effect on HI of 'Mv Magma' whereas HI was affected to the greatest extent by heat stress at first node appearance, but in 'Plainsman V' heat stress had the least effect in this stage. Laza *et al*. (2015) opined that the reduction of sink size by high night temperature due to increased spikelet degeneration, might partly explain the low harvest index and biomass under high night temperature (25°C). This is in accordance with the findings of Peng *et al*. (2004) and Zhang *et al*. (2013).

2.3 EFFECT OF HIGH TEMPERATURE STRESS ON PHYSIOLOGICAL PARAMETERS

2.3.1 Relative water content (RWC)

Moisture content is an important variable under changing ambient temperatures. High temperature caused water loss in plants more during daytime than during night when exposed to high temperature plants tend to avoid heat by maintaining temperature below critical level by efficient transpiration cooling. This might lead to decrease in water potential and perturbation of many physiological processes (Mazorra *et al*., 2002). The relative leaf water content was found to decrease with increase in temperature in wheat cultivars and the decrease was more in susceptible cultivars, particularly under late sown conditions. The wheat cultivar C 306 maintained higher RWC both under normal and late sown conditions (Sairam *et al*., 2000). Poli *et al*. (2013) reported that relative leaf water content decreased by 2.29 per cent in N22 and by 1.10 per cent in NH219 under heat stress condition (44°C) compared to ambient condition (38°C). Kavitha and Pandey (2017) found a significant difference in RWC in Indian mustard genotypes under heat stress condition and RWC ranged from 52.28 (RGN 330) to 118.61 per cent (PRO 5222) and this indicates that higher RWC content is a good indicator of temperature tolerance.

2.3.2 Stomatal conductance

In general, during heat stress period, decreased conductance through stomata is the primary cause of decline in photosynthesis. Stomatal conductance and net photosynthesis were inhibited by elevated temperature stress owing to decreased Rubisco activase enzyme (Crafts-Brander and Salvucci, 2002; Morales *et al.*, 2003). Stomatal movements provide the leaf with the opportunity to change both the partial pressure of CO_2 at the sites of carboxylation and the rate of transpiration. According to Sailaja *et al.* (2015), stomatal conductance in rice was significantly affected during vegetative phase than reproductive phase under elevated temperature and the decrease in stomatal conductance was 22% (vegetative phase) and 11% (reproductive phase). Amareshkumar *et al.* (2017) reported that rice genotype EC792192 showed lowest leaf stomatal conductance value of 1.66 mol $H_2O/m^2/s$ under late sown condition compared to normal sown condition. Similar results were reported by Agaee *et al.* (2011) and Jerry and John (2015). Most of the rice varieties showed higher values of stomatal conductance and transpiration rate under high temperature condition compared to ambient temperature (Beena *et al.*, 2018). Minimum stomatal conductance (0.07 mol $H_2O/m^2/s$) was observed in rice plants subjected to high temperature stress together with low UV-B radiation from early reproductive phase to harvest (Amjath, 2018).

2.3.3 Net photosynthetic rate

The leaf photosynthesis of rice increased from 22°C to 32°C and then decreased (Egeh *et al.*, 1992). High temperature reduced the photosynthetic rate by 40 - 60 per cent at mid ripening stage which lead to rapid senescence of the flag leaf (Oh-e *et al.*, 2007). Sanchez-Reinoso *et al.* (2014) observed an increase in the leaf photosynthetic rate in three rice cultivars (F60, F733, and F473), when the daytime temperature increased from 25 to 35°C, whereas photosynthetic rate decreased at 40 °C in all varieties and the same trend was recorded in leaf transpiration and respiration rate. The photosynthetic rate in cultivar ‘F60’ was remarkably reduced by 40 per cent compared to the other two cultivars. Sailaja *et al.* (2015) found that net photosynthetic rate in different rice cultivars reduced by 28 and 23 per cent, respectively when temperature stress was imposed at vegetative and reproductive phases, respectively. Among genotypes, the highest reduction was observed in BPT5204, Vandana, and Varadhan, whereas Jaya, N22, Rasi, KrishnaHamsa, and IR64 were found to be less sensitive. Jumiatun *et al*. (2016) stated that increase in temperature increases the leaf transpiration and photosynthetic rate and Menthik Wangl, Jatlluhur and HIPA 14 cultivars shown increased values of photosynthetic rate with increase in temperature. The lowest photosynthetic rate at high temperature was recorded by genotype EC792186 (15.80 µmol $CO_2/m^2/s$) under late sown condition and the higher photosynthetic rate was observed in EC792236 (24.72 µmol $CO_2/m^2/s$) under normal sown condition (Amareshkumar *et al*., 2017). The photosynthetic rate got significantly reduced (46 per cent reduction) under high temperature condition in different rice varieties. The highest photosynthetic rate was recorded in IET22116 (16.03 µmol/m^2/s) and lowest in IET22896 (2.87 µmol/m^2/s) (Beena *et al*., 2018).

2.3.4 Chlorophyll content

Almeselmani *et al*. (2006) observed a significant reduction in chlorophyll content under late and very late sowing in different genotypes, however tolerant genotypes HDR 77 and HD 2815 maintained higher chlorophyll content under high temperature in late sown wheat. SPAD values increased initially then fell gradually for both normal and high air temperature treatments after heading stage, whereas, high air temperature (2°C and 0.3°C above ambient day and night temperature) significantly decreased SPAD values by 31 per cent (Liu *et al*., 2013). Chlorophyll *a* content decreased by 24 and 51 per cent in vegetative and reproductive phases under heat stress condition (above 5.5°C than maximum temperature). During vegetative phase, chlorophyll *a* content increased in N22 and Sampada cultivar, however maximum reduction was recorded in BPT5204, whereas almost all cultivars showed reduction in Chl *a* during reproductive phase. The total chlorophyll content was decreased 15 during vegetative phase and 42 per cent during reproductive phase in different rice cultivars (Sailaja *et al*., 2015). Jumiatun *et al*. (2016) found that SPAD value increases with increase in average temperature from 28.3 to 33.1°C in all eight rice varieties in Indonesia. Kumar *et al*. (2017) observed higher total chlorophyll content in rice in control and lower chlorophyll content observed in rice under heat stress condition. In rice SPAD chlorophyll meter reading reduced under high temperature stress and varietal differences were significant (Beena *et al.*, 2018).

2.3.5 Chlorophyll stability index

The high chlorophyll stability index (CSI) value gives an indication of stress tolerance (Verma, 1999). The high CSI shows that the plant has the ability to convert the glutamate into proline and proline have diverse roles under different abiotic stresses. Under high temperature stress conditions, there was decline in chlorophyll stability in terms of loss of chlorophyll content in all genotypes of cotton. This decline in CSI was least in tolerant genotype and highest in susceptible genotype (Ananthi *et al.*, 2013). Mohan (2018) found that N22 genotype recorded the highest chlorophyll stability (108%) followed by (100%) and that drought and heat stress reduced the chlorophyll stability index.

2.3.6 Soluble protein

Rubisco occupied a major portion of soluble protein (50 per cent) in leaves which acts as a prime enzyme for carbon fixation in photosynthesis (Noggle and Fritz, 1986). Xu and Zhou (2006) opined that drought stress decreased leaf nitrogen but temperature stress did not influence leaf nitrogen. However, the total soluble protein content decreased during drought, temperature and a combination of drought and temperature stress. Under high air temperature (2℃ and 0.3℃ above ambient day and night temperature), the soluble protein content in rice flag leaf was reduced by 10 per cent compared to normal air temperature (Liu *et al*., 2013). Perdomo (2017) concluded that high temperature stress induced suppression of photosynthesis by mainly decreasing the proportion of soluble protein to total leaf nitrogen, adversely affecting the Rubisco protein syntheis and activity.

2.3.7 Nitrate reductase activity

The photosynthetic capacity of plants is closely associated with leaf nitrogen at cellular level. Heat stress can decrease N availability, plant N uptake, leaf N, and activities of N assimilatory enzymes (Al-Khatib and Paulsen, 1984). Nitrate reductase is the first and most important enzyme in the overall nitrogen metabolism of the plant. The reduction of NO_3 to NO_2 catalyzed by nitrate reductase is considered to be the rate-limiting step of N assimilation. Temperature above optimum could impair nutrient uptake (Singh and Sawhney, 1989). Nitrate reductase activity plays an important role in regulating N metabolism which is decreased under high temperature stress. Onwueme *et al*. (1971) found that the activity of nitrate reductase in barley seedling gradually decreased during high temperature stress for 16 to 24 hours. Kumar *et al*. (2017) observed maximum reduction (36 %) of nitrate reductase activity in the genotype IET 20924 under high temperature stress, among various genotypes studied.

2.3.8 Malondialdehyde (MDA)

Lipid peroxidation indicated as MDA content, increased under late sown conditions in various wheat cultivars. Maximum and minimum lipid peroxidation was observed in HD 2329 and C 306 respectively under late sown conditions (Sairam *et al*., 2000). Liu *et al*. (2013) studied the effect of elevated temperature on physiological parameters of rice flag leaf and found that MDA content increased by 7.78 per cent than normal air temperature. Sanchez-Reinoso *et al*. (2014) concluded that electrolytic leakage and MDA content was notably higher in the rice at 40°C and variety F60 seemed to be more susceptible. High temperatures increased the MDA content in F60 by 72 per cent compared to F473 and by 12 per cent compared to F733. Kumar *et al.* (2016) evaluated the rice genotypes under elevated temperature (12°C above ambient temperature) during flowering stage and found the lipid peroxidation level (MDA content) increased by 10 to 170 per cent over control during 2011 and 2012.

2.3.9 Membrane Stability Index (MSI)

Cell membrane stability is a physiological index widely used for evaluation of stress tolerance. High temperature results in melting the lipid bilayer, increasing membrane permeability, and increasing leakage of ions and other cellular compounds from the cell thereby affecting all other metabolic activities. Maintaining proper membrane stability is essential for temperature stress tolerance. The membrane stability index decreased under high temperature in rice cultivars and a pronounced reduction was found in susceptible varieties (Tripathy *et al*., 2000). An increase in night temperature from 27°C to 32°C increased respiration rate as well as in relative membrane injury by 85 per cent compared to normal condition (Mohammed and Tarpley, 2009). Membrane stability index (MSI) varies with varieties and in a study with different varieties Lakshmiprasanna *et al*. (2014) observed minimum reduction in MSI values in variety N22 and maximum reduction was obtained in ADT 43 under heat stress (ambient + 5°C). Response of rice genotypes to higher temperature (maximum temperature from transpanting to maturity was 5.5°C higher) was studied by Sailaja *et al*. (2015). The results revealed that heat stress increased relative injury (RI) by 40 per cent with respect to control and highest increase in relative injury was observed in BPT5204 (90%) followed by Swarna (80%), Krishna Hamsa (42.4%), and Vandana (43%) and lowest in RI was observed in variety MTU1010, IR64, N22, and Rasi (20 - 27%). Under elevated temperature of wheat variety HD 2815 and HDR 77 registered lower membrane injury index at anthesis and 15 days after anthesis than other wheat genotypes (Almeselmani *et al*., 2006). High temperature (12°C above ambient temperature) during flowering stage decreased membrane stability index in all the rice genotypes than control (Kumar *et al*., 2016).

2.3.10 Proline content

Leaf proline content to serve as an effective index to screen plant genotypes for heat tolerance. Heat stress (35 to 40°C for three hours daily for five consecutive days) imposed at anthesis and milk stages significantly increased proline concentration in leaves of all the wheat genotypes compared to control and the highest increase in proline content was recorded in genotype AS-2002 (89%) at milk stage (Khan *et al*., 2015). Sanchez-Reinoso *et al*. (2014**)** observed the effect of high temperature of 35°C and 40°C for 5 hours and proline content increased by 200 per cent in three cultivars, however proline content decreased in F733 and F473 as the temperature increased but proline concentration remained unchanged in cultivar F60. According to Kumar *et al*. (2016), elevated temperature (12°C above ambient) during flowering stage increased proline content by 15 to 40 per cent in various rice genotypes. During flowering, proline content significantly increased in all indica rice genotypes under heat stress and increase was more in new leaves compared to older leaves. Among genotypes, the highest proline content was registered in IET 20926 (113.97 µg/g) under heat stress

(Kumar *et al*., 2017). Amjath (2018) also observed highest proline content (338.51 μ mol/g) in heat stressed rice compared to control (90.85 μ mol/g). Combined drought and heat stress showed maximum proline content of 65.2 μg/g fresh weight compared to 45.3 μg/g fresh weight in control. According to Mohan (2018), the highest proline content of 115.3 μg/g fresh tissue was registered in genotype N22 among rice genotypes studied.

2.3.11 Superoxide dismutase (SOD) activity

High temperature stress in plant produces oxidative stress and it accumulates reactive oxygen species (ROS) in higher concentrations. This will result in disruption of membrane proteins, enzymes and increase the membrane fluidity. In order to detoxify the ROS, plant cells are equipped with anti-oxidative machinery comprised of both enzymatic (SOD, CAT, POX and GPX) and non-enzymatic compounds (Asthir, 2015). Exposure of plants to heat stress leads to decrease in SOD and CAT activity and this reduction was closely related to severity of heat stress and heat tolerance of rice cultivars. The content of high temperature sensitive cultivars decreased more profoundly than those of tolerant cultivars (Karuppanapandian *et al*., 2011). Almeselmani, *et al*. (2006) evaluated the effect of high temperature stress on the antioxidant enzyme activity in wheat genotypes viz., PBW 343, PBW 175, HDR-77, HD 2815 and HD 2865 and found a significant increase in SOD activity at late and very late plantings in all genotypes, however genotypes like HD 2815 and HDR 77 showed increase than other genotypes, which indicate these genotypes have better scavenging capacity and higher tolerance to heat stress than other genotypes. Sailaja *et al*. (2015) recorded increased SOD activity in BPT5204, IR64, Jaya, N22, Rasi, and Vandana rice cultivars, whereas a decrease in varieties Krishna Hamsa, Sampada, and Swarna at vegetative and reproductive phases under elevated temperature (5.5°C above maximum temperature). Kumar *et al*. (2016) studied the effect of high temperature stress (12°C above ambient temperature) during flowering stage in rice and found increased activity of superoxide dismutase in all rice genotypes. Further the increase in SOD activity was more in IET lines as compared to hybrids, which showed that hybrids are more sensitive to heat stress. In another experiment with different rice genotypes Zhao *et al*. (2017) found that SOD activity under high temperature (35/27°C day and night) of Qianjiang 3 decreased by 29.8 per cent than control (28/22; day/night), while the reduction in susceptible cultivar is Xieqinqzao was 36 per cent. The highest SOD activity (0.314/g min) was recorded from Ptb-15 followed by N22 (0.313 g/min) and plants under heat stress recorded lowest SOD activity than combined drought and heat stress (Mohan, 2018).

2.3.12 Canopy air temperature difference (CATD)

Canopy temperature can be used as a sensitive indicator of stress, which is associated with stomatal conductance. Garrity and O'Toole (1995) reported that it is possible to screen varieties of rice for reproductive-stage drought-avoidance traits, using canopy temperature and concluded that tolerant lines remained the coolest under stress. When heat stress was imposed from 56 days after sowing to harvest, leaf temperature increased around 3-6°C at 32.1°C and 33.1°C mean air temperature in all eight varieties of Indonesian rice and the highest leaf temperature was 34.7°C (Jumiatun *et al*., 2016). Amareshkumar *et al*. (2017) stated that leaf temperature significantly decreased under late sown condition in genotype EC792231 (25.42) compared to normal sown condition, which lead to reduction in photosynthesis and grain filling. Beena *et al*. (2018) stated that canopy temperature in rice increased under high temperature condition (6-8°C above the ambient condition) from panicle initiation to maturity than ambient condition. Maintenance of minimum canopy temperature through evaporative cooling system is an adaptive mechanism shown by tolerant genotypes.

2.2.13 Protein content in grains

In rice terminal heat stress is reported to influence quality of rice grains. High temperature stress influences grain protein content and its composition. Campbell and Davidson (1979) reported that grain protein content of spring wheat was greater at high temperature 27/12°C than at 22/12°C (day/night temperature). Grain protein content increased with heat stress, the greatest effect was observed when stress was imposed early in grain filling (Castro *et al*., 2007). However, Samol *et al.* (2015) reported that grain protein content was decreased under elevated temperature (6.40 %) than ambient temperature (8.69 %). Similarly, the grain protein content of rice decreased under increased atmospheric CO_2 levels and high temperature (Liu *et al*., 2017).

2.3 EFFECT OF HIGH TEMPERATURE STRESS ON NUTRIENT UPTAKE

Plants absorbs nutrients mainly through roots and there are reports that high temperature stress reduces root growth which affects the growth of above ground portion by restricting the supply of water and mineral nutrients, affecting production of hormones synthesized in roots and transported to shoots, and altering source sink relationships between shoots and roots (Rennenberg *et al*., 2006; Wahid *et al*., 2007). Bassirirad *et al*. (1991) opined that extreme temperature (35°C) significantly decreased ion flux, particularly potassium and nitrate ions to the xylem of roots of barley and sorghum plants. The shoot N and P content of *Andropogon gerardii* increased with increase in soil temperature from 5 to 20°C and remained relatively constant at higher soil temperature whereas inverse pattern was observed for root N and P (De-Lucia *et al*., 1992). Ercoli *et al*. (1996) studied the effect of different temperature regimes (at 21, 24, 27 and 30°C) in nutrient uptake by sorghum. The result showed that leaf, stem and root N and P contents were highest at 27 °C. The root and shoot uptake of P and Zn increased with increase in root zone temperature from 25 to 35 °C, whereas beyond 35°C transport of nutrients to shoots decreased and restricted absorption (Stolzfus *et al*., 1998). Similar findings were reported by Lal (1974) and Klock *et al*. (1996).

Uptake of N, S and Mg decreased with increase in temperature from 15 to 30°C, whereas K uptake increased at higher temperature. Exposure of roots to supraoptimal temperature (35°C) while maintaining shoots at normal temperature (20°C) or at 35°C decreased N, P and K content in shoots and roots of two creeping bentgrass cultivars (Huang and Xu, 2000). Chen *et al*. (2013) found enhanced plant N uptake, increased soluble protein and carbohydrate content in rice at the vegetative stage under high night temperature. Nitrogen content in rice grain as well as total N uptake significantly decreased with increase in temperature and total N uptake reduced from 1.5 g/pot to 1.1 g/pot with 3.9°C rise in temperature which was attributed to reduce root biomass and above ground biomass at high temperature (Raj and Chakrabarti, 2016).

2.4 EFFECT OF HIGH TEMPERATURE STRESS ON HEAT UNITS

Singh *et al*. (1990) studied the effect of sowing date on growing days, heliothermal units, photothermal units and phenology of winter maize and the results indicated that, days to tasselling, silking and maturity gradually decreased with delay in sowing. Also, observed that correlation between cumulative heat sums, cumulative heliothermal units and cumulative photothermal units for various growth stages showed that the onset of growth stages depended more on temperature than on sunshine hours and daylength. Rani and Maragatham (2013) found that the accumulated growing degree days were higher under elevated temperature of 4°C and nearer value for 2°C viz., 1641 and 1583 from that of ambient temperature in rice and also observed that growing degree days, photo thermal units and heat use efficiency values were higher during rabi season as compared to kharif season. The number of days taken for transplanting to maturity in rice was decreased in delayed plantings due to increase in GDD (Vysakh, 2015). According to Prakash *et al*. (2017), early sowing (16^{th} February) of sorghum cultivars significantly reduced GDDs and HTU by 45.9°C days and 663.6°C days hour respectively and also grain yield reduced significantly than sown on 3^{rd} March.

2.5 MITIGATION OF HIGH TEMPERATURE STRESS THROUGH NITROGEN AND POTASSIUM NUTRITION

Plant nutrients can play a major role in improving the temperature stress tolerance. Hence, adoption of proper nutrient management practices could be an important step towards realization of high and stable yield under high temperature conditions, expected in future due to global warming. High temperature affect mineral nutrient uptake in plants and thus influence plant growth negatively.

Nitrogen plays a very crucial role in temperature stress tolerance. Batts *et al.* (1998) observed the use of nitrogenous fertilizers in heat tolerant variety as a very effective way to decrease heat damage through lowering the canopy temperature by enhancing evapotranspiration. Kato *et al*. (2003) opined that plants grown under high light intensity with high N supply had greater tolerance to photo oxidative damage and higher photosynthesis capacity than crops grown under similar light intensity with a low N supply This indicates that nitrate adequate plants were able to tolerate excess light by maintaining photosynthesis at high rates and developing protective mechanisms. According to Huang *et al*. (2004) rice grown under high light intensity with N deficiency resulted in enhanced lipid peroxidation. Also form of nitrogen applied affects plant tolerance to damage caused by temperature stress Nitrogen in the form of nitric oxide (NO) is a highly reactive, membrane-permeant free radical with a broad spectrum of regulatory functions in many physiological processes, such as seed germination, leaf expansion, cell senescence, stomatal closure and cell death to heat stress (Bendixen *et al*., 2001). Zhu *et al*. (2000) reported that beans supplied with nitrate fertilizers had high tolerance to photo damage than with ammonium fertilizers. High temperature was detrimental to several yield components which were alleviated by high rate of NO_3^- fertilizer (Campbell and Davidson, 1979). In winter wheat, an increase of temperature induced a decrease of grain protein, whereas grain protein percentage increased significantly with the N supply (Daniel and Triboi, 2000).

Modhej *et al*. (2008) studied the effect of post-anthesis heat stress and nitrogen levels (50, 100 and 150 kg N/ha) on yield and yield attributes of different wheat genotypes. The result indicated that grain yield reduction was 44 per cent with 50 kg N/ha and 26 per cent with 100 kg N/ha when compared with 150 kg N/ha under heat stress condition due to reduction in number of grains and 1000 grain weight. In nitrogen deficient treatments, grain number per unit area was reduced due to decrease in number of fertile florets and panicles/m^2. Chen *et al*. (2013) evaluated that combined effect of different night time temperature (22°C-control and 27°C- high night time temperature) and different nitrogen levels in hydroponic solution (10, 40, and 160 mg N/L) imposed during vegetative phase (transplanting to panicle initiation stage) in rice. The results revealed that shoot nitrogen concentrations were 16.1 and 16.7 per cent higher under high nitrogen doses than in control under 160 and 40 mg N/L. Application of 40 and 160 mg N/L increased plant height, leaf area, maximum root length and soluble leaf protein content in high night time temperature than in control.

A pot culture experiment was conducted by Raj and Chakrabarti (2016) inside temperature gradient tunnel to study the impact of elevated temperature on biomass portioning and N chemistry with five different temperatures and three nitrogen doses (0, 0.8, 1 g N/pot). The results revealed that the partitioning of biomass towards root and grain decreases significantly but partitioning towards shoot got increased. N uptake, agronomic efficiency and recovery efficiency decreased significantly with 3.9℃ increase in temperature. High temperature induced floral sterility, decreased translocation rate of photosynthates and nitrogen from shoot to grain, resulted in lower grain weight and higher shoot N content.

Liu *et al*. (2019) compared that yields of five super hybrid rice varieties and examined their heat tolerance under four N levels (0, 210, 300, 390 kg/ha) in two seasons 2015 (normal temperature) and 2016 (high temperature). In 2015, the highest yield (10.5 t/ha) was recorded by application of 210 kg N/ha. When N level increased to 360 kg/ha, the grain yield decreased to 9.4 t/ha. But in 2016 (high temperature), the highest grain yield (9.35 t/ha) was obtained with 390 kg N/ha followed by 8.9 t/ha in 300 kg N/ha. Among cultivars during 2016 grain yield of YLY1 was significantly higher than other cultivars. Also higher N levels increased the number of spikelets per panicle and reduced the number of degenerated spikelets under high temperature. These results confirmed that increased N application could alleviate yield loss caused by high temperature in rice during flowering stage.

Potassium also plays a crucial role in survival of crop plants under environmental stress condition. Potassium is essential for many physiological process, such as photosynthesis, translocation, turgidity and activation of enzymes under heat stress condition (Mengel and Kirkby, 2001). Potassium deficiency causes severe reduction in photosynthetic CO_2 fixation, impairment in portioning and utilization of photosynthates, stimulation of ROS production during both electron transport and NADPH – oxidizing enzyme reactions involved in membrane damage and chlorophyll degradation. The percentage spikelet sterility induced by high temperature decreased remarkably with the increase of potassium supply (Haque, 1988).

A field experiment was conducted by Rahman *et al*. (2014) to evaluate the effect of foliar application of potassium orthophosphate on grain yield and quality of three wheat cultivars under terminal heat stress. The results revealed that two foliar applications of 0.1 per cent potassium orthophosphate at 70 and 80 DAS increased SPAD value, leaf area and improved kernel quality. This also resulted in higher number of panicles/m^2, grains per panicle, 1000 grain weight and the highest grain yield (4.23 t/ha) compared to control (3.46 t/ha) and among cultivars, Prodip and Shatabdi were more responsive than Kanchan.

Ahmad and Akram (2017) evaluated potassium application in spring maize under early and late sown conditions. Under late sown conditions, the higher grain yield (4.31t/ha) was obtained with 200 kg K/ha which was on par with 100 kg K/ha (4.28 t/ha). In another field experiment on performance of wheat under high temperature stress, foliar spray of KNO_3 at the rate of 0.5 per cent during booting and anthesis in a short duration variety DBW-14 was beneficial to mitigate the ill effects of high temperature stress and enhanced the grain yield (Chaurasiya *et al*., 2018)

Material and Methods

3. MATERIAL AND METHODS

The present study entitled "Management of high temperature stress in aerobic rice (*Oryza sativa* L.)" was conducted at the Department of Agronomy, College of Horticulture, Vellanikkara, Thrissur during the period 2017-2019. The objective of the study was to assess the response of a few aerobic and wetland rice varieties to high temperature stress at different growth phases with respect to growth, yield attributes, yield and physiological parameters and the effect of nitrogen and potassium nutrition on mitigation of high temperature stress. The details of the material used and the methods adopted for the study are presented in this chapter.

3.1 DETAILS OF THE EXPERIMENT

3.1.1. Soil and climate of experimental site

The experiment was conducted at the Agronomy Farm of College of Horticulture, Vellanikkara, Kerala Agricultural University. Geographically, the area is situated at 10° 31' N latitude, 76° 13' E longitude and an altitude of 40.30 m above mean sea level.

The soil of the experimental field was sandy loam belonging to the taxonomical order Inceptisol. The physico-chemical properties of the soil are given in Table 1.

Data on weather parameters during the experimental period are furnished in Appendix I, II and depicted in Fig. 1,2,3, and 4.

There were two pot culture experiments in the first year (Dec 2017- Mar 2018) followed by a field experiment in the second year (Jan 2019 – April 2019). The details of each experiment are given below:

3.1.2 Experimental details

a) Experiment I: Assessment of aerobic rice varieties for high temperature stress tolerance

The experiment was conducted as a pot culture study and involved four different varieties and high temperature stress imposed at different stages of crop

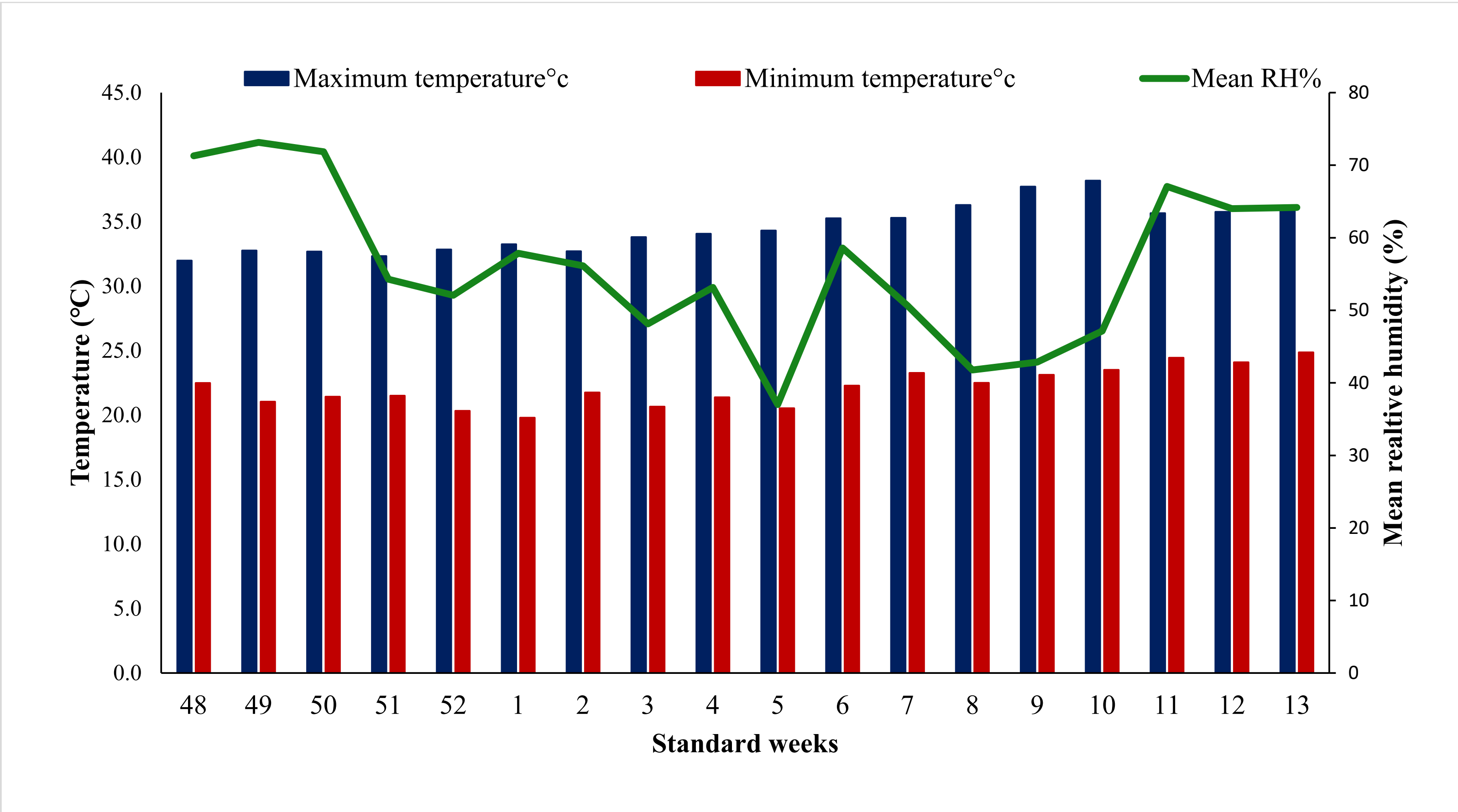


Fig 1. Mean weekly atmospheric temperature and relative humidity during December 2017 to March 2018

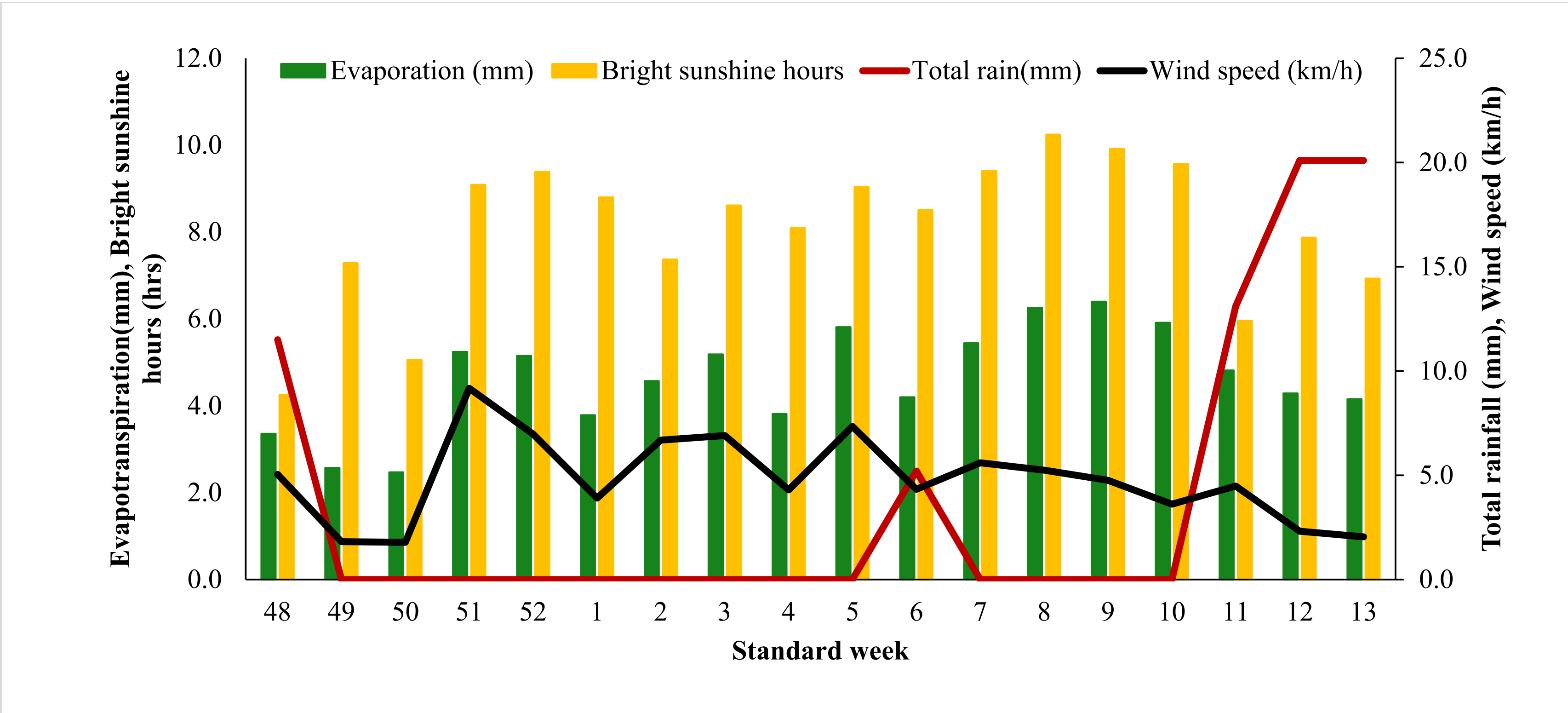


Fig 2. Mean weekly evaporation, bright sunshine hours, rainfall and wind speed during December 2017 to March 2018

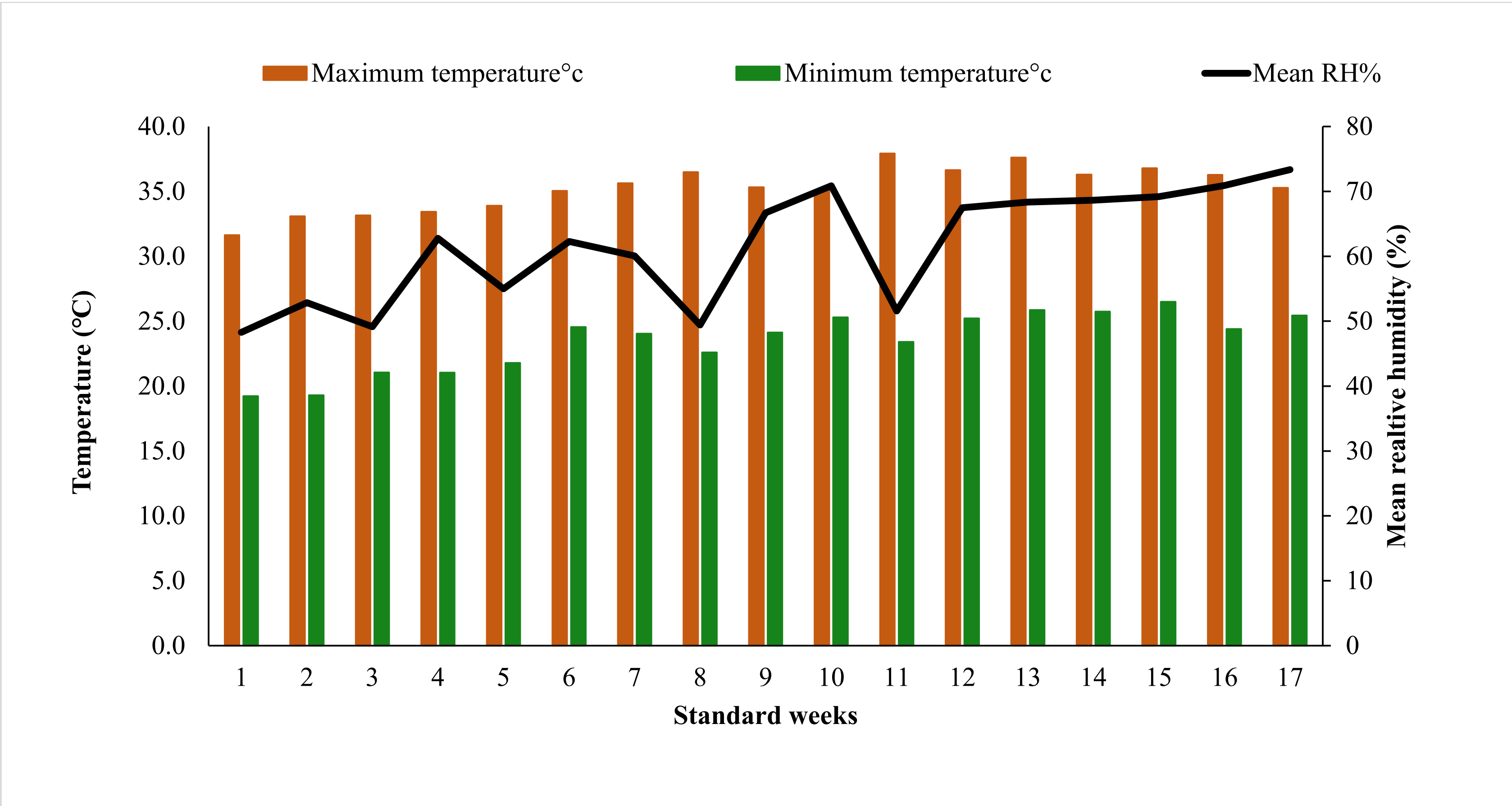


Fig 3. Mean weekly atmospheric temperature and relative humidity during January 2019 to April 2019

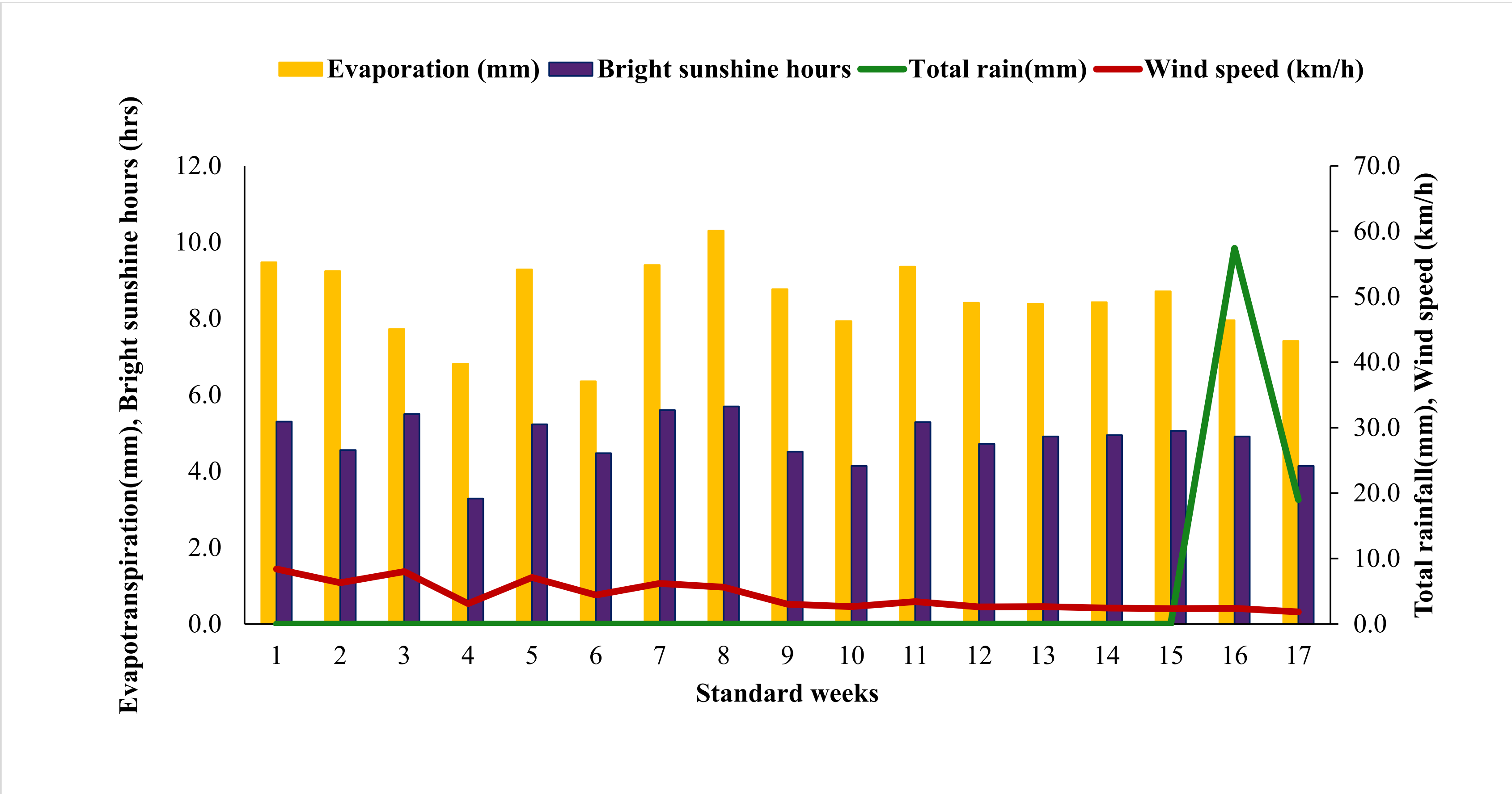


Fig 4. Mean weekly evaporation, bright sunshine hours, rainfall and wind speed during January 2019 to April 2019

Table 1. Characteristics of soil used for pot and field experiment

Particulars	Value		Methodology
A. Physical properties			
Bulk density (g/cm^3)	1.58		Core method (Piper, 1966)
Particle density (g/cm^3)	2.60		
B. Texture	Sandy clay loam		International pipette method (Piper, 1966)
C. Chemical properties			
	Pot culture experiment (Exp I and II)	**Field experiment (Exp III)**	
pH	4.74	4.72	1:2.5 (soil: water) suspension by pH meter (Jackson, 1973)
EC (dS/m)	0.46	0.51	EC meter (Jackson, 1973)
Organic carbon (%)	0.65	0.63	Chromic acid wet digestion method (Walkley and Black, 1934)
Available N (kg/ha)	113	125	Alkaline permanganate method (Subbiah and Asija,1956)
Available P_2O_5 (kg/ha)	21	19	Bray extraction and photoelectric colorimetry (Jackson, 1973)
Available K_2O (kg/ha)	211	222	Flame photometry (Stanford and English, 1949)

growth. The design was factorial CRD with sixteen treatment combinations and three replications. The treatments included combinations of two factors viz., Factor A (four different aerobic rice varieties) and Factor B (high temperature stress at three different growth stages of rice along with control). Details of the treatments are given below (Table 2). Four pots were kept per treatment in each replication and each pot had three hills of rice. Six to eight seeds were sown per pot and thinning done at 15 days after sowing (DAS) to maintain three seedlings per pot. Sowing was done at 1st December of 2017.

Table 2. Treatments details of Experiment I

Factor A: Varieties	
V1	Swarnaprabha (105-110 days)
V2	Sharadha (105-110 days)
V3	Vaishak (117-125 days)
V4	MDU-6 (110 days)
Factor B: High temperature stress (2-3 °C above ambient) at different stages	
S0	No stress
S1	Stress during tillering to panicle initiation stage
S2	Stress during panicle initiation to flowering stage
S3	Stress during flowering to maturity stage

b) Experiment II: Assessment of wetland rice varieties for high temperature stress tolerance

The experimental outline and procedure followed for the screening of wetland varieties for tolerance to high temperature stress was similar to that in the Experiment I. Hence high yielding varieties recommended for wetland system were included

Table 3. Treatments details of Experiment II

Factor A: Varieties	
V1	Kanchana (105-110 days)
V2	Jyothi (110-115 days)
V3	Uma (115-120 days)
V4	Aishwarya (120 - 125 days)
Factor B: High Temperature stress (2-3 °C above ambient) at different stages	
S0	No stress (ambient from tillering to maturity stage)
S1	Stress during tillering to panicle initiation stage
S2	Stress during panicle initiation to flowering stage
S3	Stress during flowering to maturity stage

3.1.3 Design of portable transparent polythene chambers

For imposing temperature stress, portable transparent polythene chambers with the dimensions of 2 m x 2 m x 1.5 m were fabricated (Plate 1). Top of the chamber was covered with UV stabilized polythene sheet (200 micron) and sides were covered using polythene sheet (120 gsm), leaving a gap of 15 cm from the ground level at the base for free air passage. Pots were transferred into the portable growth chambers at respective growth stages *viz.*, tillering to panicle initiation, panicle initiation to flowering and flowering to maturity stage according to the duration of variety. After the completion of each growth stage, the plants were taken out from the growth chambers and kept under normal ambient temperature condition for studying the yield traits (Fig. 5). Each chamber could accommodate 16 pots and four pots were maintained per treatment in each replication. The temperature inside the chamber was monitored and was observed to be 2-3°C above ambient condition. Plants grown under ambient temperature condition were considered as control. The mean temperature prevailed at different growth stages of rice are presented in Table 4.

Plate 1. Design of portable polythene chamber

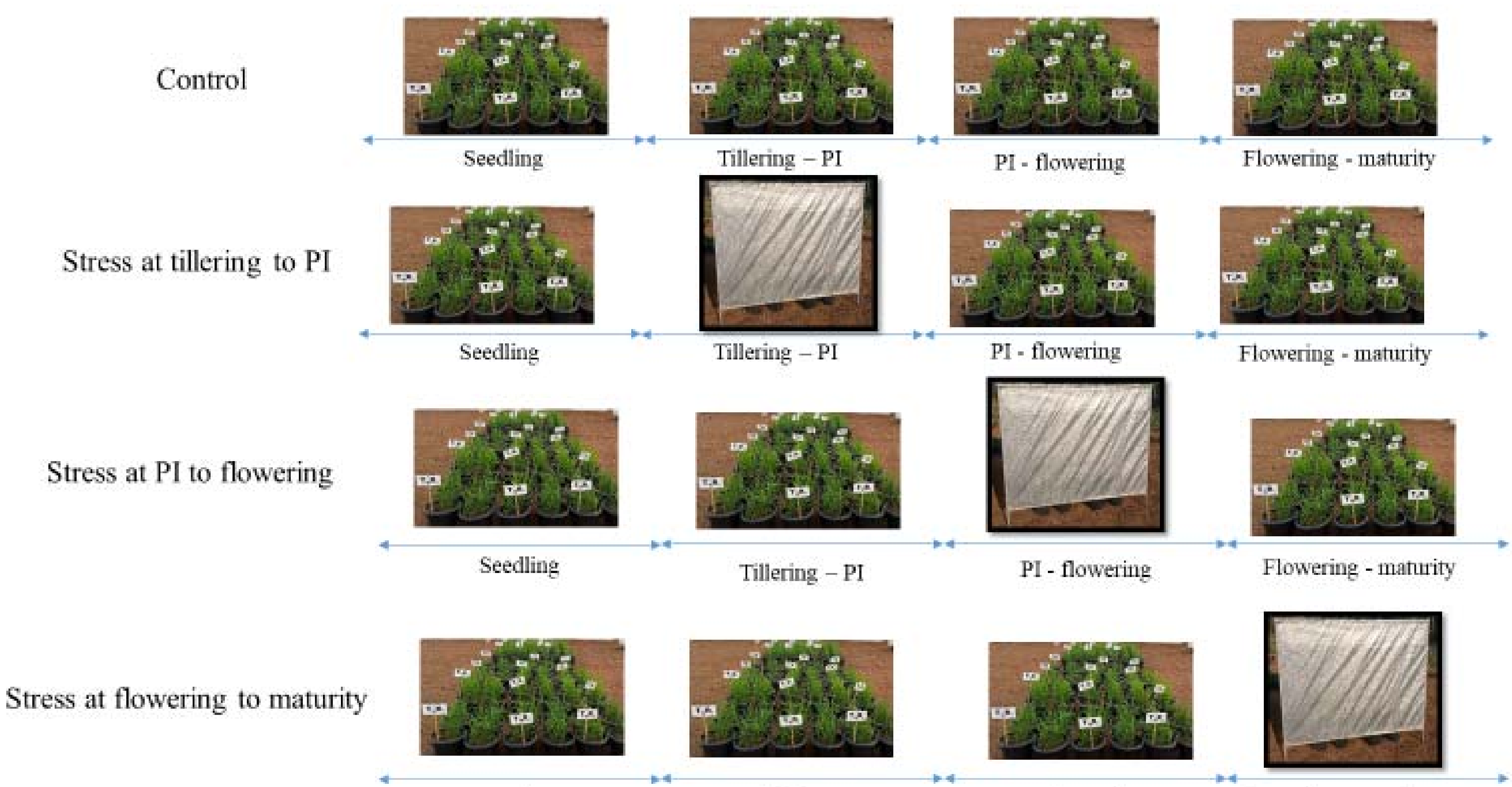


Fig 5. Diagrammatic representation of high temperature stress imposition at various stages of growth of rice plant

Table 4. Mean temperature (°C) prevailed at different growth stages of rice during the experiment

	Tillering to PI		PI to flowering		Flowering to maturity	
	Ambient	**Inside chamber**	**Ambient**	**Inside chamber**	**Ambient**	**Inside chamber**
Short duration varieties	26.85	29.35	28.22	30.72	30.16	32.66
Medium duration varieties	27.13	29.63	29.03	31.53	30.19	32.96

* Mean temperature prevailed during December 2017 to March 2018 and Jan 2019 to April 2019.

3.1.4 Crop management practices

a) Application of manures

The pots were filled with 10 kg of soil and farmyard manure @ 22 g/pot was applied uniformly mixed well with top soil. Recommended dose of fertilizers (60:30:30 N:P_2O_5:K_2O kg/ha) was applied and management of practices as per Package of Practices (KAU, 2016) were done. Nitrogen was applied equally as three split doses first as basal application, second at active tillering and third at panicle initiation stage. Full dose of phosphorus was applied basally. Potassium was applied in two equal splits, first as basal application and the remaining at panicle initiation stage.

b) Plant protection

Chlorantraniliprole @ 0.2 ml/l of water was sprayed to control stem borer attack observed during active tillering stage. Oberon @ 0.8 ml/l was sprayed to control mite during active tillering stage. Malathion @ 2 ml/l of water was mixed with Nimbicidine @ 6 ml/l of water and sprayed three times at weekly intervals from milk stage to grain filling stage for controlling earhead bug.

c) Irrigation

Irrigation was given daily once during initial stages of growth and twice during later growth phase.

d) Harvest

The crop was harvested at full physiological maturity. The grain and straw were dried separately weighed, and observations recorded and expressed in g/hill.

3.1.5. Experiment- III: Effect of nitrogen and potassium nutrition on mitigation of high temperature stress in aerobic rice

Based on the results of Experiments I and II, the most sensitive stage to high temperature stress was found to be that from flowering to maturity. A field experiment was laid out with six treatments. For imposing temperature stress, portable transparent polythene chambers were kept in each plot at the time of flowering stage up to maturity stage. Yield observations from outside the chamber were taken as control in the case of all the treatments. The temperature inside the chambers was monitored and was observed to be 2-3ºC above ambient condition. Treatments consisted of combination of two varieties and three nitrogen and potassium levels along with high temperature stress at most sensitive stage (six combinations). The varieties Vaishak and Aishwarya were selected for the field study. There were six treatments replicated thrice and the design was Randomized Block Design (Fig 6). 60: 30: 30 Kg N: P_2O_5: K_2O per ha is the recommended dose for upland rice as per Package of Practices (KAU, 2016). Plot size was 5 m x 4 m, and the growth chambers of 2 m x 2 m x 1.5 m dimensions used for the pot culture experiment were kept in field during flowering to maturity phase of rice (Plate 4). Observations were taken from sample plants inside the chamber.

Treatments

T1: Vaishak applied with 60: 30 N:K_2O kg/ha

T2: Vaishak applied with 90: 45 N:K_2O kg/ha

T3: Vaishak applied with 120: 60 N:K_2O kg/ha

T4: Aishwarya applied with 60: 30 N:K_2O kg/ha

T5: Aishwarya applied with 90: 45 N:K_2O kg/ha

T6: Aishwarya applied with 120: 60 N:K_2O kg/ha

Uniform dose of 30 kg P_2O_5 /ha was applied to all treatments basally.

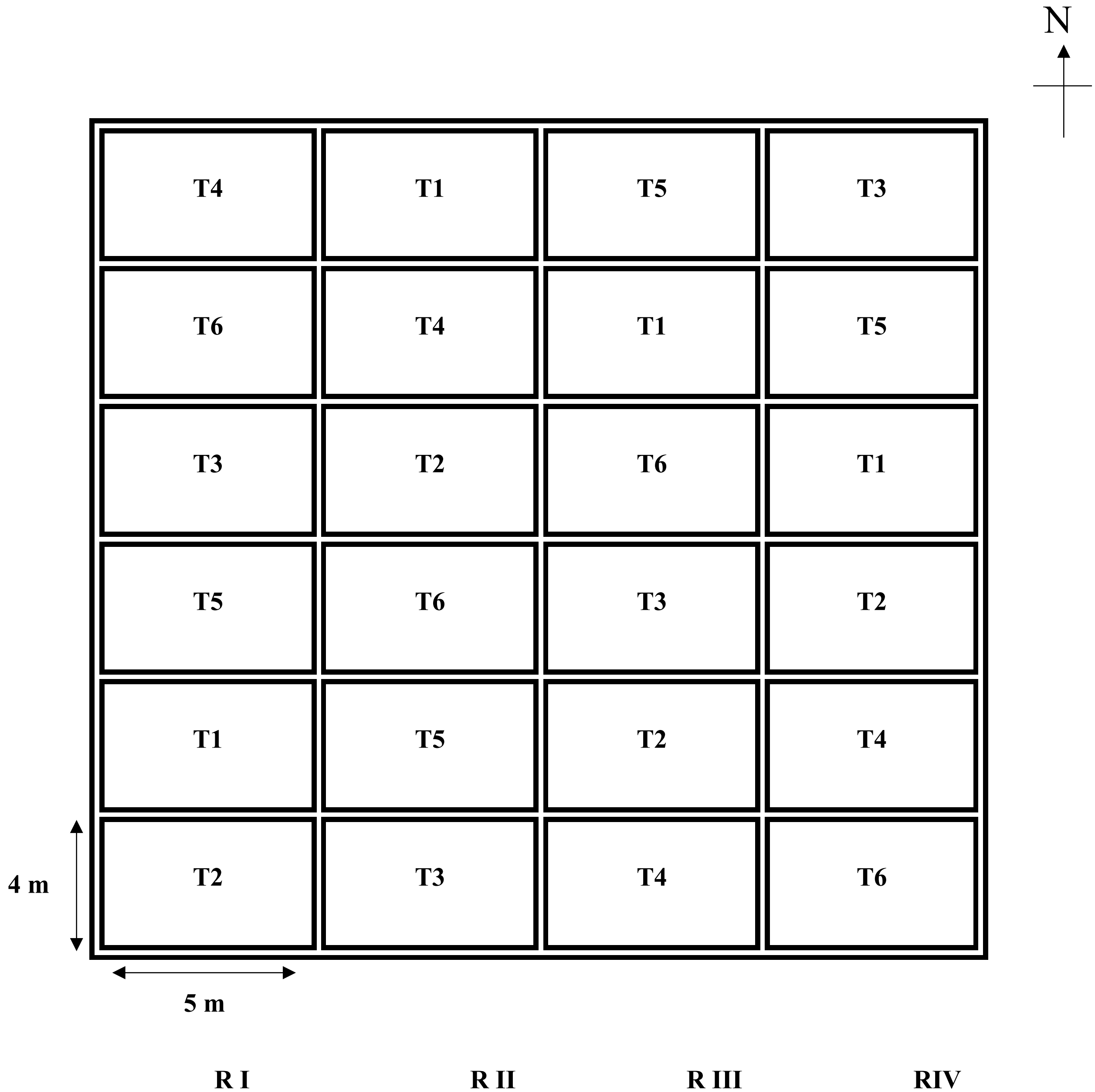


Fig.6. Layout of the field experiment (Experiment III)

T1: Vaishak applied with 60: 30 N:K_2O kg/ha

T2: Vaishak applied with 90: 45 N:K_2O kg/ha

T3: Vaishak applied with 120: 60 N:K_2O kg/ha

T4: Aishwarya applied with 60: 30 N:K_2O kg/ha

T5: Aishwarya applied with 90: 45 N:K_2O kg/ha

T6: Aishwarya applied with 120: 60 N:K_2O kg/ha

a) Land preparation

The field was ploughed twice, levelled and laid out as per the experimental design (Fig 6). Soil samples were taken from the field for analysis.

b) Seeds and sowing

Seeds were dibbled at a spacing of 20 x 15 cm in each plot. Three to four seeds were dibbled per hill. Sowing was done on 1st January, 2019.

c) Application of manures and fertilizers

Farmyard manure @ 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 first as basal, second at active tillering and third at panicle initiation stage. Full dose of phosphorus was applied at the time of land preparation.

d) Weed management

Pre emergence application of oxyfluorfen 1.5 ml/l of water was done two days after sowing (DAS). Two hand weedings were carried out, one at 30 DAS and another at 60 DAS.

e) Irrigation

The crop was irrigated daily and irrigation was withheld one week before harvest.

f) Plant protection

Chlorantraniliprole @ 0.4 ml/L of water was sprayed to control stem borer attack during active tillering stage. Malathion @ 2ml/l of water mixed with Nimbicidine @ 6 ml/l of water was sprayed 3 times at weekly intervals from milk stage to grain filling stage for controlling earhead bug damage.

g) Harvest

The crop was harvested at maturity. The plants outside the chamber was harvested first and plants inside the chamber were harvested separately from each plot.

The grain and straw were separately dried and weighed and yields recorded. Harvesting was done on 30^{th} April, 2019.

3.2. OBSERVATIONS

3.2.1 Experiment I and II

3.2.1.1 Growth parameters

a) Plant height

In the pot culture study, height of three randomly selected plants from four pots were recorded at harvest. At harvest, the plant height was measured from the base of the stem to the tip of the panicle.

b) Number of tillers per hill

The tiller number per hill also was observed at harvest from the randomly selected three plants of four pots and mean values were computed.

c) Leaf Area

Leaf area was measured at 60 DAS and calculated using the formula.

Total leaf area = L x B x 0.75 x Total number of leaves

Where, L - Maximum length of the 3rd leaf blade from the top (cm)

B - Maximum width of the leaf blade (cm)

d) Days to flowering

Number of days to flowering was recorded from each pot and the mean was worked out.

e) Dry matter production

The total dry matter production was recorded at harvest. Five plants per replication for pot culture experiment were randomly selected, uprooted, washed, sun dried and oven dried at 80 °C to constant weight and expressed in gram per hill.

f) Root dry weight

After harvest stumps were uprooted, roots were cleaned and then dried in a hot air oven at 80°C till constant weight. The dry weight was expressed in gram per hill.

3.2.1.2 Yield attributes and yield

a) Number of productive tillers per hill

The number of productive tillers were recorded from five randomly selected hills per replication at harvest and mean values were calculated.

b) Length of panicle

The panicle length was measured from the neck to the tip of the panicle in three central panicles of the tagged hills and mean length of panicle was calculated and expressed in cm.

c) Total number of spikelets per panicle, filled, unfilled grains and 1000 grain weight

The spikelets from panicles collected from the sample plants in each replication were separated, counted and separated into filled and unfilled grains. The 1000 grains from each sample were weighed and expressed in gram.

d) Grain yield (kg/ha)

The grains were harvested from each pot separately and dried under sun to a constant weight. Grain yield was recorded in g per hill in pot culture experiment from each replication separately and weighed after drying.

e) Straw yield (kg/ha)

The straw harvested from each pot were collected separately and weight was recorded after drying under sun, and expressed in g per hill.

f) Harvest Index

The harvest index was calculated using the formula

$$HI = \text{Economic yield} / \text{Biological yield}$$

3.2.1.3 Physiological parameters

Observations on physiological parameters were taken at the end of each temperature stress period inside the portable chambers and simultaneously observations were taken from plants in ambient conditions (Control).

a) Stomatal conductance (m mol $H_2O/m^2/s$)

Stomatal conductance of three plants per replication was measured using portable photosynthesis system LI-6400 (LI-COR 4GC, USA)

b) Net photosynthetic rate (µ mol CO2 /m^2/s)

Net photosynthetic rates of three plants per replication in pot culture experiment were measured using portable photosynthesis system LI-6400 (LI-COR 4GC, USA)

c) Transpiration rate (m mol $H_2O/m^2/s$)

Transpiration rates of three plants per replication in pot culture experiment were measured using portable photosynthesis system LI-6400 (LI-COR 4GC, USA)

d) Relative water content

`Relative water content was calculated according to the formula given by Slatyer and Barrs (1965) and expressed in per cent.

$$RWC (\%) = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Turgid weight} - \text{Dry weight}} \times 100$$

e) Chlorophyll content

Chlorophyll content of leaves was calculated using the formula given by Yoshida *et al*. (1972). A known weight of fresh leaf sample was collected from each replication and the chlorophyll was extracted using Dimethyl Sulphoxide (DMSO).

Then the intensity of colour was read using Spectronic 20 spectrophotometer at 663 nm and 645 nm. The formula for calculating chlorophyll content are given below.

Total Chlorophyll (mg/g) = (18.02 x OD at 663) + (20.2 x OD at 645) x V/(1000 x W)

Where,

OD – Optical Density

V – Final volume of extractant

W – Weight of leaf sample (g)

f) Soluble protein

Soluble protein content was estimated from the leaf samples using the method of Lowry *et al*. (1951) and expressed as mg/g fresh weight.

g) Nitrate reductase activity

Nitrate reductase activity was determined by following the method of Nichholas *et al*. (1976) and expressed as µmol/g.

h) Membrane stability index

The cell membrane stability was studied by observing the leakage of the membrane under stress. Leaf bits of 0.1g weight were taken in a test tube and 15 ml of distilled water was added and kept for three hours. The leaf bits were removed and the electrical conductivity of the solution was measured. After the initial measurements, leaf pieces were returned to the original solution and boiled for ten minutes, removed and the solution was cooled. The electrical conductivity of the solution was observed again (Dexter *et al*., 1932).

$$\text{Membrane stability index} = \frac{\text{Initial conductivity}}{\text{Final conductivity}} \times 100$$

i) Malondialdehyde (MDA)

The lipid peroxidation level was estimated by quantifying the malondialdehyde using 2- thiobarbituric acid (TBA), as described by Hodges *et al*. (1999) and expressed in n mol/g of fresh weight.

j) Proline content

Proline content in leaves was estimated by using the method of Bates *et al*. (1973) and was expressed in µmol/g of fresh weight.

k) Super Oxide Dismutase (SOD)

Superoxide dismutase activity was estimated by using nitro blue tetrazolium (NBT) salt as described by Beauchamp and Fridovich (1971). Superoxide dismutase was expressed as enzyme unit g/min.

l) Canopy air temperature difference (CATD)

The canopy air temperature difference measured from three plants per replication using portable photosynthesis system LI-6400 (LI-COR 4GC, USA).

3.2.1.4 Plant analysis

a) NPK uptake

Uptake of N, P and K nutrients were estimated by multiplying nutrient content of the sample and respective dry weight of plant samples and expressed in g/hill.

b) Protein content of grain

The crude protein content of grain was calculated by multiplying the nitrogen content with the factor 6.25 (Simpson *et al*., 1965).

3.2.1.5 Heat Units

Heat units were worked out from the direct weather parameters to develop meaningful conclusions on the growth and yield of the crop. The following derived weather parameters were computed for the respective stages *viz.* tillering to panicle initiation, panicle initiation to flowering and flowering to maturity.

a) Growing degree days (GDD)

The growing degree days were calculated for the entire crop growth period. The growing degree days were calculated using Peterson equation (1985).The formula is given below. The base temperature used in the calculation of GDD is 10°C for rice (Gao and Jin, 1992).

$$GDD = \sum_{i=1}^{n} \frac{[T\max + T\min]}{2} - Tb$$

Where,

Tmax - Maximum Temperature (°C), Tmin - Minimum Temperature (°C), and Tb - Base Temperature (°C) i.e., 10°C

b) Helio thermal units (HTU)

The helio thermal units were calculated using the formula given by Rajput (1980). The calculated helio thermal units was expressed in degree day hour.

HTU = Growing Degree Day X Bright sunshine hours (n)

c) Photo thermal units (PTU)

Photo thermal unit (PTU) for rice was calculated for different phenophases of the crop. This was computed using the formula given by Major *et al*. (1975). The value of day length (N) was adopted from Doorenbos and Pruitt (1977).

PTU = Growing Degree Day X Mean day length (N)

d) Heat use efficiency (HUE)

Heat Use Efficiency (HUE) or Thermal Time Use Efficiency (TTUE) is the net amount of dry matter produced per unit of thermal time or growing degree day (Kiniry *et al*., 1989). It was computed using the following formula and expressed in g/m^2 °C day.

HUE = Yield ÷ GDD

3.2.2. Observations recorded for Experiment III

3.2.2.1 Growth parameters

a) Plant height (cm)

In the field experiment, height of five plants selected randomly from each replication were observed at 30 DAS, 60 DAS and at harvest and expressed in cm. Plant height was measured from the base of the tiller to the tip of the top most leaf. At harvest, the plant height was measured from the base of the stem to the tip of the panicle.

b) Number of tillers per hill

The tiller number per hill from five randomly selected plants were recorded from each replication at 30 DAS, 60 DAS and at harvest and mean values were computed.

c) Leaf Area Index

The maximum length and breadth of the 3rd leaf from the top of three tagged plants were measured at 60 DAS and the mean value was multiplied with total number of leaves. The LAI was worked out using the formula given by Yoshida *et al*. (1976).

d) Dry matter production

The total dry matter production was recorded at harvest. Five hills inside the chamber were randomly selected, uprooted, washed, sun dried and oven dried at 80 °C to constant weight and expressed in gram per hill.

3.2.2.2 Yield attributes and yield

a) Number of productive tillers per hill

The number of productive tillers were recorded from five randomly selected hills. Yield and yield attributes were recorded for both plants inside and outside the chamber at harvest from each replication in field experiment and mean values were calculated.

b) Length of panicle

The panicle length was measured from the neck to the tip of the panicle in ten central panicles of tagged plants from each replication and mean length of panicle was calculated and expressed in cm.

c) Total number of spikelets per panicle, filled, and unfilled grains and 1000 grain weight

The spikelets from ten panicles collected from the five sample plants from each replication were removed, counted and separated into filled and unfilled grains. The mean value were worked out and 1000 grains from each sample were weighed and expressed in gram.

d) Grain and straw yield

Plants were harvested from each replication separately from both inside and outside chamber and dried under sun to a constant weight. Grain and straw were separated, dried and expressed in kg/ha.

e) Straw yield

In field experiment, the straw harvested from five plants inside the chamber kept in each plot area was collected separately and weighed after drying and was expressed in kg/ha.

f) Harvest Index

The harvest index was calculated as ratio of economic yield to biological yield.

$$HI = \text{Economic yield} \div \text{Biological yield}$$

3.2.2.3 Physiological parameters

Observations on physiological parameters were taken at the end of temperature stress period (from flowering to maturity stage). The procedure for estimation is mentioned in chapter 3.2.1.3, was followed. The parameters observed were stomatal conductance (m mol $H_2O/m^2/s$), net photosynthetic rate (μ mol $CO_2/m^2/s$), canopy air temperature difference (°C), relative water content (%), chlorophyll content (mg/g), and membrane stability index (%)

3.2.3 Economic analysis

a) Benefit – Cost ratio (BCR)

The cost of cultivation, net income and gross income were calculated and expressed as Rs/ha and then BC ratio was calculated as ratio of gross return to total cost of cultivation.

3.2.4 Plant analysis

Plant uptake of N, P and K and protein content in grain were estimated after harvest. The procedure for estimation is mentioned under 3.2.4.

3.2.5 Soil analysis

Before the start of experiment soil samples were collected randomly from the experimental field. Similarly, soil samples were also collected plot-wise after harvest. The soil samples were processed and analyzed for available N, P_2O_5, and K_2O which were expressed in kg/ha. Methods adopted for analysis of the soil samples are indicated in Table 1.

3.2.6 Weather parameters

The following weather parameters were recorded during the period of experiment [first year (Dec 2017- Mar 2018) and in the second year (Jan 2019 – April 2019)].

a. Maximum temperature (℃)

b. Minimum temperature (℃)

c. Relative humidity (%)

d. Rainfall (mm)

e. Bright sunshine hours (hrs)

f. Solar radiation (cal /cm^2/d)

3.3 STATISTICAL ANALYSIS

The data generated during the course of investigation were subjected to Analysis of Variance as per the methods suggested by Panse and Sukhatme (1985). Wherever statistical significance was observed, critical difference (CD) at 0.05 level of probability was worked out for comparison. Non-significant comparisons were indicated as 'NS'.

Results

4. RESULTS

The present study included two pot culture experiments in the first year followed by a field experiment in the second year (Jan 2019 – April 2019). The Experiment I was 'Assessment of aerobic rice varieties for tolerance to high temperature stress' and experiment II was 'Assessment of wetland rice varieties for tolerance to high temperature stress'. The third experiment was to study the effect of nitrogen and potassium nutrition on mitigation of high temperature stress in aerobic rice. The results of these experiments are presented in this chapter.

4.1 EXPERIMENT I: ASSESSMENT OF AEROBIC RICE VARIETIES TO HIGH TEMPERATURE STRESS

4.1.1 Growth parameters

a. Plant height

The data on plant height of different rice varieties as influenced by high temperature stress at different growth stages are presented in Table 5.

Variety Vaishakh was taller than other varieties and recorded significantly higher plant height at harvest. Sharada and MDU-6 were the shortest varieties and recorded comparable plant heights of 72.31 cm and 75.67 cm.

High temperature stress at different growth stages significantly influenced the plant height. At harvest, plants exposed to high temperature stress from tillering to PI stage recorded the tallest plants (92.75 cm) which was comparable with stress imposed from PI to flowering stage (89.22 cm) and superior to stress from flowering to maturity and control.

Interaction effect of variety and stress was significant throughout the period of observation. At harvest, the tallest plants were recorded for Vaishakh when plants exposed high temperature stress from tillering to PI and PI to flowering stage (112.65 and 104.39 cm) which was comparable with its control (104.14 cm) and Swarnaprabha when stress was imposed from tillering to PI stage (104.71). The shortest plants were recorded for Sharada under control (71.19 cm).

Table 5. Effect of high temperature stress on plant height (cm) at harvest of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	92.11	104.71	103.16	101.94	**100.48**
Sharada	71.19	74.21	71.83	72.00	**72.31**
Vaishakh	104.14	112.65	104.39	101.61	**105.70**
MDU-6	73.36	79.43	77.50	72.40	**75.67**
Mean	**85.20**	**92.75**	**89.22**	**86.99**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			4.43	4.43	8.86

Table 6. Effect of high temperature stress on number of tillers at harvest of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	11.56	12.12	11.18	10.23	**11.27**
Sharada	14.50	15.23	14.08	13.84	**14.41**
Vaishakh	11.85	12.21	11.53	10.74	**11.58**
MDU-6	13.35	14.02	13.06	12.65	**13.27**
Mean	**12.82**	**13.40**	**12.46**	**11.87**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.67	0.67	1.35

Table 7. Effect of high temperature stress on leaf area (cm^2) at 60 DAS of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Mean
Swarnaprabha	1364	1698	1436	**1452**
Sharada	1199	1906	1207	**1376**
Vaishakh	1529	1953	1433	**1577**
MDU-6	1260	1619	1268	**1338**
Mean	**1338**	**1794**	**1336**	
	CD(0.05)	**Varieties**	**Stress**	**V x S**
		72	72	143

b. Number of tillers per hill

Significant difference between varieties were observed with respect to number of tillers per hill (Table 6). At harvest, Sharada produced the highest number of tillers per hill (14.41) which was superior to all varieties and the lowest tiller number per hill was recorded in Swarnaprabha (11.27).

Plants exposed to high temperature stress from tillering to PI stage produced higher number of tillers per hill at harvest. At harvest, higher tillers per hill (13.40) was observed in plants exposed from tillering to PI stage, which was comparable with control (12.82). High temperature stress imposed from flowering to maturity produced lower number of tillers per hill (11.87).

At harvest, effect of variety and high temperature stress on number of tillers per hill was significant. Higher number of tillers per hill was recorded for Sharada under high temperature stress compared to other varieties. The variety Vaishakh recorded the lowest tiller number (10.23) when stress was induced from flowering to maturity which was on par with other varieties under stress except Sharada.

c. Leaf Area

There was significant difference in leaf area of different varieties (Table 7). The variety Vaishakh recorded highest leaf area (1577 cm^2) superior to other varieties and lowest value was recorded for MDU-6 (1338 cm^2).

High temperature stress had significant effect on leaf area of rice. Among high temperature stress, the highest leaf area value was registered when stress imposed from tillering to PI stage (1794 cm^2) which was on par with stress at remaining stages.

Interaction between varieties and high temperature stress was significant with respect to leaf area. The highest leaf area value was observed for Vaishakh (1953 cm^2) and Sharada (1906 cm^2) when stress was imposed from tillering to PI stage compared with other treatments.

d. Days to flowering

Significant difference in days to flowering was observed among the varieties (Table 8). Early flowering was recorded in short duration varieties MDU-6 (68.78

Table 8. Effect of high temperature stress on number of days to flowering of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Mean
Swarnaprabha	77.33	74.00	75.00	**75.44**
Sharada	76.00	74.00	76.67	**75.56**
Vaishakh	78.33	77.00	77.00	**77.44**
MDU-6	71.00	67.00	68.33	**68.78**
Mean	**75.67**	**73.00**	**74.25**	
	CD(0.05)	**Varieties**	**Stress**	**V x S**
		4.27	NS	1.53

Table 9. Effect of high temperature stress on dry matter production (g/hill) at harvest of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	29.47	35.86	29.94	25.91	**30.30**
Sharada	30.42	33.78	30.14	27.64	**30.49**
Vaishakh	34.69	35.14	34.22	31.50	**33.89**
MDU-6	27.81	29.25	26.08	25.78	**27.23**
Mean	**30.60**	**33.51**	**30.10**	**27.71**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			1.45	1.45	2.90

Table 10. Effect of high temperature stress on root dry weight (g/hill) at harvest of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	9.85	8.54	8.42	8.51	**8.83**
Sharada	9.05	8.21	7.95	7.80	**8.25**
Vaishakh	10.30	8.70	8.50	8.45	**8.99**
MDU-6	8.01	7.59	7.45	7.52	**7.64**
Mean	**9.30**	**8.26**	**8.08**	**8.07**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.43	0.43	0.86

days) followed by Sharada (75.56 days) and Swarnaprabha (75.44 days). The variety Vaishakh took 77.44 days to flowering.

High temperature stress at different stages significantly influenced days to flowering. Early flowering was observed when stress imposed from tillering to PI (73.00) followed by stress from PI to flowering (74.25 days).

The interaction effect of varieties and high temperature stress on days to flowering is shown in Table 15. Early flowering was observed in variety MDU-6 when stress imposed from tillering to PI and PI to flowering stage which was significantly different from other treatments. Late flowering was observed for Vaishakh under control and stress imposed at all growth stages, which indicates that high temperature does not influenced days to flowering of variety Vaishakh.

e. Dry matter production

Among the varieties, the highest dry matter production was obtained for Vaishakh (33.89 g/hill) which was significantly superior to other varieties and lowest dry matter production was observed in MDU-6 (27.23 g/hill) (Table 9).

When plants were exposed to high temperature stress from tillering to PI stage they produced higher dry matter production (33.51 g/hill) which was statistically superior to other stress phases. This was followed by ambient condition (30.60 g/hill) and stress imposed from PI to flowering (30.10 g/hill). The lowest dry matter production of 27.71 g/hill was produced when stress induced from flowering to maturity.

Significant interaction effect of variety and high temperature stress on dry matter production was registered (Table 9). The variety Swarnaprabha exposed to high temperature stress from tillering to PI stage registered highest dry matter production (35.86 g/hill), which was on par with variety Vaishakh exposed to high temperature stress from PI to flowering and in control. The lowest dry matter production was for Sharada when exposed to high temperature stress from flowering to maturity (25.78 g/hill).

f. Root dry weight

The data pertaining to root dry weight are shown in Table 10. Among varieties, Vaishakh and Swarnaprabha registered higher root dry weights which were comparable and superior to Sharada and MDU-6.

The highest root dry weight was recorded in control (9.30 g/hill) which was superior to plants grown under high temperature stress at different stages.

Interaction effect was also significant with respect to root dry weight of rice (Table 10). Vaishakh and Swarnaprabha grown under ambient condition produced highest root dry weight (10.30 and 9.85 g/hill) which was superior to other treatments. The lowest root dry weight was recorded for MDU-6 exposed to high temperature stress at all stages.

4.1.2 Yield characters and yield

a. Number of panicles per hill

The data on panicles per hill of different varieties under high temperature stress at different growth stages are presented in Table 11. Among the varieties, significantly higher number of panicles per hill was observed for Sharada (11.98) whereas it was lower for Swarnaprabha (9.10) which was comparable with Vaishakh (9.27).

Plants grown under ambient condition produced higher as well as comparable number of panicles to those under stress except stress during tillering to panicle initiation stage.

All varieties produced higher number of panicles under ambient temperature compared to heat stressed condition. It was seen that in variety Sharada panicle number per hill was not influenced by temperature 2-3°C above normal as comparable productive tiller was seen when stress was induced at various growth phases. The lowest number of panicles was recorded in variety Vaishakhh (8.60) when high temperature stress was imposed during tillering to PI stage.

Table 11. Effect of high temperature stress on number of panicles per hill of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	9.53	8.67	9.08	9.11	**9.10**
Sharada	12.89	11.12	11.48	12.42	**11.98**
Vaishakh	9.83	8.60	9.78	8.89	**9.27**
MDU-6	10.95	9.15	10.64	9.77	**10.13**
Mean	**10.80**	**9.39**	**10.24**	**10.05**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.75	0.75	1.50

Table 12. Effect of high temperature stress on number of filled grains per panicle at harvest of aerobic rice varieties

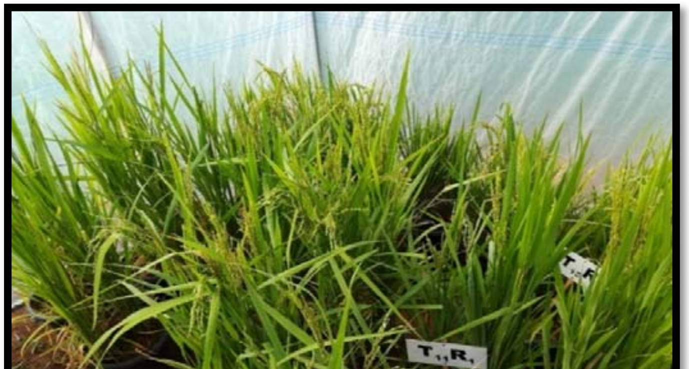
Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	86.13	81.43	79.63	75.73	**80.73**
Sharada	85.10	86.37	77.17	73.13	**80.44**
Vaishakh	109.55	92.37	88.53	95.92	**96.59**
MDU-6	93.50	87.47	85.07	82.05	**87.02**
Mean	**93.57**	**86.91**	**82.60**	**81.71**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			4.29	4.29	8.59

Table 13. Effect of high temperature stress on chaff per cent of aerobic rice varieties

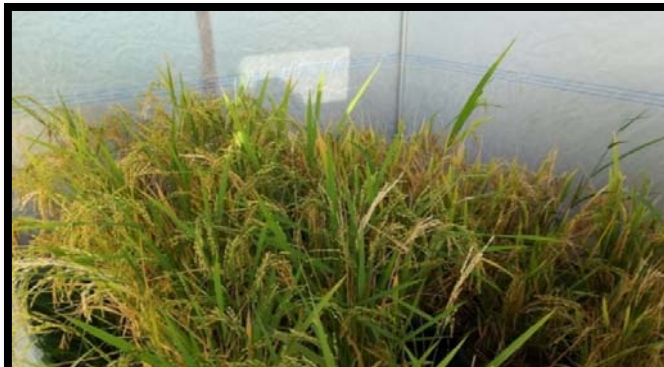
Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	20.10	15.85	14.83	27.04	**19.46**
Sharada	7.50	4.74	4.85	18.14	**8.81**
Vaishakh	8.36	7.75	7.10	14.10	**9.33**
MDU-6	7.27	7.37	8.72	15.39	**9.69**
Mean	**10.81**	**8.93**	**8.88**	**18.67**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.71	0.71	1.42

Seedling stage

Active tillering stage



Flowering stage



Maturity stage

Plate 2. Different growth stages of aerobic and wetland rice varieties in pot culture experiment

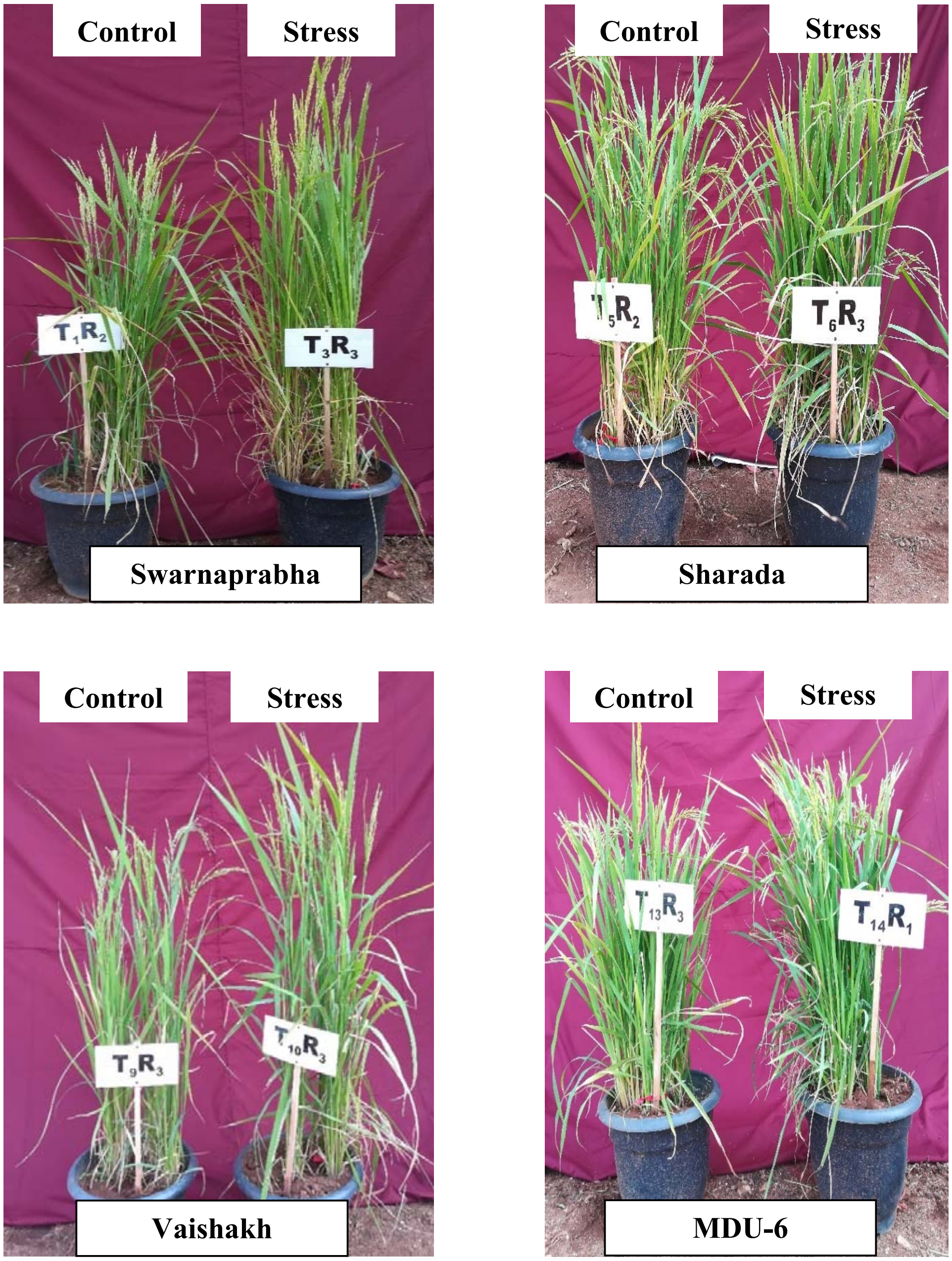


Plate 3. Comparison of different varieties under ambient and elevated temperature condition during panicle initiation stage

Plate 4. View of pot culture experiment I and II

Plate 5. View of field experiment at flowering stage

a. Levelling of plots

b. Sowing

Plate 6. Land preparation and sowing of rice in field experiment

Seedling stage

Tillering stage

Booting stage

High temperature induced at flowering stage

Plate 7. Different growth stages of rice under aerobic condition in field Experiment

b. Number of filled grains per panicle

Vaishakh produced the highest number of filled grains per panicle (96.59) compared to other three varieties. Sharada and Swarnaprabha were inferior (Table 12).

It is clear that temperature stress had a significant influence on grain filling. The highest number of filled grains per panicle was recorded under control (93.57). It was also seen that the reproductive phase of rice is sensitive to high temperature as stress imposed during PI to maturity stage showed lower number of filled grains per panicle.

All varieties produced higher number of filled grains per panicle under ambient condition. A lower number of filled grains per panicle was noticed in Sharada exposed to high temperature stress from flowering to maturity (73.13) which was on par with Swarnaprabha and Sharada exposed to high temperature from PI to flowering stage.

c. Chaff per cent

Varietal sensitivity to high temperature was evident in per cent chaff also (Table 13). The variety Swarnaprabha was found most susceptible with 19.46 per cent chaff and Sharada recorded lowest chaff per cent (8.81%) which was on par with Vaishakh (9.33 %).

High temperature stress imposed from flowering to maturity showed highest chaff per cent (18.67 %) indicating the sensitivity of this stage and response was similar in all the varieties tried.

The highest chaff per cent was recorded for Swarnaprabha exposed to high temperature stress from flowering to maturity stage. The variety Sharada exposed to high temperature stress from tillering to flowering recorded lowest chaff per cent.

d. Total number of grains per panicle

The total grain number was significantly higher in Vaishakh (106.66) and the lowest number was for variety Sharada (88.27).

Table 14. Effect of high temperature stress on total number of grains per panicle of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	107.80	96.77	93.50	103.80	**100.47**
Sharada	92.00	90.67	81.10	89.33	**88.27**
Vaishakhh	119.55	100.13	95.30	111.67	**106.66**
MDU-6	100.83	94.43	93.20	96.97	**96.36**
Mean	**105.05**	**95.50**	**90.77**	**100.44**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			4.88	4.88	9.76

Table 15. Effect of high temperature stress on thousand grain weight of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	24.69	24.40	23.76	22.65	**23.88**
Sharada	22.76	21.14	22.56	19.84	**21.58**
Vaishakh	28.99	26.25	26.38	25.67	**26.82**
MDU-6	25.74	23.88	21.31	20.78	**22.93**
Mean	**25.55**	**23.92**	**23.50**	**22.23**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			1.46	1.46	2.92

Table 16. Effect of high temperature stress on panicle length of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	19.68	20.61	21.14	20.57	**20.50**
Sharada	19.98	19.77	20.76	20.70	**20.30**
Vaishakh	19.95	20.33	20.41	23.19	**20.97**
MDU-6	20.78	21.43	20.52	21.39	**21.03**
Mean	**20.10**	**20.53**	**20.71**	**21.46**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.68	0.68	1.36

Temperature stress during PI to flowering showed least number of grains per panicle, which was on par with stress imposed from tillering to PI stage (Table 14).

For all the varieties, total grains per panicle were higher under ambient condition compared to high temperature stress. Higher and statistically comparable number of grains per panicle was observed for Vaishakh under control (119.55) and when exposed to stress from flowering to maturity (111.67). The lowest number of grains per panicle was recorded for Sharada when stress was imposed from PI to flowering (81.10) was on par with Sharada imposed to stress at other stages.

e. Thousand grain weight

The test weight varied significantly with variety (Table 15). The test weight of 26.82 g was noticed in Vaishakh which was significantly higher than other three varieties and lowest was recorded in Sharada (21.58 g).

Similar trend of filled grains per panicle was observed for thousand grain weight. The 1000 grain weight was higher under control (25.55 g) and plants exposed to high temperature stress from flowering to maturity recorded the lowest thousand grain weight (22.23 g).

The highest test weight value was registered for Vaishakh under control (28.99 g) and stress imposed from tillering to flowering stage. In all varieties, plants exposed to high temperature stress from flowering to maturity registered lowest 1000 grain weight compared to stress at other stages.

f. Panicle length

The data related to panicle length are presented in Table 16. The longest panicle were recorded for variety MDU-6 (21.03 cm) which was on par with Vaishakh and Swarnaprabha. The variety Sharada had the shortest panicle. However this was statistically comparable to panicle length of both Swarnaprabha and Vaishakh.

High temperature stress induced from flowering to maturity registered longest panicle which was significantly superior to stress at remaining stages and control.

The interaction effect of varieties and high temperature stress on panicle length showed significant difference (Table 16). Vaishakh exposed to high temperature stress from flowering to maturity produced longest panicle compared to other treatments.

g. Grain yield

Significant difference in grain yield was noticed among the varieties and they differed statistically from each other (Table 17). The highest grain yield was observed for Vaishakh (14.69 g/hill) which was significantly higher than Sharada (13.57 g/hill) and Swarnaprabha (12.48 g/hill). The lowest grain yield of 11.43 g/hill was registered for MDU-6.

High temperature stress imposed from PI to flowering and flowering to maturity resulted in lowest grain yield which was 10 per cent lower than control.

The variety Vaishakh produced higher grain yield under high temperature stress at all growth stages compared to others. The lowest grain yield was observed in MDU-6 when high temperature stress imposed from flowering to maturity (10.56 g/hill).

h. Straw yield

The data shows significant difference in straw yield among varieties (Table 18). Vaishakh as well as Swarnaprabha recorded comparable values and were superior to MDU-6 and Sharada. The variety MDU-6 was dwarf compared to others which resulted in lower straw yield.

Temperature stress at vegetative phase favourably influenced straw yield and the maximum straw yield was observed under high temperature stress from tillering to PI stage (19.92 g/hill).

Higher straw yield was recorded for Swarnaprabha, Vaishakh and Sharada under when temperature stress was imposed in vegetative phase.

h. Harvest index

No significance difference was observed among the varieties in harvest index (Table 19). Plants under high temperature stress from tillering to PI stage recorded lowest harvest index (0.41). The maximum harvest index of 0.48 was recorded under

Table 17. Effect of high temperature stress on grain yield (g/hill) of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	13.19	13.03	12.36	11.33	**12.48**
Sharada	14.53	14.39	13.45	11.92	**13.57**
Vaishakh	15.64	15.00	14.31	13.81	**14.69**
MDU-6	12.01	11.92	11.22	10.56	**11.43**
Mean	**13.84**	**13.58**	**12.83**	**11.90**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.60	0.60	1.19

Table 18. Effect of high temperature stress on straw yield (g/hill) of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	16.28	22.83	17.59	14.58	**17.82**
Sharada	15.89	19.39	16.70	15.72	**16.92**
Vaishakh	19.06	20.14	19.92	17.69	**19.20**
MDU-6	15.80	17.33	14.86	15.22	**15.80**
Mean	**16.76**	**19.92**	**17.27**	**15.81**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			1.54	1.54	3.08

Table 19. Effect of high temperature stress on harvest index of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	0.45	0.36	0.42	0.44	**0.42**
Sharada	0.48	0.43	0.45	0.43	**0.45**
Vaishakh	0.45	0.43	0.42	0.44	**0.44**
MDU-6	0.43	0.41	0.43	0.41	**0.42**
Mean	**0.45**	**0.41**	**0.43**	**0.43**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			NS	0.03	0.05

control in variety Sharada. The variety MDU-6 exposed to high temperature stress from flowering to maturity and tillering to PI recorded lowest harvest index (0.41).

4.1.3 Biochemical parameters

a. Relative water content (RWC)

The data on RWC showed significant difference among varieties during different growth phases (Table 20). At PI stage, MDU-6 registered highest RWC value (89.71 %) which was statistically superior to other varieties. MDU-6 and Sharada were found to have significantly higher RWC per cent compared to Swarnaprabha and Vaishakh when high temperature stress was induced from PI to flowering. However no significant difference could be observed in RWC at maturity phase when stress was imposed during later phase of crop growth.

Plants exposed to high temperature stress registered lower RWC compared to plants under control at all stages.

The variety MDU-6 under control recorded higher RWC at all the growth stages whereas Swarnaprabha exposed to high temperature stress showed lowest RWC at all stages.

b. Stomatal conductance

Higher and comparable stomatal conductance (0.156 mol $H_2O/m^2/s$) was observed for Swarnaprabha and Vaishakh whereas, it was lowest for MDU-6 (0.126 mol $H_2O/m^2/s$) during PI stage (Table 21). The variety MDU-6 registered higher stomatal conductance which was on par with Vaishakh, while lower value was observed for Sharada during flowering stage. At maturity, higher value was recorded for Swarnaprabha which was superior to all varieties.

Significant difference between plants under stress and ambient temperature was observed during all stages with respect to stomatal conductance. Plants exposed to high temperature stress showed significantly low stomatal conductance compared to plants under control during crop growth period.

Table 20. Effect of high temperature on relative water content (%) of aerobic rice varieties

Relative water content (%)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	80.69	70.18	**75.44**
Sharada	81.62	68.27	**74.95**
Vaishakh	82.69	79.54	**81.12**
MDU-6	92.65	86.76	**89.71**
Mean	**84.41**	**76.19**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	6.80	4.81	9.62
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	67.10	65.60	**66.35**
Sharada	86.25	79.23	**82.74**
Vaishakh	72.52	66.52	**69.52**
MDU-6	90.13	75.62	**82.88**
Mean	**79.00**	**71.74**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	6.51	4.61	9.21
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	77.80	77.81	**77.81**
Sharada	78.52	74.09	**76.31**
Vaishakh	79.09	74.83	**76.96**
MDU-6	79.79	69.67	**74.73**
Mean	**78.80**	**74.10**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	NS	4.56	NS

Table 21. Effect of high temperature on stomatal conductance (m mol H_2O /m^2/s) of aerobic rice varieties

Stomatal conductance (m mol H_2O /m^2/s)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	0.175	0.135	**0.155**
Sharada	0.156	0.123	**0.140**
Vaishakh	0.185	0.127	**0.156**
MDU-6	0.145	0.106	**0.126**
Mean	**0.165**	**0.123**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.015	0.011	0.022
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	0.131	0.125	**0.128**
Sharada	0.127	0.103	**0.115**
Vaishakh	0.186	0.120	**0.153**
MDU-6	0.203	0.123	**0.163**
Mean	**0.162**	**0.118**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.012	0.009	0.017
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	0.191	0.164	**0.178**
Sharada	0.102	0.076	**0.089**
Vaishakh	0.177	0.109	**0.143**
MDU-6	0.174	0.148	**0.161**
Mean	**0.161**	**0.124**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.015	0.010	0.021

Swarnaprabha exposed to high temperature stress recorded higher stomatal conductance which was superior to all treatments whereas MDU-6 and Sharada had comparable conductance under high temperature stress during PI stage. At flowering stage, MDU-6 (0.203 mol $H_2O/m^2/s$) and Vaishakh under control (0.186 mol $H_2O/m^2/s$) recorded higher values, while Sharada under high temperature stress, showed lower stomatal conductance (0.103 mol $H_2O/m^2/s$). At maturity phase, the variety Swarnaprabha recorded higher value, whereas Shardha showed lower value of stomatal conductance.

c. Photosynthetic rate

The data on photosynthetic rate showed significant difference among varieties (Table 22). The variety Swarnaprabha registered higher photosynthetic rate compared to other varieties at all crop growth stages, whereas the lower photosynthetic rate was observed for Sharada and MDU-6.

Plants exposed to high temperature stress recorded lower photosynthetic rate compared to plants under control at all stages. The photosynthetic rate was higher at flowering stage compared to PI and maturity.

The variety Swarnaprabha under control registered higher photosynthetic rate. During flowering, the variety Vaishakh under control recorded higher photosynthetic value (2.00 $\mu mol/m^2/s$) which was comparable with MDU-6 and Swarnaprabha under control. Lower photosynthetic rate of 0.44 $\mu mol/m^2/s$ was recorded for MDU-6 exposed to high temperature stress.

d. Transpiration rate

The highest transpiration rate (2.33 mol $H_2O/m^2/s$) was observed for MDU-6 whereas it was lowest for Sharada (1.24 mol $H_2O/m^2/s$) during PI stage. During flowering, the variety Swarnaprabha registered higher transpiration rate which was on par with Sharada, while lower value was observed for MDU-6. At maturity, a trend similar to that during PI stage was observed (Table 23).

Table 22. Effect of high temperature on photosynthetic rate (µmol/m²/s) of aerobic rice varieties

Photosynthetic rate (µmol/m²/s)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	2.56	1.78	**2.17**
Sharada	1.58	0.71	**1.14**
Vaishakh	1.28	1.14	**1.21**
MDU-6	1.33	0.95	**1.14**
Mean	**1.69**	**1.15**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.12	0.09	0.18
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	1.87	1.33	**1.60**
Sharada	1.27	1.47	**1.37**
Vaishakh	2.00	0.79	**1.40**
MDU-6	1.88	0.44	**1.16**
Mean	**1.76**	**1.01**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.13	0.09	0.18
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	2.69	1.85	**2.27**
Sharada	0.65	0.51	**0.58**
Vaishakh	1.49	0.83	**1.16**
MDU-6	1.06	0.54	**0.80**
Mean	**1.47**	**0.93**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.11	0.08	0.16

Table 23. Effect of high temperature on transpiration rate (m mol H_2O /m^2/s) of aerobic rice varieties

Transpiration rate (m mol H_2O /m^2/s)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	2.06	1.25	**1.66**
Sharada	1.73	0.75	**1.24**
Vaishakh	2.21	1.85	**2.03**
MDU-6	2.58	2.09	**2.33**
Mean	**2.15**	**1.49**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.16	0.11	0.23
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	2.41	2.13	**2.27**
Sharada	2.17	2.16	**2.17**
Vaishakh	2.15	1.10	**1.62**
MDU-6	2.13	0.77	**1.45**
Mean	**2.22**	**1.54**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.67	0.12	0.24
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	1.68	1.04	**1.36**
Sharada	1.06	0.83	**0.95**
Vaishakh	1.63	1.13	**1.38**
MDU-6	1.60	1.19	**1.39**
Mean	**1.49**	**1.05**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.11	0.08	0.15

Significant difference between plants under stress and ambient temperature was observed at stages of observation with respect to transpiration rate. Plants exposed to high temperature stress showed significantly low transpiration rate compared to plants under control during all stages of crop growth.

Vaishakh and MDU-6 exposed to high temperature stress recorded higher transpiration rate whereas Sharada had lower value (0.75 m mol $H_2O/m^2/s$) under high temperature stress compared to their control during PI stage. At flowering stage, Sharada (2.16 m mol $H_2O/m^2/s$) and Swarnaprabha (2.13 m mol $H_2O/m^2/s$) recorded higher values, while Sharada under high temperature stress, showed lower transpiration rate (0.77 m mol $H_2O/m^2/s$) compared to its control. At maturity phase, a trend similar to that during PI stage was observed.

e. Total chlorophyll content

Among varieties, Vaishakh registered the highest chlorophyll content comparable with Swarnaprabha and superior to Sharada and MDU-6 during panicle initiation stage (Table 24). At flowering stage, higher chlorophyll was observed for Swarnaprabha (2.35 mg/g) which was significantly higher than other varieties. Sharada and Vaishakh registered higher chlorophyll content whereas lower chlorophyll content observed in MDU-6 during maturity stage.

Rice exposed to high temperature stress had lower total chlorophyll content at all stages compared to control, and chlorophyll content was higher at PI stage (2.28 mg/g) compared to flowering and maturity phase(1.95 mg/g). (Table 24).

Higher chlorophyll content was observed for variety Vaishakh under control during PI and Sharada at maturity stage. During flowering stage, Swarnaprabha under control registered higher chlorophyll content (2.45 mg/g). The variety MDU-6 exposed to high temperature stress showed lower chlorophyll content during all flowering and maturity stages.

f. Soluble protein content

Soluble protein content in leaves of all varieties were higher during PI stage, however during later stages difference was registered. Soluble protein content showed a declined trend with progress in plant growth (Table 25).

Table 24. Effect of high temperature on total chlorophyll content (mg/g) of aerobic rice varieties

Total chlorophyll content (mg/g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	2.52	2.42	**2.47**
Sharada	2.45	2.14	**2.30**
Vaishakh	2.84	2.35	**2.60**
MDU-6	2.32	2.22	**2.27**
Mean	**2.53**	**2.28**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.20	0.14	0.29
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	2.45	2.24	**2.35**
Sharada	2.26	1.95	**2.11**
Vaishakh	2.00	1.84	**1.92**
MDU-6	2.14	1.78	**1.96**
Mean	**2.21**	**1.95**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.18	0.13	0.25
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	2.26	1.87	**2.07**
Sharada	2.53	2.16	**2.35**
Vaishakh	2.64	2.01	**2.33**
MDU-6	2.27	1.74	**2.01**
Mean	**2.43**	**1.95**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.19	0.13	0.37

Table 25. Effect of high temperature on soluble protein content (mg/g) of aerobic rice varieties

Soluble protein content (mg/g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	20.48	17.10	**18.79**
Sharada	20.94	15.99	**18.47**
Vaishakh	20.64	18.71	**19.68**
MDU-6	19.92	16.54	**18.23**
Mean	**20.50**	**17.08**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	NS	1.13	2.25
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	18.09	15.64	**16.87**
Sharada	15.39	13.78	**14.59**
Vaishakh	14.26	11.56	**12.91**
MDU-6	10.65	8.69	**9.67**
Mean	**14.60**	**12.42**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	1.15	0.82	1.63
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	14.02	12.76	**13.39**
Sharada	11.73	10.80	**11.27**
Vaishakh	12.03	11.94	**11.99**
MDU-6	12.44	11.42	**11.93**
Mean	**12.55**	**11.73**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	1.02	0.72	1.44

All varieties when exposed to high temperature stress had lower soluble protein content at all the growth stages. At flowering, Swarnaprabha under control recorded highest soluble protein content compared to other varieties. The lowest soluble protein content was recorded for MDU-6 (8.69 mg/g) when high temperature stress was imposed during PI stage.

g. Nitrate reductase activity

The data on nitrate reductase activity showed significant difference between varieties and high temperature stress (Table 26). Among varieties, Sharada recorded highest nitrate reductase activity at all growth stages whereas lowest was observed for Vaishakh during PI and maturity stages, under ambient condition. Among growth stages, nitrate reductase activity was the highest during flowering period and sharply decreased at maturity.

Similar trend to soluble protein content was observed for nitrate reductase activity. Rice exposed to high temperature stress at different growth stages had decreased nitrate reductase than plants grown under ambient condition and values ranged from 203.18 µ mol/g (control) to 36.94 (stressed) µ mol/g.

Interaction effect of variety and high temperature stress was significant. The variety Sharada under control registered higher value for nitrate reductase during all growth stages whereas lowest nitrate reductase was observed for Vaishakh under high temperature stress during all growth stages, except at flowering stage, where MDU-6 had lowest nitrate reductase content.

h. Membrane stability index (MSI)

The data on membrane stability index are presented in Table 27. During PI stage, the highest MSI value was recorded for Swarnaprabha (90.35 %) which was comparable with Sharada and MDU-6 whereas, the value was lower for Vaishakh. At flowering stage, Swarnaprabha recorded higher MSI value which was on par with Sharada and Vaishakh and lowest MSI was observed for MDU-6. At maturity stage, all varieties were shown to be significantly different from each other with respect to MSI and MDU-6 recorded highest MSI value.

Table 26. Effect of high temperature on nitrate reductase activity (µ mol/g) of aerobic rice varieties

Nitrate reductase (µ mol/g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	197.49	150.56	**174.03**
Sharada	231.45	200.12	**215.79**
Vaishakh	110.87	102.64	**106.75**
MDU-6	147.86	137.41	**142.90**
Mean	**171.92**	**147.81**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	14.32	10.13	20.25
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	276.39	246.23	**261.31**
Sharada	284.59	263.59	**274.09**
Vaishakh	151.46	140.16	**145.81**
MDU-6	100.26	96.54	**98.40**
Mean	**203.18**	**186.63**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	17.54	12.41	24.81
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	68.59	38.57	**53.58**
Sharada	78.76	37.88	**58.32**
Vaishakh	27.43	25.07	**26.25**
MDU-6	52.50	46.23	**49.37**
Mean	**56.82**	**36.94**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	4.30	3.04	6.09

Table 27. Effect of high temperature on membrane stability index (%) of aerobic rice varieties

Membrane stability index (%)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	96.06	84.63	**90.35**
Sharada	95.76	80.27	**88.01**
Vaishakh	81.88	70.91	**76.40**
MDU-6	89.05	75.13	**82.09**
Mean	**90.69**	**77.73**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	9.76	6.90	13.80
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	87.12	77.56	**82.34**
Sharada	83.84	74.65	**79.25**
Vaishakh	80.21	73.85	**77.03**
MDU-6	75.56	60.35	**67.96**
Mean	**81.68**	**71.60**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	6.49	4.59	9.18
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	44.10	36.39	**40.25**
Sharada	57.38	53.79	**55.59**
Vaishakh	77.52	44.54	**61.03**
MDU-6	73.07	57.87	**65.47**
Mean	**63.02**	**48.15**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	3.16	2.24	4.47

Plants grown under high temperature stress showed significantly less MSI value than plants under control during all growth stages.

During flowering stage, Swarnaprabha and Sharada under control registered highest MSI value whereas Vaishakh and MDU-6 under high temperature stress showed lower values (Table 27). However at maturity, MDU-6 and Vaishakh under control registered higher and comparable MSI under ambient temperature. Swarnaprabha exposed to high temperature stress at maturity had lower MSI.

i. Malondialdehyde

During all growth stages, plants exposed to high temperature stress recorded highest MDA content compared to plants under ambient temperature condition (Table 28). At PI stage the increase in MDA was very conspicuous in variety Sharada under temperature stress (18.88 n mol/g) compared to MDI under ambient temperature (7.54 n mol/g). This sharp increase was not observed in other three varieties. At maturity phase variety Vaishakh maintained higher MDA of 15.03 n mol/g which was comparable to value under ambient condition.

The variety Sharada exposed to stress from tillering to PI stage recorded highest MDA content (18.88 n mol/g) whereas lowest MDA content was for MDU-6 under control (2.11 n mol/g). During flowering and maturity stage, Vaishakh under control recorded higher MDA content whereas Sharada and Swarnaprabha recorded lowest MDA values.

j. Proline content

Among varieties, Swarnaprabha recorded the highest proline content (235.56 µ mol/g) followed by Sharada under temperature stress at PI stage. Lower proline content was for MDU-6 (63.21 µ mol/g) and Vaishakh (65.21 µ mol/g) during PI stage under ambient condition. During flowering stage, MDU-6 registered highest proline content and lower value for Vaishakh. But Vaishakh produced significantly higher proline content when stress was imposed during flowering to maturity while Swarnaprabha was inferior (Table 29).

Rice plants exposed to high temperature stress showed increased proline content than plants under ambient condition at PI and flowering stages whereas stress

Table 28. Effect of high temperature on malondialdehyde (n mol /g) of aerobic rice varieties

Malondialdehyde (n mol /g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	11.66	12.34	**12.00**
Sharada	7.54	18.88	**13.21**
Vaishakh	6.07	8.22	**7.14**
MDU-6	2.11	3.38	**2.74**
Mean	**6.84**	**10.70**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.84	0.59	1.19
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	7.01	9.23	**8.12**
Sharada	4.99	5.85	**5.42**
Vaishakh	13.63	12.03	**12.83**
MDU-6	12.86	12.06	**12.46**
Mean	**9.62**	**9.79**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.84	0.60	1.19
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	7.03	10.77	**8.90**
Sharada	8.58	10.84	**9.71**
Vaishakh	15.03	14.52	**14.77**
MDU-6	12.45	9.94	**11.20**
Mean	**10.77**	**11.52**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.96	0.68	1.35

Table 29. Effect of high temperature on proline content (µ mol/g) of aerobic rice varieties

Proline content (µ mol/g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	174.75	235.56	**205.16**
Sharada	159.06	160.34	**159.70**
Vaishakh	65.21	137.91	**101.56**
MDU-6	63.81	115.91	**89.86**
Mean	**115.71**	**162.43**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	26.24	18.55	37.10
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	54.43	48.55	**51.49**
Sharada	51.67	56.66	**54.16**
Vaishakh	35.12	37.14	**36.13**
MDU-6	64.54	72.45	**68.50**
Mean	**51.44**	**53.70**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	4.61	3.26	6.52
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	29.24	26.13	**27.69**
Sharada	48.82	35.03	**41.93**
Vaishakh	54.34	49.92	**52.13**
MDU-6	58.47	11.95	**35.21**
Mean	**47.72**	**30.76**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	3.56	2.51	5.03

during maturity did not exhibit an increase in proline content over ambient temperature condition.

But stress during maturity stage showed a slight reduction in proline content as compared to control in all varieties. The variety Swarnaprabha exposed to stress from tillering to PI stage recorded highest proline content (235.56 µmol/g) and MDU-6 under control recorded lowest proline content. During flowering, MDU-6 exposed to stress produced higher proline content whereas though the effect was not significant during flowering to maturity, the higher proline content was for MDU-6 under control.

k. Superoxide dismutase

Data recorded for superoxide dismutase activity of rice varieties under high temperature stress at different stages are presented in Table 30. Among varieties, Swarnaprabha recorded the highest SOD activity (0.634 and 0.285 g/min) and lowest was recorded by Vaishakh (0.098 and 0.148 g/min) during PI and flowering stage. During maturity stage, the highest SOD activity was observed for Vaishakh which was superior to all other varieties.

Increased SOD activity during PI stage was observed under temperature stress whereas decrease in remaining growth stages compared to plants under ambient condition.

In Swarnaprabha and Sharada, the SOD activity was increased under high temperature stress condition over control at PI stage. At maturity, the SOD activity decreased under high temperature stress as compared to control in all varieties except Vaishakh. The result revealed that the SOD activity was increased only in variety Vaishakh during later growth stages when exposed to high temperature stress.

l. Canopy air temperature difference (CATD)

Among varieties, Vaishakh registered highest CATD on exposure to high temperature stress from tillering to PI (1.05°C), whereas during flowering Sharada recorded higher CATD values (1.42°C). At PI and flowering, the lowest CATD value was recorded for MDU-6 and at maturity Sharada showed lower value (1.02°C).

Table 30. Effect of high temperature on superoxide dismutase (g/min) of aerobic rice varieties

Superoxide dismutase (g/min)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	0.220	1.047	**0.634**
Sharada	0.109	0.762	**0.435**
Vaishakh	0.121	0.076	**0.098**
MDU-6	0.122	0.114	**0.118**
Mean	**0.143**	**0.500**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.033	0.023	0.046
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	0.364	0.205	**0.285**
Sharada	0.209	0.198	**0.204**
Vaishakh	0.053	0.243	**0.148**
MDU-6	0.225	0.185	**0.205**
Mean	**0.213**	**0.208**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.018	0.013	0.026
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	0.114	0.092	**0.103**
Sharada	0.112	0.107	**0.109**
Vaishakh	0.117	0.142	**0.129**
MDU-6	0.109	0.097	**0.103**
Mean	**0.113**	**0.109**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.009	0.007	0.013

Table 31. Effect of high temperature on canopy air temperature difference (°C) of aerobic rice varieties

Canopy air temperature difference (°C)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	0.86	0.75	**0.81**
Sharada	0.90	0.83	**0.87**
Vaishakh	1.12	0.97	**1.05**
MDU-6	0.78	0.70	**0.74**
Mean	**0.92**	**0.81**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.07	0.05	0.11
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	1.23	0.97	**1.10**
Sharada	1.59	1.24	**1.42**
Vaishakh	1.26	1.01	**1.14**
MDU-6	1.03	0.86	**0.95**
Mean	**1.28**	**1.02**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.10	0.07	0.14
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Swarnaprabha	1.27	1.01	**1.14**
Sharada	1.21	0.84	**1.02**
Vaishakh	1.44	1.39	**1.41**
MDU-6	1.71	1.21	**1.46**
Mean	**1.41**	**1.11**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.11	0.08	0.15

Rice plants exposed to high temperature stress registered decreased CATD value compared to plants grown under ambient condition at all growth stages. The value ranges from 1.41 to 0.81°C (Table 31).

The CATD values decreased under high temperature stress in all varieties compared to control at all growth stages. The highest CATD value was recorded for Vaishakh under control (1.12°C) during PI stage, Sharada (1.59°C) at flowering and MDU-6 at maturity (1.71°C). At PI and flowering, the variety MDU-6 exposed to high temperature recorded lowest CATD value, whereas Sharada under stress recorded lowest value (0.84°C) at maturity.

4.1.3 Plant analysis

a. Uptake of Nitrogen

The data on nitrogen uptake by different varieties are presented in Table 32. The highest N uptake was recorded for Vaishakh (0.137 g/hill) which was superior to all varieties.

Plants exposed to high temperature stress from tillering to PI stage recorded highest total N uptake (0.142 g/hill) which was higher than stress at remaining stages (Table 32).

Interaction effect of variety and stress was significant. The highest total N content (0.163 g/hill) was observed in Vaishakh exposed to high temperature stress from tillering to PI stage whereas MDU-6 exposed to high temperature stress from flowering to maturity recorded lowest values (0.099 g/hill).

b. Uptake of Phosphorus

Significant difference between varieties were observed in phosphorus uptake (Table 33). The variety MDU-6 registered higher total P uptake at harvest (0.076 g/hill) whereas lower for Swarnaprabha (0.051 g/hill).

However non-significant difference due to treatments was observed in total phosphorus uptake. Plants exposed to high temperature stress from tillering to flowering recorded higher total P uptake of 0.065 g/hill and lower values were

Table 32. Effect of high temperature stress on N uptake (g/hill) of aerobic rice varieties at harvest

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	0.114	0.148	0.105	0.101	**0.117**
Sharada	0.116	0.127	0.109	0.115	**0.117**
Vaishakh	0.141	0.163	0.127	0.117	**0.137**
MDU-6	0.112	0.128	0.123	0.099	**0.116**
Mean	**0.121**	**0.142**	**0.116**	**0.108**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.016	0.016	0.017

Table 33. Effect of high temperature stress on P uptake (g/hill) of aerobic rice varieties at harvest

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	0.046	0.061	0.057	0.041	**0.051**
Sharada	0.064	0.058	0.062	0.054	**0.060**
Vaishakh	0.050	0.065	0.074	0.067	**0.064**
MDU-6	0.084	0.075	0.068	0.077	**0.076**
Mean	**0.061**	**0.065**	**0.065**	**0.060**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.005	0.005	0.010

Table 34. Effect of high temperature stress on K uptake (g/hill) of aerobic rice varieties at harvest

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	0.390	0.479	0.407	0.349	**0.406**
Sharada	0.385	0.421	0.346	0.352	**0.376**
Vaishakh	0.426	0.500	0.381	0.406	**0.428**
MDU-6	0.360	0.423	0.328	0.355	**0.366**
Mean	**0.390**	**0.456**	**0.366**	**0.365**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.033	0.033	0.066

recorded for plants exposed to high temperature from flowering to maturity (0.060 g/hill).

The variety MDU-6 under control registered higher total P uptake (0.084 g/hill) whereas lowest value was observed for Swarnaprabha exposed to high temperature stress from flowering to maturity (0.041 g/hill).

c. Uptake of Potassium

Among varieties, the highest total K uptake was recorded for Vaishakh (0.428 g/hill) whereas lowest was registered in MDU-6 and Sharada (Table 34).

Plants exposed to high temperature stress from tillering to PI stage recorded higher total K uptake (0.456 g/hill) whereas lower values were observed in plants exposed to flowering to maturity.

Interaction effect of variety and high temperature stress on potassium uptake was significant. The highest total K uptake was noticed in variety Vaishakh exposed to high temperature stress from tillering to PI stage (0.500 g/hill) while MDU-6 exposed to high temperature stress from PI to flowering stage recorded lowest uptake (0.328 g/hill).

d. Grain protein content

The data shows significant difference in grain protein content among the varieties (Table 35). Higher grain protein content was observed for MDU-6 (4.66 %) which was superior to all varieties. Sharada recorded lowest grain protein content of (4.01 %) which was comparable with Swarnaprabha (4.04 %).

Rice plants exposed to high temperature stress from tillering to PI stage had highest grain protein content (4.60 %) which was superior to stress at remaining stages and control. Lower protein content was observed under control, which was comparable to contents from PI to maturity.

The variety MDU-6 exposed to high temperature stress from tillering to flowering registered higher grain protein content which was comparable with Vaishakh exposed to stress from tillering to PI stage. Lower grain protein content was

Table 35. Effect of high temperature stress on grain protein content (%) of aerobic rice varieties at harvest

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	4.33	4.33	3.55	3.94	**4.04**
Sharada	3.94	3.94	3.68	4.47	**4.01**
Vaishakh	3.94	5.12	4.20	4.33	**4.40**
MDU-6	4.07	4.99	5.38	4.21	**4.66**
Mean	**4.07**	**4.60**	**4.20**	**4.24**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.22	0.22	0.45

Table 36. Requirement of growing degree days in rice as influenced by high temperature stress of aerobic rice varieties (°C day)

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	1934	1953	1972	2002	**1965**
Sharada	1914	1953	1992	1979	**1960**
Vaishakh	1954	2012	2012	1999	**1994**
MDU-6	1799	1802	1828	1867	**1824**
Mean	**1901**	**1930**	**1951**	**1962**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			100	NS	201

Table 37. Effect of high temperature stress on helio thermal units (°C day h) of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	16207	16572	16641	16819	**16560**
Sharada	16121	16572	16807	16723	**16556**
Vaishakh	16308	16841	16943	16682	**16693**
MDU-6	15331	15297	15566	15979	**15543**
Mean	**15992**	**16321**	**16489**	**16550**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			848	NS	1696

noticed in variety Swarnaprabha exposed to high temperature from PI to flowering stage.

4.1.4 Heat Units

a. Growing degree days (GDD)

Among varieties, Vaishakh registered higher GDD of 1994 day °C which was comparable with Sharada and Swarnaprabha whereas lowest GDD was observed for MDU-6 (1824 °C day).

No significance difference was observed between stages of stress imposed with respect to GDD (Table 36). The highest GDD value was recorded when plants were exposed to high temperature from flowering to maturity (1962 °C day) whereas lower values was observed under control (1901 °C day).

Interaction effect between varieties and high temperature stress in relation to GDD was significant (Table 36). The variety Vaishakh exposed to high temperature stress from tillering to flowering stage registered higher GDD (2012 °C day) whereas lowest GDD was for variety MDU-6 under control (1799 °C day).

b. Helio thermal units (HTU)

The data on helio thermal units for different varieties are shown in Table 37. The higher HTU value was registered for variety Vaishakh (16693 °C day h) which was on par with Swarnaprabha and Sharada whereas lowest GDD was recorded for MDU-6 (15543 °C day h).

Similar trend of GDD was observed for HTU. The helio thermal units was higher for plants exposed to flowering to maturity (16550 °C day h) which was however, comparable with stress at remaining stages and control.

Interaction effect was non-significant (Table 45). The highest HTU value was recorded for Vaishakh exposed to high temperature from PI to flowering (16943 °C day h) and lowest for MDU-6 exposed to high temperature from tillering to PI stage.

c. Photo thermal units (PTU)

Among varieties, Vaishakh registered higher PTU value (23268 ℃ day h) which was comparable with Swarnaprabha and Sharada and they were superior to MDU-6 (Table 38).

No significant difference was observed among the stressed and non stressed rice plants in relation to PTU values. High temperature stress imposed from flowering to maturity showed higher photothermal units (22884 ℃ day h) than stress at remaining stages and control.

Interaction effect between varieties and stress was significant (Table 38). The highest PTU value of 23473 ℃ day h was recorded for Vaishakh exposed to high temperature stress from PI to flowering and lowest for MDU-6 under control (20952 ℃ day h).

d. Heat use efficiency (HUE)

The variety Vaishakh registered highest heat use efficiency (0.34 g/m^2 ℃ day) compared to all varieties whereas lowest HUE was observed for MDU-6 (0.30 g/m^2 ℃ day).

Plants exposed to high temperature from tillering to PI stage registered higher HUE (0.35 g/m^2 ℃ day) which was superior to stress at remaining stages and control. The lower HUE of 0.28 g/m^2 ℃ day was observed for plants exposed to stress from flowering to maturity.

In all varieties higher HUE was recorded during tillering to PI stage registered higher HUE whereas lower during flowering to maturity (Table 39). The highest HUE was observed for Swarnaprabha exposed to high temperature stress from tillering to PI stage (0.37 g/m^2 ℃ day) and the same variety exposed to high temperature from flowering to maturity recorded lowest HUE value (0.26 g/m^2 ℃ day).

Table 38. Effect of high temperature stress on photo thermal units (°C day h) of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	22558	22749	22993	23361	**22915**
Sharada	22320	22749	23231	23094	**22848**
Vaishakh	22799	23462	23473	23336	**23268**
MDU-6	20952	20952	21275	21744	**21231**
Mean	**22157**	**22478**	**22743**	**22884**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			1169	NS	2339

Table 39. Effect of high temperature stress on heat use efficiency (g/m^2 °C day) of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Swarnaprabha	0.31	0.37	0.30	0.26	**0.31**
Sharada	0.32	0.34	0.30	0.28	**0.31**
Vaishakh	0.35	0.35	0.34	0.31	**0.34**
MDU-6	0.31	0.33	0.29	0.28	**0.30**
Mean	**0.32**	**0.35**	**0.31**	**0.28**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.02	0.02	0.03

4.2 EXPERIMENT II: ASSESSMENT OF WETLAND RICE VARIETIES TO HIGH TEMPERATURE STRESS

4.2.1 Growth parameters

a. Plant height

Plant height varied with variety as well as with temperature stress (Table 40). At harvest, Aiswarya registered taller plants (102.15 cm) which was significantly superior to Kanchana (85.50 cm), Jyothi (85.26 cm) and Uma (83.26 cm).

Among high temperature stress at different stages, the tallest plants were recorded in plants imposed to stress from tillering to flowering stage at all observations. At harvest, plants exposed from tillering to PI recorded tallest plants (94.17 cm) which was on par with stress imposed from PI to flowering stage (89.85 cm). The shortest plants were recorded under control (85.21 cm) and stress imposed from flowering from maturity (86.93 cm).

Interaction effect of variety and high temperature stress on plant height was significant at harvest. At harvest, Aiswarya exposed to high temperature stress from tillering to PI stage and PI to flowering recorded taller plants (107.25 and 104.26 cm) whereas shortest plants were observed for Uma under control (77.58 cm).

b. Number of tillers per hill

Significant difference in number of tillers per hill was noticed among the varieties (Table 41). The highest number of tillers was observed for Kanchana during all stages. At harvest, there was no significant difference between the varieties. Tiller number varied from 11.31 to 10.90 per hill.

Effect of high temperature stress on tiller number showed significant difference between stress phases. At all stages plants exposed to high temperature from tillering to PI stage registered higher number of tillers per hill. At harvest, plants imposed to high temperature from tillering to PI stage produced highest tillers per hill (11.70) which was comparable with plants grown under control and lowest tillers were recorded when stress imposed from flowering to maturity.

Table 40. Effect of high temperature stress on plant height at harvest of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	83.65	88.24	85.86	84.25	**85.50**
Jyothi	81.20	89.95	85.62	84.25	**85.26**
Uma	77.58	91.25	83.65	80.56	**83.26**
Aiswarya	98.42	107.25	104.26	98.65	**102.15**
Mean	**85.21**	**94.17**	**89.85**	**86.93**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			4.75	4.75	9.50

Table 41. Effect of high temperature stress on number of tillers at harvest of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	11.22	11.78	10.89	10.56	**11.11**
Jyothi	10.39	11.22	10.89	11.17	**10.92**
Uma	11.50	11.78	11.00	9.33	**10.90**
Aiswarya	11.89	12.01	11.33	10.02	**11.31**
Mean	**11.25**	**11.70**	**11.03**	**10.27**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			NS	0.58	1.15

Table 42. Effect of high temperature stress on leaf area (cm^2) at 60 DAS of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Mean
Kanchana	847	1388	1105	**1113**
Jyothi	1006	1135	1024	**1055**
Uma	1260	1431	1283	**1325**
Aiswarya	1238	1662	1456	**1452**
Mean	**1088**	**1404**	**1217**	
	CD(0.05)	**Varieties**	**Stress**	**V x S**
		72	62	124

Aiswarya exposed to high temperature stress from tillering to PI stage recorded highest number tillers per hill at harvest and the lowest tiller number was registered for Uma exposed to high temperature from flowering to maturity.

c. Leaf area

Varietal difference were significant. The variety Aiswarya recorded highest leaf area (1452 cm^2) value which was superior to other varieties at 60 DAS. The lowest LAI value was registered for Jyothi (1055 cm^2) (Table 42).

Among high temperature stress condition, the highest leaf area value was recorded when temperature stress was induced from tillering to PI (1404 cm^2). Plants grown under ambient condition (control) recorded lowest LAI value (1088 cm^2).

Interaction effect of variety and temperature stress on leaf area was significant. The highest Leaf area of 1662 cm^2 was recorded for Aiswarya exposed to high temperature stress from tillering to PI stage which was superior to all other treatments and Kanchana under control registered lowest leaf area.

d. Days to flowering

Varietal sensitivity to days to flowering were also observed. Among varieties, early flowering occured in Kanchana and Jyothi which were short duration varieties, whereas, Aiswarya and Uma which were of medium duration registered late flowering (Table 43).

High temperature stress at different stages also resulted in significant difference in days to flowering. Plants exposed to high temperature stress from tillering to PI stage came to flowering (69.83 days) early compared to stress at other stages.

The variety Kanchana and Jyothi when exposed to high temperature stress during vegetative phase showed early flowering. The other two variety Uma and Aiswarya flowered late irrespective of high temperature stress at different stages.

Table 43. Effect of high temperature stress on days to flowering of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Mean
Kanchana	70.00	66.67	68.00	**68.22**
Jyothi	71.00	66.67	68.00	**68.56**
Uma	77.00	72.00	73.00	**74.00**
Aiswarya	78.33	74.00	76.00	**76.11**
Mean	**74.08**	**69.83**	**71.25**	
	CD(0.05)	**Varieties**	**Stress**	**V x S**
		3.69	NS	7.38

Table 44. Effect of high temperature stress on dry matter production (g/hill) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	31.28	32.60	31.23	30.04	**31.29**
Jyothi	29.59	30.66	30.14	29.21	**29.90**
Uma	32.74	33.86	32.84	31.83	**32.82**
Aiswarya	34.79	35.15	34.38	33.57	**34.47**
Mean	**32.10**	**33.07**	**32.15**	**31.16**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			1.67	1.67	3.35

Table 45. Effect of high temperature stress on root dry weight (g/hill) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	9.05	8.95	8.64	8.88	**8.88**
Jyothi	8.58	8.36	8.35	8.54	**8.46**
Uma	9.25	9.15	9.10	9.32	**9.21**
Aiswarya	9.54	9.36	9.24	9.46	**9.40**
Mean	**9.11**	**8.96**	**8.83**	**9.05**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.47	NS	0.94

e. Dry matter production

Among the varieties, the higher dry matter production was registered for Aiswarya (34.47 g/hill) which was comparable with Uma (32.82 g/hill), whereas it was lower for Kanchana and Jyothi (Table 44).

Plants grown under high temperature stress at tillering to PI and PI to flowering stage and control produced higher dry matter than plants exposed to high temperature from flowering to maturity (31.16 g/hill).

All the varieties when grown under high temperature stress at vegetative stages produced higher dry matter compared to plants under ambient condition. The highest dry matter production was registered for variety Aiswarya exposed to high temperature from tillering to PI stage which was comparable with stress at other stages, and Uma exposed to stress at all stages.

f. Root dry weight

Among the varieties, the highest root dry weight was recorded for Aiswarya which was on par with Uma whereas superior to Kanchana and Jyothi (Table 45).

No significant difference was observed between high temperature stress and ambient conditions (Table 45) with respect to root dry weight. However, interaction effect of variety and high temperature stress was significant. The variety Jyothi exposed to high temperature stress at different stages and its control recorded lower root dry weight compared to other treatments.

4.2.2 Yield attributes and yield

a. Number of panicles per hill

No significant difference was noticed in number of panicles per hill between varieties and also among stress condition and the average number of panicles per hill was 9.84 (Table 46).

However, all varieties produced higher number of panicles under ambient condition compared to high temperature stress. The variety Uma exposed to high temperature stress from flowering to maturity was inferior to all other treatments.

Table 46. Effect of high temperature stress on number of panicles per hill of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	10.49	10.33	10.04	9.72	**10.15**
Jyothi	10.12	9.56	9.83	9.11	**9.66**
Uma	9.48	9.63	9.56	8.78	**9.36**
Aiswarya	10.36	9.89	10.78	9.72	**10.19**
Mean	**10.11**	**9.85**	**10.05**	**9.33**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.96	NS	1.92

Table 47. Effect of high temperature stress on filled grains per panicle of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	77.60	70.23	67.30	62.00	**69.28**
Jyothi	70.97	69.97	68.30	59.40	**67.16**
Uma	94.43	92.53	81.13	80.27	**87.09**
Aiswarya	107.10	90.33	87.33	89.17	**93.48**
Mean	**87.53**	**80.77**	**76.02**	**72.71**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			4.73	4.73	9.45

Table 48. Effect of high temperature stress on chaff per cent of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	7.57	8.66	8.83	19.18	**11.06**
Jyothi	12.54	11.04	10.79	24.61	**14.74**
Uma	9.22	10.09	10.64	20.12	**12.52**
Aiswarya	10.05	12.96	9.64	12.48	**11.28**
Mean	**9.84**	**10.69**	**9.97**	**19.10**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.96	0.96	1.92

b. Number of filled grains per panicle

Varietal differences in number of filled grains per panicle was significant (Table 47). Aiswarya produced highest number of filled grains per panicle (93.48) compared to other varieties. Jyothi and Kanchana were inferior.

Plants grown under ambient condition produced highest number of filled grains per panicle (87.53) whereas the lowest was recorded when stress was imposed from flowering to maturity stage which was on par with stress imposed from PI to flowering stage.

In all the varieties, high temperature stress imposed from flowering to maturity stage registered lower number of filled grains per panicle except in Aiswarya, where highest number was observed when stress was imposed from PI to flowering. Aiswarya under control produced highest filled grains per panicle of 107.10 whereas lowest filled grains per panicle was observed for Jyothi exposed to high temperature stress from flowering to maturity (59.40).

c. Chaff per cent

Varietal sensitivity to high temperature was evident in per cent chaff also (Table 48). The variety Jyothi was found most susceptible with 15 per cent chaff and Kanchana recorded lowest chaff per cent which was comparable with Aiswarya.

A trend similar to that of filled grains per panicle could be observed in case of chaff per cent also. The highest chaff per cent (19.10 %) was registered in plants imposed to high temperature stress from flowering to maturity and response was similar in all the varieties tried.

d. Total number of grains per panicle

Varietal difference in relation to total number of grains per panicle was significant (Table 49). Total number of grains was significantly higher in Aiswarya (105.28) and lowest number was for variety Kanchana (77.82) which was comparable with Jyothi (78.73).

High temperature stress during PI to flowering resulted in least number of total grains per panicle (84.44) whereas the highest number of grains per panicle was produced under control (97.02).

For all the varieties, total grains per panicle were higher under ambient condition compared to high temperature stress. The highest number of total grains per panicle was observed for Aiswarya under ambient condition was superior to all other treatments. Lesser number of grains per panicle was registered for variety Jyothi and Kanchana under high temperature stress.

e. Thousand grain weight

Significant difference was observed in 1000 grain weight among different varieties (Table 50). Kanchana registered test weight of 26.98 g which was comparable with Aiswarya (26.85 g) and Jyothi (25.65 g) whereas Uma recorded lowest 1000 grain weight of 24.68 g.

Similar trend of filled grains per panicle as mentioned earlier was observed in the case of thousand grain weight. The highest thousand grain weight was recorded under control (26.89 g) and plants exposed to high temperature stress from flowering to maturity showed the lower thousand grain weight (24.88 g).

The highest thousand grain weight (27.80) was recorded for Kanchana under control whereas lowest thousand grain weight was observed for Uma when high temperature stress exposed from flowering to maturity (23.85 g).

f. Panicle length

Varieties differed significantly from each other (Table 51). Aiswarya produced longest panicle which was statistically superior to all other varieties whereas shortest panicle was observed in Kanchana.

No significant difference was observed with high temperature stress at different stages and ambient condition.

Interaction effect of variety and high temperature stress on panicle length was also not significant.

Table 49. Effect of high temperature stress on total number of grains per panicle of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	83.93	76.87	73.80	76.67	**77.82**
Jyothi	81.13	78.47	76.53	78.80	**78.73**
Uma	104.00	102.87	90.80	100.47	**99.53**
Aiswarya	119.00	103.67	96.63	83.93	**105.28**
Mean	**97.02**	**90.47**	**84.44**	**89.44**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			4.86	4.86	9.71

Table 50. Effect of high temperature stress on thousand grain weight (g) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	27.80	27.45	27.14	25.54	**26.98**
Jyothi	26.35	26.05	25.96	24.23	**25.65**
Uma	25.89	24.54	24.42	23.85	**24.68**
Aiswarya	27.51	27.16	26.82	25.91	**26.85**
Mean	**26.89**	**26.30**	**26.09**	**24.88**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			1.37	1.37	2.74

Table 51. Effect of high temperature stress on panicle length (cm) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	18.20	18.03	17.96	18.22	**18.10**
Jyothi	18.57	18.15	18.26	18.45	**18.36**
Uma	19.46	19.38	18.96	19.14	**19.24**
Aiswarya	20.95	20.64	20.12	20.45	**20.54**
Mean	**19.30**	**19.05**	**18.83**	**19.06**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			1.00	NS	NS

g. Grain yield

Significant difference in grain yield was obtained among the varieties (Table 52). The highest grain yield of 14.22 g/hill was produced by Aiswarya which was significantly superior to Uma (12.91 g/hill) which was on par with Kanchana (12.24 g/hill). The lowest grain yield was recorded for variety Jyothi (11.62 g/hill).

High temperature stress imposed from flowering to maturity recorded lowest grain yield (12.04 g/hill) which was comparable with stress from PI to flowering (12.49 g/hill). Plants grown under control produced highest grain yield (13.52 g/hill) which was on par with stress imposed from tillering to PI stage.

The variety Aiswarya produced higher grain yield under control and also high temperature stress at all growth stages compared to other varieties. The lowest grain yield was recorded for Jyothi when high temperature stress imposed from flowering to maturity.

h. Straw yield

The data on straw yield shows significant difference among varieties (Table 53). Aiswarya (20.25 g) produced highest straw yield which was on par with Uma. Kanchana and Jyothi produced lower straw yield.

High temperature stress at vegetative phase favourably influenced straw yield and plants exposed to high temperature stress from tillering to PI stage produced higher straw yield (20.12 g/hill) which was comparable with stress at other stages whereas lower straw yield was recorded under control.

The varieties Aiswarya, Uma and Kanchana exposed to high temperature stress during vegetative phase recorded higher straw yield.

i. Harvest Index

Among varieties there was no significant difference in relation to harvest index and the highest harvest index value was recorded for Aiswarya compared to others (Table 54).

Table 52. Effect of high temperature stress on grain yield (g/hill) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	13.05	12.42	11.88	11.62	**12.24**
Jyothi	12.10	11.87	11.62	10.87	**11.62**
Uma	13.72	13.04	12.56	12.3	**12.91**
Aiswarya	15.22	14.44	13.88	13.35	**14.22**
Mean	**13.52**	**12.94**	**12.49**	**12.04**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.67	0.67	1.34

Table 53. Effect of high temperature stress on straw yield (g/hill) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	18.23	20.18	19.35	18.42	**19.04**
Jyothi	17.49	18.79	18.52	18.34	**18.28**
Uma	19.02	20.82	20.28	19.52	**19.91**
Aiswarya	19.57	20.71	20.5	20.23	**20.25**
Mean	**18.58**	**20.12**	**19.66**	**19.13**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			1.01	1.01	2.01

Table 54. Effect of high temperature stress on harvest index of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	0.42	0.38	0.38	0.39	0.39
Jyothi	0.41	0.39	0.38	0.37	0.39
Uma	0.42	0.39	0.38	0.39	0.39
Aiswarya	0.44	0.41	0.40	0.40	0.41
Mean	0.42	0.39	0.39	0.39	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			NS	0.02	0.04

Harvest index of plants under ambient condition was significantly higher than high temperature stress at different stages.

The highest harvest index was observed in Aiswarya under control (0.44) and high temperature stress at all stages which was comparable with Kanchana under control. The variety Jyothi exposed to high temperature stress from flowering to maturity recorded lowest harvest index value of 0.37.

4.2.3 Biochemical Parameters

a. Relative water content (RWC)

Significance difference between varieties were observed in RWC during PI and flowering stage (Table 55). The variety Jyothi and Kanchana recorded comparable RWC values which was superior to Uma and Aishawarya during flowering stage. There was no significance difference among varieties in RWC at maturity stage (Table 69).

Rice plants exposed to high temperature stress registered lower RWC compared to plants grown under ambient condition compared at all stages.

Interaction between varieties and stress was significant with respect to RWC. Kanchana and Jyothi under control registered higher RWC at all the stages whereas Uma exposed to high temperature stress at all stages recorded lower RWC.

b. Stomatal conductance

Temperature stress significantly reduced the stomatal conductance of rice at all growth stages compared to control and values ranged from 0.211 to 0.107 m mol $H_2O/m^2/s$ (Table 56).

Significant difference between varieties were observed in stomatal conductance (Table 56). At PI stage higher stomatal conductance was observed for Jyothi (0.201 m mol $H_2O/m^2/s$) which was superior to all varieties. Kanchana recorded higher stomatal conductance (0.188 m mol $H_2O/m^2/s$) which was on par with Jyothi. At maturity, Kanchana showed higher stomatal conductance (0.174 m mol $H_2O/m^2/s$) and lower value was registered for Jyothi.

Table 55. Effect of high temperature stress on relative water content (%) of wetland rice varieties

Relative water content (%)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	93.66	82.28	**87.97**
Jyothi	90.27	85.87	**88.07**
Uma	80.73	72.96	**76.85**
Aiswarya	79.85	73.38	**76.62**
Mean	**86.13**	**78.62**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	6.59	4.66	9.32
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	90.65	83.31	**86.98**
Jyothi	84.13	78.06	**81.10**
Uma	79.56	68.56	**74.06**
Aiswarya	76.85	70.23	**73.54**
Mean	**82.80**	**75.04**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	6.68	4.72	9.45
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	77.54	71.23	**74.39**
Jyothi	78.00	66.54	**72.27**
Uma	78.09	67.06	**72.58**
Aiswarya	75.56	71.41	**73.49**
Mean	**77.30**	**69.06**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	6.19	4.38	8.76

Table 56. Effect of high temperature stress on stomatal conductance (m mol H_2O /m^2/s) of wetland rice varieties

Stomatal conductance (m mol H_2O /m^2/s)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	0.224	0.125	**0.174**
Jyothi	0.245	0.156	**0.201**
Uma	0.189	0.141	**0.165**
Aiswarya	0.186	0.135	**0.161**
Mean	**0.211**	**0.139**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.015	0.011	0.022
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	0.205	0.170	**0.188**
Jyothi	0.185	0.163	**0.174**
Uma	0.169	0.138	**0.154**
Aiswarya	0.176	0.149	**0.163**
Mean	**0.184**	**0.155**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.015	0.010	0.021
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	0.211	0.136	**0.174**
Jyothi	0.127	0.076	**0.102**
Uma	0.136	0.102	**0.119**
Aiswarya	0.180	0.112	**0.146**
Mean	**0.164**	**0.107**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.012	0.008	0.017

The variety Jyothi exposed to high temperature stress from tillering to PI stage registered higher stomatal conductance and at flowering stage Jyohti and Kanchana showed higher stomatal conductance. At maturity stage, the highest stomatal conductance was observed for Kanchana, however lower values were observed for Uma exposed to high temperature stress.

c. Photosynthetic rate

The variety Kanchana showed higher photosynthetic rate at flowering, whereas Jyothi had lower values. During maturity, the highest and lowest photosynthetic rates were observed in varieties Kanchana and Aiswarya respectively (Table 57).

Photosynthetic rate in rice showed an increasing trend towards flowering stage after which a decline was observed.

Interaction effect of variety and high temperature stress was significant. The varieties Uma, Kanchana and Aiswarya under control recorded higher photosynthetic rate which were comparable with each other during PI stage, whereas lower value was noticed for Jyothi exposed to high temperature stress. During maturity, Kanchana under control registered highest photosynthetic rate, however Jyothi and Uma exposed to high temperature showed lowest value.

d. Transpiration rate

Significant difference between varieties were observed in transpiration rate (Table 58). The highest transpiration rate was observed for Aiswarya under ambient condition at all stages of growth which was superior to all varieties during PI stage but comparable to that of Kanchana at both flowering and maturity stages. Lower values were observed for Jyothi at all stages of observation.

Temperature stress significantly reduced the transpiration rate of rice at all growth stages compared to control and values ranged from 1.11 to 2.44 m mol $H_2O/m^2/s$ (Table 58).

The variety Aiswarya (2.02 m mol $H_2O/m^2/s$) and Kanchana (1.74 m mol $H_2O/m^2/s$) registered higher transpiration rate when plants exposed to high temperature stress from tillering to PI stage compared to their control. During

Table 57. Effect of high temperature stress on photosynthetic rate (μ mol/m^2/s) of wetland rice varieties

Photosynthetic rate (μ mol/m^2/s)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	1.19	1.11	**1.15**
Jyothi	1.07	0.56	**0.82**
Uma	1.12	0.76	**0.94**
Aiswarya	1.19	0.75	**0.97**
Mean	**1.15**	**0.79**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.08	0.06	0.12
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	1.54	1.11	**1.33**
Jyothi	1.00	0.86	**0.93**
Uma	1.24	0.78	**1.01**
Aiswarya	1.21	0.99	**1.10**
Mean	**1.25**	**0.93**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.09	0.07	0.13
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	1.25	0.95	**1.25**
Jyothi	1.10	0.82	**0.95**
Uma	0.96	0.72	**1.10**
Aiswarya	1.05	0.94	**0.82**
Mean	**1.09**	**0.86**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.08	0.06	0.12

Table 58. Effect of high temperature on transpiration rate (m mol H_2O /m^2/s) of wetland rice varieties

Transpiration rate (m mol H_2O /m^2/s)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	1.97	1.74	**1.86**
Jyothi	2.04	1.17	**1.61**
Uma	1.90	1.40	**1.65**
Aiswarya	2.57	2.02	**2.29**
Mean	**2.12**	**1.58**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.16	0.11	0.23
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	2.56	2.01	**2.29**
Jyothi	2.34	1.75	**2.05**
Uma	2.49	1.84	**2.16**
Aiswarya	2.38	1.92	**2.15**
Mean	**2.44**	**1.88**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.18	0.13	0.26
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	1.25	1.18	**1.22**
Jyothi	1.05	1.02	**1.04**
Uma	1.11	1.07	**1.09**
Aiswarya	1.21	1.15	**1.18**
Mean	**1.16**	**1.11**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.09	0.07	0.13

flowering and maturity stage, the highest transpiration rate was observed for Kanchana. However lower values were observed for Jyothi exposed to high temperature stress at all stages of observation compared to their control.

e. Total chlorophyll content

The data on total chlorophyll content showed significant difference among varieties (Table 59). The variety Aiswarya registered higher chlorophyll content which was comparable with Kanchana whereas lower chlorophyll content was observed for Jyothi during all growth stages.

Plants exposed to high temperature stress showed significantly reduced chlorophyll content than plants under ambient condition during all growth stages.

Interaction effect of variety and high temperature stress on chlorophyll content also significant. Aiswarya and Kanchana under control (2.70 and 2.66 mg/g) recorded highest chlorophyll content whereas Jyothi exposed to high temperature stress showed lowest chlorophyll content (1.95 mg/g) during PI stage. Same trend was followed during remaining growth stages.

f. Soluble protein content

The data on soluble protein content showed significant difference among varieties at all stages (Table 60). Kanchana produced higher soluble protein in all stages whereas lower values was registered for Uma from PI and maturity stages.

Plants exposed to high temperature stress recorded lower soluble protein content compared to plants under control at all stages and the values ranged from 18.47 to 8.06 mg/g (Table 60).

All varieties when exposed to high temperature stress showed reduction in soluble protein content. Kanchana and Uma under ambient condition registered higher values at all stages. The variety Uma exposed to high temperature stress recorded lower soluble protein content at both PI and maturity stages (12.15 and 6.50 mg/g).

Table 59. Effect of high temperature stress on total chlorophyll content (mg/g) of wetland rice varieties

Total chlorophyll content (mg/g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	2.66	2.38	**2.52**
Jyothi	2.36	1.95	**2.16**
Uma	2.54	2.13	**2.34**
Aiswarya	2.70	2.44	**2.57**
Mean	**2.57**	**2.23**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.21	0.15	0.29
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	2.45	2.06	**2.26**
Jyothi	2.15	1.86	**2.01**
Uma	2.30	1.90	**2.10**
Aiswarya	2.52	2.23	**2.38**
Mean	**2.36**	**2.01**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.19	0.13	0.26
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	2.36	2.13	**2.25**
Jyothi	1.95	1.68	**1.82**
Uma	2.13	1.76	**1.95**
Aiswarya	2.46	2.10	**2.28**
Mean	**2.23**	**1.92**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.18	0.13	0.25

Table 60. Effect of high temperature stress on soluble protein content (mg/g) of wetland rice varieties

Soluble protein content (mg/g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	20.50	18.55	**19.53**
Jyothi	20.51	17.40	**18.96**
Uma	16.79	12.15	**14.47**
Aiswarya	16.09	15.30	**15.69**
Mean	**18.47**	**15.85**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	1.47	1.04	2.08
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	15.84	14.37	**15.10**
Jyothi	13.54	12.89	**13.22**
Uma	16.79	11.56	**14.18**
Aiswarya	10.36	8.74	**9.55**
Mean	**14.13**	**11.89**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	1.12	0.79	1.58
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	12.74	9.08	**10.91**
Jyothi	10.77	7.99	**9.38**
Uma	10.62	6.50	**8.56**
Aiswarya	10.15	8.65	**9.40**
Mean	**11.07**	**8.06**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.80	0.57	1.13

g. Nitrate reductase activity

The data on nitrate reductase activity showed significant difference among varieties at all stages (Table 61). The variety Jyothi recorded higher nitrate reductase activity at PI and maturity stages whereas lower activity observed in Uma at all stages.

Temperature stress significantly reduced nitrate reductase activity in all growth stages compared to control and values ranged from 171.92 to 45.93 mg/g (Table 61).

Interaction effect of variety and high temperature stress was significant. The variety Jyothi and Kanchana under control recorded higher values of nitrate reductase at all stages. The lowest nitrate reductase activity was recorded for Uma exposed to high temperature stress at all stages.

h. Membrane stability index

The data on MSI showed significant difference among varieties at all stages (Table 62). Aiswarya recorded highest MSI value during PI and flowering stages whereas Jyothi showed higher MSI values at maturity.

Plants exposed to high temperature stress registered lower MSI value compared to plants grown under ambient condition at all stages, ranging from 41.65 to 28.81 per cent (Table 62).

Aiswarya under control recorded highest value during tillering to flowering and Jyothi under control showed higher value during flowering to maturity. The lowest MSI value was observed for variety Uma at PI stage, Jyothi at flowering and Aiswarya at maturity stage under high temperature stress.

i. Malondialdehyde

Among varieties, Uma produced higher MDA content which was superior to all varieties during flowering and maturity stage and comparable with Aiswarya during PI stage. The lowest MDA content was observed for Aiswarya during flowering and maturity stages (Table 63).

Rice plants exposed to high temperature stress registered higher MDA content compared to control and values ranged from 9.21 to 14.21 n mol/g.

Table 61. Effect of high temperature stress on nitrate reductase activity (µ mol/g) of wetland rice varieties

Nitrate reductase activity (µ mol/g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	175.30	146.76	**161.03**
Jyothi	149.48	100.85	**125.17**
Uma	155.64	115.46	**135.55**
Aiswarya	122.52	96.62	**109.57**
Mean	**150.74**	**114.92**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	11.29	7.99	15.97
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	90.21	75.50	**82.86**
Jyothi	72.89	59.69	**66.29**
Uma	56.69	38.40	**47.55**
Aiswarya	84.90	58.85	**71.88**
Mean	**76.17**	**58.11**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	5.82	4.11	8.22
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	68.58	45.25	**56.91**
Jyothi	66.62	50.35	**58.49**
Uma	43.10	37.22	**40.16**
Aiswarya	60.74	50.90	**55.82**
Mean	**59.76**	**45.93**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	4.61	3.26	6.52

Table 62. Effect of high temperature stress on membrane stability index (%) of wetland rice varieties

Membrane stability index (%)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	40.06	33.63	**36.84**
Jyothi	38.76	31.58	**35.17**
Uma	36.28	26.62	**31.45**
Aiswarya	43.49	37.23	**40.36**
Mean	**39.65**	**32.26**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	6.85	4.84	9.69
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	32.55	19.43	**25.99**
Jyothi	22.19	18.21	**20.20**
Uma	39.58	28.72	**34.15**
Aiswarya	56.35	48.87	**52.61**
Mean	**37.67**	**28.81**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	3.97	2.81	5.62
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	40.56	32.29	**36.43**
Jyothi	56.25	44.83	**50.54**
Uma	41.23	30.78	**36.01**
Aiswarya	28.56	23.04	**25.80**
Mean	**41.65**	**32.74**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	3.34	2.36	4.73

Table 63. Effect of high temperature stress on malondialdehyde (n mol /g) of wetland rice varieties

Malondialdehyde content (n mol /g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	10.19	11.76	**10.98**
Jyothi	8.52	13.03	**10.77**
Uma	12.04	13.00	**12.52**
Aiswarya	11.40	13.85	**12.63**
Mean	**10.54**	**12.91**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.99	0.70	1.41
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	3.65	8.93	**6.29**
Jyothi	6.54	9.87	**8.21**
Uma	9.23	12.32	**10.78**
Aiswarya	4.30	5.70	**5.00**
Mean	**5.93**	**9.21**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.66	0.47	0.93
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	10.02	13.61	**11.82**
Jyothi	9.32	16.45	**12.89**
Uma	11.52	16.84	**14.18**
Aiswarya	8.32	9.94	**9.13**
Mean	**9.80**	**14.21**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	1.02	0.72	1.44

The variety Uma exposed to high temperature stress produced higher MDA content at all stages. The lower MDA was recorded for Jyothi under control during PI stage, Kanchana and Aiswarya under control during flowering and Aiswarya under control during maturity stage.

j. Proline content

The variety Kanchana and Jyothi produced highest proline content whereas lower values was registered for variety Uma during PI and flowering stages. At maturity, the highest proline content was observed for Jyothi (37.29 μ mol/g) and was comparable with Uma and Aiswarya whereas superior to Kanchana (Table 64).

Plants exposed to high temperature stress from tillering to flowering stage registered increased proline content compared to control, whereas stress during flowering to maturity decreased proline content.

The varieties Kanchana and Jyothi exposed to high temperature stress showed higher proline content, however Uma and Aiswarya showed lower values during PI and flowering stages. The highest proline content was observed for Jyothi under control (39.56 μ mol/g) and lowest proline content of 28.13 μ mol/g was noticed in Kanchana exposed to high temperature stress from flowering to maturity.

k. Superoxide dismutase

Among varieties, Aiswarya recorded higher SOD activity from PI and maturity stages whereas Kanchana showed higher activity which was comparable with Jyothi during flowering stage. Uma produced lower SOD activity in all growth stages (Table 65).

Plants exposed to high temperature stress registered higher SOD activity at all growth stages compared to control and values ranged from 0.126 to 0.321 g/min.

The SOD activity increased in all varieties when high temperature stress was imposed from tillering to flowering stage compared to control. Aiswarya registered higher SOD value when high temperature stress was imposed from tillering to PI and flowering to maturity, while during flowering the higher values were observed in Kanchana and Jyothi. The lowest SOD activity was observed for Uma under control

Table 64. Effect of high temperature stress on proline content (µ mol/g) of wetland rice varieties

Proline content (µ mol/g)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	95.10	148.48	**121.79**
Jyothi	74.25	104.20	**89.22**
Uma	70.06	87.71	**78.88**
Aiswarya	63.44	116.397	**89.92**
Mean	**75.71**	**114.20**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	7.56	5.35	10.70
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	44.88	56.26	**50.57**
Jyothi	42.26	62.40	**52.33**
Uma	32.52	40.23	**36.38**
Aiswarya	35.60	43.21	**39.41**
Mean	**38.82**	**50.53**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	3.83	2.71	5.41
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	33.54	28.13	**30.84**
Jyothi	39.56	35.02	**37.29**
Uma	38.56	33.26	**35.91**
Aiswarya	32.56	36.54	**34.55**
Mean	**36.06**	**33.24**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	2.98	2.10	4.21

Table 65. Effect of high temperature stress on superoxide dismutase (g/min) of wetland rice varieties

Superoxide dismutase (g/min)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	0.108	0.158	**0.133**
Jyothi	0.085	0.120	**0.102**
Uma	0.065	0.098	**0.082**
Aiswarya	0.098	0.175	**0.137**
Mean	**0.089**	**0.138**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.010	0.007	0.014
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	0.398	0.412	**0.405**
Jyothi	0.368	0.389	**0.379**
Uma	0.098	0.125	**0.112**
Aiswarya	0.264	0.358	**0.311**
Mean	**0.282**	**0.321**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.027	0.019	0.038
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	0.102	0.089	**0.095**
Jyothi	0.116	0.142	**0.129**
Uma	0.104	0.085	**0.095**
Aiswarya	0.125	0.189	**0.157**
Mean	**0.112**	**0.126**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.010	0.010	0.015

during flowering, and from flowering to maturity it was noticed in Kanchana exposed to high temperature.

l. Canopy air temperature difference (CATD)

The variety Aiswarya registered highest CATD value (1.55 and 1.30°C) which was comparable with Uma during PI and flowering stages (1.48 and 1.28°C) and Kanchana recorded highest value during maturity. The lowest CATD value was registered for Jyothi during all the growth stages (Table 66).

Rice plants exposed to high temperature stress showed lesser CATD value compared to plants under control during all growth stages.

Interaction effect of variety and high temperature stress was significant (Table 66). The variety Aiswarya during PI and flowering stages registered higher CATD value, whereas during maturity stage the higher values were observed in Kanchana (1.52°C) under high temperature stress. The lowest CATD value was recorded in variety Jyothi exposed to high temperature stress at all stages.

4.2.4 Chemical properties

a. Uptake of Nitrogen

The data shows significant difference in grain, straw and total nitrogen uptake among varieties (Table 67). The variety Aiswarya registered higher total N uptake (0.163 g/hill) which was superior to all varieties, whereas lowest value was seen for Jyothi (0.122 g/hill) and Uma (0.128 g/hill).

Plants grown under control registered highest total N uptake (0.150 g/hill) which was on par with when plants were exposed to high temperature from tillering to PI stage. Temperature stress induced from flowering to maturity recorded lowest total N uptake (0.129 g/hill).

Aiswarya under control and exposed to high temperature from tillering to PI stage recorded highest total N uptake (0.177 and 0.174 g/hill) whereas, variety Jyothi exposed to high temperature from flowering to maturity observed lower values of 0.114 g/hill.

Table 66. Effect of high temperature stress on canopy air temperature difference (°C) of wetland rice varieties

Canopy air temperature difference (°C)			
Panicle initiation stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	1.46	1.35	**1.41**
Jyothi	1.33	1.07	**1.20**
Uma	1.50	1.45	**1.48**
Aiswarya	1.63	1.47	**1.55**
Mean	**1.48**	**1.34**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.12	0.09	0.17
Flowering stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	1.25	1.13	**1.19**
Jyothi	1.02	0.95	**0.99**
Uma	1.30	1.25	**1.28**
Aiswarya	1.36	1.24	**1.30**
Mean	**1.23**	**1.14**	
CD (0.05)	**Varieties**	**Stress**	**V x S**
	0.10	0.07	0.14
Maturity stage			
Treatment	**Control**	**Stressed**	**Mean**
Kanchana	1.52	1.46	**1.49**
Jyothi	1.10	0.97	**1.04**
Uma	1.39	1.32	**1.36**
Aiswarya	1.39	1.30	**1.35**
Mean	**1.35**	**1.26**	
CD (0.05)	**Variety**	**Stress**	**V x S**
	0.11	0.08	0.15

Table 67. Effect of high temperature stress on N uptake (g/hill) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	0.155	0.161	0.128	0.138	**0.145**
Jyothi	0.129	0.121	0.125	0.114	**0.122**
Uma	0.138	0.129	0.124	0.122	**0.128**
Aiswarya	0.177	0.174	0.158	0.142	**0.163**
Mean	**0.150**	**0.147**	**0.134**	**0.129**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.009	0.009	0.018

Table 68. Effect of high temperature stress on P uptake (g/hill) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	0.060	0.057	0.108	0.064	**0.072**
Jyothi	0.064	0.061	0.062	0.058	**0.061**
Uma	0.065	0.060	0.052	0.054	**0.058**
Aiswarya	0.093	0.071	0.070	0.076	**0.078**
Mean	**0.070**	**0.062**	**0.073**	**0.063**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.005	0.005	0.011

Table 69. Effect of high temperature stress on K uptake (g/hill) of aerobic rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	0.370	0.308	0.335	0.363	**0.344**
Jyothi	0.381	0.313	0.314	0.310	**0.330**
Uma	0.370	0.345	0.332	0.387	**0.359**
Aiswarya	0.337	0.329	0.383	0.389	**0.359**
Mean	**0.365**	**0.324**	**0.341**	**0.362**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.028	0.028	0.057

b. Uptake of Phosphorus

Among varieties, Aiswarya showed highest total P uptake (0.078 g/hill) whereas, the lowest total uptake was observed in variety Uma (0.058 g/hill) (Table 68).

Rice plants exposed to high temperature from PI to flowering recorded highest total P uptake (0.073 g/hill) whereas lower values was obtained when plants exposed to high temperature from tillering to PI (0.062 g/hill) and flowering to maturity (0.063 g/hill).

The higher values of total P uptake of 0.108 g/hill was observed in Kanchana exposed to high temperature stress from PI to flowering and the lowest total P uptake was recorded for Uma exposed to stress from PI to flowering (0.052 g/hill).

c. Uptake of Potassium

The data on total uptake of potassium for different varieties are shown in Table 69. Aiswarya and Uma registered higher total K uptake (0.359 g/hill) whereas lower uptake was seen for Jyothi (0.330 g/hill).

High temperature induced from tillering to PI stage showed lowest total K uptake of 0.324 g/hill which was significantly inferior to stress at remaining stages and control.

Interaction effect was also significant with respect to total potassium uptake (Table 69). High temperature stress imposed from flowering to maturity for variety Aiswarya and Uma resulted in higher total K uptake (0.389 and 0.387 g/hill) however lower uptake was registered for Kanchana exposed to stress from tillering to PI stage (0.308 g/hill).

d. Grain protein content

The data on grain protein content are presented in Table 70. Kanchana recorded highest protein content in grain (4.88 %) which was comparable with Aiswarya whereas lower values observed for Jyothi and Uma.

Table 70. Effect of high temperature stress on grain protein content (%) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	4.97	5.35	4.44	4.76	**4.88**
Jyothi	4.07	3.94	3.87	4.01	**3.97**
Uma	4.38	4.11	4.04	4.32	**4.21**
Aiswarya	5.12	5.39	4.56	4.22	**4.82**
Mean	**4.64**	**4.70**	**4.23**	**4.33**	
		CD (0.05)	**Varieties**	**Stress**	**V x S**
			0.24	0.24	0.47

Table 71. Requirement of growing degree days in rice as influenced by high temperature stress of wetland rice varieties (°C day)

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	1793	1807	1828	1843	**1818**
Jyothi	1814	1807	1828	1867	**1829**
Uma	1934	1912	1934	1977	**1939**
Aiswarya	1954	1954	1992	1999	**1975**
Mean	**1874**	**1870**	**1896**	**1921**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			99	NS	198

Table 72. Effect of high temperature stress on HTU (°C day h) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	15266	15266	15266	15266	**15482**
Jyothi	15336	15336	15336	15336	**15585**
Uma	15566	15566	15566	15566	**16407**
Aiswarya	15763	15763	15763	15763	**16597**
Mean	**15810**	**15873**	**16141**	**16248**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			837	NS	1674

Plants exposed to high temperature stress from tillering to PI stage (4.70 %) and control (4.64 %) recorded higher grain protein content in rice, and were significantly superior to stress at remaining stages.

The varieties Aiswarya and Kanchana exposed to high temperature stress from tillering to PI stage (5.39 and 5.35 %) and their respective controls recorded highest grain protein contents. The lowest grain protein content of 4.01 per cent was noticed for Jyothi exposed to high temperature stress from tillering to maturity.

4.2.5 Heat Units

a. Growing degree days (GDD)

The data shows significant difference in GDD among the varieties (Table 71). Aiswarya registered higher GDD (1975 °C day) which was on par with Uma, and lowest GDD was observed for Kanchana (1818 °C day).

Significant difference could not be observed among high temperature stress during different stages with respect to GDD. The highest GDD was observed when plants were exposed to high temperature stress from flowering to maturity (1921 °C day).

The variety Aiswarya exposed to high temperature stress from flowering to maturity recorded higher GDD of 1999 °C day and lowest value was for Kanchana under control (1793 °C day).

b. Helio thermal units (HTU)

Significant difference in HTU was noticed among varieties (Table 72). The highest GDD was registered for Aiswarya (16597 °C day h) which was on par with Uma and variety Kanchana recorded lowest HTU (15482 °C day h) which was comparable with Jyothi.

Rice plants exposed to high temperature stress from flowering to maturity recorded highest HTU (16248 °C day h) which was on par with stress at other stages and control.

Interaction effect with respect to HTU was non-significant (Table 72). A trend similar to that of GDD was observed for HTU also.

c. Photo thermal units (PTU)

The highest PTU value was observed Aiswarya (23034 °C day h) which was on par with Uma. The variety Kanchana registered lowest PTU of 21151 °C day h (Table 73).

A trend similar to that of GDD was observed for PTU. The photo thermal units were higher for plants exposed to flowering to maturity (22401 °C day h) which was comparable with stress at remaining stages and control.

The interaction effect of varieties and temperature on PTU was non-significant (Table 73). The variety Aiswarya exposed to high temperature stress from flowering to maturity recorded highest PTU value (23336 °C day h) whereas lowest was recorded for variety Kanchana under ambient condition (20867 °C day h).

d. Heat use efficiency (HUE)

Among varieties, Aiswarya and Kanchana recorded higher HUE (0.35 g/m^2day °C) and they were on par with Uma whereas lower HUE was observed in Jyothi (0.33 g/m^2day °C) (Table 74).

The higher HUE was observed when high temperature stress was imposed from tillering to flowering and in control, however rice plants exposed to high temperature from flowering to maturity recorded lower HUE (0.32 g/m^2day °C) which was inferior to others.

The variety Aiswarya and Kanchana exposed to high temperature stress from tillering to PI stage recorded higher HUE (0.36 g/m^2day °C) which was comparable with all other treatments except variety Uma exposed to high temperature stress from flowering to maturity which showed lowest HUE.

Table 73. Effect of high temperature stress on PTU (°C day h) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	20867	21003	21275	21461	**21151**
Jyothi	21120	21003	21275	21744	**21285**
Uma	22558	22271	22540	23065	**22608**
Aiswarya	22799	22766	23235	23336	**23034**
Mean	**21836**	**21761**	**22081**	**22402**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			1151	NS	2301

Table 74. Effect of high temperature stress HUE (g/m^{2}day °C) of wetland rice varieties

Treatment	Control	Stress at tillering to PI	Stress at PI to flowering	Stress at flowering to maturity	Mean
Kanchana	0.35	0.36	0.34	0.33	**0.35**
Jyothi	0.33	0.34	0.33	0.31	**0.33**
Uma	0.34	0.35	0.34	0.32	**0.34**
Aiswarya	0.36	0.36	0.35	0.34	**0.35**
Mean	**0.34**	**0.35**	**0.34**	**0.32**	
		CD(0.05)	**Varieties**	**Stress**	**V x S**
			0.02	0.02	0.04

4.3 EXPERIMENT III: EFFECT OF NITROGEN AND POTASSIUM NUTRITION ON MITIGATION OF HIGH TEMPERATURE STRESS IN AEROBIC RICE

4.3.1 Growth parameters

a. Plant height

The variety Vaishakh was taller than Aiswarya at all stages of growth and the plant height at harvest was 113.41 cm for Vaishakh where as it was only 89.30 cm for Aiswarya at recommended dose of NPK for upland rice (Table 75). Though these two varieties differed significantly from each other at various growth stages, the effect of nutrient levels on a particular variety was not significant. At harvest, plant height of Vaishakh was comparable at all the three N and K levels. In variety Aiswarya, also the same trend was observed.

b. Number of tillers per hill

Significant difference in tiller number per hill was observed with different NK levels (Table 76).

At 30 DAS, the higher number of tillers per hill was produced by Vaishakh as well as Aiswarya applied with 120 kg N and 60 kg K_2O which were on par. Lowest tiller number were observed with application of 60 kg N and 30 kg K_2O both in Vaishakh (9.00) and Aiswarya (9.23).

At later stages (60 DAS and at harvest), higher and comparable tiller number per hill were registered by application of 120 kg N and 60 kg K_2O and 90 kg N and 45 kg K_2O. A reduction in tiller number was observed in both varieties by harvest stage at all nutrient levels. Tiller number in all treatments except Aiswarya applied with 120: 60 N: K_2O kg/ha were statically comparable.

c. Leaf Area Index (LAI)

Significant difference in leaf area index was observed (Table 75). Application of 120 kg N and 60 kg K_2O in Vaishakh resulted in highest LAI value of 5.68 which was comparable with Aiswarya same NK dose (5.44) and Vaishakh applied with 90 kg N and 45 kg K_2O (5.13) and they were superior to other treatments. The lowest

Table 75. Effect of N and K nutrition on plant height (cm) and LAI under high temperature stress

Treatments		Plant height			LAI at 60 DAS
Varieties	Fertilizer levels (kg/ha)	30 DAS	60 DAS	At harvest	
Vaishakh	60: 30 N:K_2O	26.92	82.98	113.41	4.56
	90: 45 N:K_2O	27.05	82.88	117.30	5.13
	120: 60 N:K_2O	28.96	85.71	122.20	5.68
Aiswarya	60: 30 N:K_2O	23.76	62.43	89.30	4.34
	90: 45 N:K_2O	24.77	66.78	97.70	4.96
	120: 60 N:K_2O	25.15	68.00	105.57	5.44
CD (0.05)		3.21	9.13	13.12	0.62

Table 76. Effect of N and K nutrition on number of tillers per hill and DMP (g/hill) under high temperature stress

Treatments		Tiller numbers per hill at harvest			DMP (g/hill)
Varieties	Fertilizer levels (kg/ha)	30 DAS	60 DAS	At harvest	
Vaishakh	60: 30 N:K_2O	9.00	11.56	11.05	32.60
	90: 45 N:K_2O	10.30	12.64	11.52	35.21
	120: 60 N:K_2O	12.64	13.02	11.88	42.95
Aiswarya	60: 30 N:K_2O	9.23	13.12	11.54	31.07
	90: 45 N:K_2O	10.60	14.68	12.40	33.61
	120: 60 N:K_2O	11.56	15.13	13.50	38.81
CD (0.05)		1.32	1.66	1.48	4.42

value was observed for Aiswarya and Vaishaskh applied with 60 kg N and 30 kg K_2O (4.34 and 4.56).

d. Dry matter production

The higher and comparable DMP was produced by application of 120 kg N and 60 kg K_2O in Vaishakh (42.95 g/hill) and Aiswarya (38.81 g/hill). The lowest DMP was observed in Aiswarya and Vaishakh applied with 60 kg N and 30 kg K_2O and 90 kg N and 45 kg K_2O (Table 76).

4.3.2 Biochemical parameters

a. Photosynthetic rate

The data on photosynthetic rate showed significant difference among treatments (Table 77). The highest photosynthetic rate was observed for Aiswarya applied with 120 kg N and 60 kg K_2O (1.414 µmol/m^2/s) which was superior to all treatments. Aiswarya applied with 60 kg N and 30 kg K_2O registered lowest photosynthetic rate value (0.568 µmol/m^2/s).

b. Stomatal conductance

Significant difference between treatments were observed in stomatal conductance (Table 77). The highest stomatal conductance was registered by Vaishakh and Aiswarya applied with 120 kg N and 60 kg K_2O (0.695 and 0.522 mol H_2O/m^2/s) which was superior to all treatments. The variety Vaishakh applied with 60 kg N and 30 kg K_2O recorded low stomatal conductance (0.146 mol H_2O/m^2/s).

c. Canopy air temperature difference (CATD)

The data on CATD showed significant difference, due to varying NK levels under high temperature stress (Table 77). Application of 120 kg N and 60 kg K_2O in Vaishakh registered highest CATD value (0.74°C) which was comparable with Aiswarya with same N and K level (0.70°C). The lowest CATD value was recorded for Aiswarya applied with lower N and K levels (0.45°C).

Table 77. Effect of N and K nutrition on photosynthetic rate, stomatal conductance and CATD under high temperature stress

Treatments		Photosynthetic rate ($\mu mol/m^2/s$)	Stomatal conductance (mol $H_2O/m^2/s$)	CATD (°C)
Varieties	Fertilizer levels			
Vaishakh	60: 30 N:K_2O kg/ha	1.076	0.146	0.56
	90: 45 N:K_2O kg/ha	0.711	0.471	0.65
	120: 60 N:K_2O kg/ha	1.122	0.695	0.74
Aiswarya	60: 30 N:K_2O kg/ha	0.568	0.207	0.45
	90: 45 N:K_2O kg/ha	0.875	0.211	0.59
	120: 60 N:K_2O kg/ha	1.414	0.522	0.70
CD (0.05)		0.120	0.052	0.08

Table 78. Effect of N and K nutrition on RWC, total chlorophyll content and MSI under high temperature stress

Treatments		RWC (%)	Total chlorophyll content (mg/g)	MSI (%)
Varieties	Fertilizer levels			
Vaishakh	60: 30 N:K_2O kg/ha	66.48	2.12	34.44
	90: 45 N:K_2O kg/ha	68.32	2.45	37.78
	120: 60 N:K_2O kg/ha	70.28	2.56	53.62
Aiswarya	60: 30 N:K_2O kg/ha	70.05	1.92	31.90
	90: 45 N:K_2O kg/ha	86.83	2.13	35.25
	120: 60 N:K_2O kg/ha	77.32	2.46	47.46
CD (0.05)		9.18	0.27	5.02

d. Relative leaf water content

No definite trend could be observed in RWC (Table 78). However, with increasing N and K levels the RWC showed an increasing trend. Application of 90 kg N and 45 kg K_2O to Aiswarya recorded highest RWC (86.83 %) which was significantly superior to all treatments. The lowest RWC was observed for Vaishakh (66.48 %) applied with 60 kg N and 30 kg K_2O. In variety Aiswarya both higher and lower levels of N and K resulted in comparable RWC.

e. Total chlorophyll content

Significant difference between treatments were observed in chlorophyll content (Table 78).The highest chlorophyll content was registered with application of 120 kg N and 60 kg K_2O in Vaishakh (2.56 mg/g) and Aiswarya (2.46 mg/g) which was superior to other treatments whereas lower value was observed for both varieties applied with 60 kg N and 30 kg K_2O.

f. Membrane stability index

The data on membrane stability index are presented in Table 78. The highest MSI of 53.62 per cent was observed for Vaishakh applied with 120 kg N and 60 kg K_2O which was significantly superior to all treatments. In both varieties, MSI increased with increasing NK levels.

4.3.3 Yield attributes and yield

a. Number of panicles per hill

The data on panicles per hill of rice varieties influenced by N and K levels under high temperature stress are presented in Table 79. Application of 120 kg N and 60 kg K_2O to Aiswarya produced highest panicles per hill (12.90) which was on par with its same variety applied with 90 kg N and 45 kg K_2O. The lower number of panicles were obtained in Vaishakh applied with 60 kg N and 30 kg K_2O and Aiswarya applied with 60 kg N and 30 kg K_2O comparable with remaining N K levels.

The data on number of panicles per hill was significant under ambient temperature (Table 80). A trend similar to that under high temperature stress was observed. Application of 120 kg N and 60 kg K_2O to Aiswarya produced highest panicles per hill (13.11) which was superior to all other treatments. The lower number of panicles were obtained in Vaishakh applied with 60 kg N and 30 kg K_2O and Aiswarya applied with 60 kg N and 30 kg K_2O which was comparable with Vaishakh applied with 90 kg N and 45 kg K_2O.

b. Number of filled grains per panicle

The data on number of filled grains per panicle was significant (Table 79). The highest filled grains per panicle were produced by application of 120 kg N and 60 kg K_2O to Vaishakh (94.90) and Aiswarya (94.00). They were comparable with Vaishakh applied with 90 kg N and 45 kg K_2O (89.80). The lowest filled grains per panicle was observed for Vaishakh and Aiswarya applied with 60 kg N and 30 kg K_2O which were comparable with Aiswarya applied with 90 kg N and 45 kg K_2O.

Number of filled grains per panicle was higher under ambient temperature (control) than plants grown under high temperature stress (Table 80). However, a trend similar to that under stress could be observed here also. Application of 120 kg N and 60 kg K_2O to Vaishakh (99.23) and Aiswarya (97.30) recorded higher filled grains per panicle which was comparable with Vaishakh applied with 90 kg N and 45 kg K_2O.

c. Chaff per cent

The chaff per cent was also significantly influenced by N and K levels under high temperature stress as well as under ambient conditions (Table 79). Application of 60 kg N and 30 kg K_2O in Aiswarya registered highest chaff per cent (17.53) which was on par with Aiswarya applied with 90 kg N and 45 kg K_2O (15.94). The lowest chaff per cent was observed for Vaishakh (8.23) applied with 120 kg N and 60 kg K_2O.

A trend similar to that under high temperature stress was observed under ambient condition also. The highest chaff per cent (15.34) was registered in Aiswarya applied with 60 kg N and 30 kg K_2O which differed significantly from all other treatments. The lowest and comparable chaff per cent was observed for Vaishak applied with 120:60 kg N: K_2O and 90:45 kg N: K_2O.

Table 79. Effect of N and K nutrition on yield attributes of rice under high temperature stress

Varieties	Fertilizer levels	Number of panicles /hill	Number of filled grains per panicle	Chaff per cent (%)	Total number of grains per panicle	1000 grain weight (g)	Panicle length (cm)
Vaishakh	60: 30 N:K_2O kg/ha	9.90	80.80	13.49	93.40	27.91	20.66
	90: 45 N:K_2O kg/ha	10.56	89.80	10.33	100.15	28.53	21.73
	120: 60 N:K_2O kg/ha	11.05	94.90	8.23	103.30	28.94	22.62
Aiswarya	60: 30 N:K_2O kg/ha	9.94	75.75	17.53	91.85	26.67	19.56
	90: 45 N:K_2O kg/ha	11.65	81.20	15.94	96.60	26.85	20.12
	120: 60 N:K_2O kg/ha	12.90	94.00	10.22	104.70	27.06	20.77
CD (0.05)		1.36	10.52	1.67	NS	NS	NS

Table 80. Effect of N and K nutrition on yield attributes of rice under control

Treatments		Number of panicles/hill	Number of filled grains per panicle	Chaff per cent (%)	Total number of grains per panicle	1000 grain weight
Varieties	Fertilizer levels (kg/ha)					
Vaishakh	60: 30 $N:K_2O$	10.02	85.60	10.51	94.60	28.62
	90: 45 $N:K_2O$	10.65	93.50	6.68	99.74	28.85
	120: 60 $N:K_2O$	11.00	99.23	5.68	104.87	29.10
Aiswarya	60: 30 $N:K_2O$	9.96	80.21	15.34	92.51	26.90
	90: 45 $N:K_2O$	11.55	85.65	13.49	97.20	27.20
	120: 60 $N:K_2O$	13.11	97.30	9.25	106.30	27.65
CD (0.05)		1.38	11.19	1.41	NS	NS

Table 81. Effect of N and K nutrition on grain and straw yields and HI of rice

Treatments		High temperature stress during flowering to maturity			Control		
Varieties	Fertilizer levels (kg/ha)	Grain yield (kg/ha)	Straw yield (kg/ha)	Harvest index	Grain yield (kg/ha)	Straw yield (kg/ha)	Harvest index
Vaishakh	60: 30 $N:K_2O$	2026	2822	0.42	2420	2993	0.45
	90: 45 $N:K_2O$	2275	2981	0.43	2780	3083	0.47
	120: 60 $N:K_2O$	2727	3426	0.44	3022	3456	0.47
Aiswarya	60: 30 $N:K_2O$	1894	2644	0.42	2130	2676	0.44
	90: 45 $N:K_2O$	2250	2845	0.44	2680	2883	0.48
	120: 60 $N:K_2O$	2569	3012	0.46	2853	3108	0.48
CD (0.05)		283	365	NS	325	373	NS

d. Number of total grains per panicle

No significant difference was observed on number of grains per panicle (Table 79). The highest total number of grains per panicle was recorded for Vaishakh and Aiswarya applied with 120:60 kg N:K_2O kg/ha (104.70 and 103.30). The lowest grains were observed in application of 60 kg N and 30 kg K_2O in Aiswarya (91.85) and Vaishakh (93.40).

A trend similar to that under high temperature stress was observed with respect to total number of grains in control. No significant difference was observed (Table 80).

e. Thousand grain weight

No significant difference was observed in 1000 grain weight (Table 79). Application of 120 kg N and 60 kg K_2O registered higher 1000 grain weight of 28.94 g in Vaishakh, whereas the lowest thousand grain weight (26.67 g) was observed in Aiswarya applied with 60 kg N and 30 kg K_2O.

Under control also no significant difference was observed in relation to 1000 grain weight (Table 80). The higher 1000 grain weight of 29.10 g was recorded for Vaishakh applied with 120 kg N and 60 kg K_2O and lower 1000 grain weight (26.90 g) was observed in Aiswarya applied with 60 kg N and 30 kg K_2O.

f. Panicle length

Panicle length was not influenced by different NK levels (Table 79). The longest panicle were produced by application of 120 kg N and 60 kg K_2O in Vaishakh (22.62 cm) whereas shortest panicle were registered by application of 60 kg N and 30 kg K_2O in Aiswarya (19.56 cm).

g. Grain yield

Significant increase in grain yield was obtained with different N and K levels under high temperature stress and a linear trend could be observed with increase in N and K levels (Table 81). The highest grain yield of 2727 kg/ha was obtained by application of 120 kg N and 60 kg K_2O to Vaishakh which was on par with variety Aiswarya at same NK level (2569 kg/ha) and were superior to all treatments. The next highest yield was registered by application of 90 kg N and 45 kg K_2O in Vaishakh

(2275 kg/ha) and Aiswarya (2250 kg/ha). The lowest grain yield was recorded with 60 kg N and 30 kg K_2O (1894 and 2026 kg/ha).

Under ambient temperature situation, higher grain yield was realized at all levels of N and K, irrespective of variety. As in the case of elevated temperature condition, an increasing trend in yield with progressive increase in N and K nutrition was observed. The highest grain yield of 3022 kg/ha was realized with the application of 120 kg N and 60 kg K_2O to Vaishakh which was on par with variety Aiswarya at same NK level (2853 kg/ha) and Vaishakh applied with 90 kg N and 45 kg K_2O (Table 81). Application of 60 kg N and 30 kg K_2O recorded lowest and comparable grain yield in both the varieties (2130 and 2420 kg/ha), which in turn was on par with grain yield of Aiswarya at 90 kg N and 45 kg K_2O.

h. Straw yield

Almost the same trend as that of grain yield was observed under high temperature (Table 81). The highest straw yield of 3426 kg/ha was registered for Vaishakh applied with 120 kg N and 60 kg K_2O which was superior to all treatments. The lowest straw yield was recorded for variety Aiswarya (2644 kg/ha) and Vaishakh (2822 kg/ha) applied with 60 kg N and 30 kg K_2O.

Under control, significantly higher straw yield of 3456 kg/ha was registered with 120 kg N and 60 kg K_2O in both varieties and Vaishakh applied with 90 kg N and 45 kg K_2O (3083 kg/ha). The lowest straw yield was recorded for variety Aiswarya (2676 kg/ha) applied with 60:30 kg N: K_2O and 90:45 kg N: K_2O and they were on par with Vaishakh applied with 60:30 kg N: K_2O.

i. Harvest index

Harvest index was not altered by N and K application under high temperature stress and at ambient temperature (Table 81). Values were statistically comparable and ranged from 0.46 to 0.42 under stress and 0.48 to 0.44 under ambient temperature. Under stress, higher harvest index was recorded for Aiswarya applied with 120 kg N and 60 kg K_2O (0.46), whereas application of 60 kg N and 30 kg K_2O in Vaishakh and Aiswarya registered lower harvest index (0.42).

4.3.4 Plant analysis

a. Uptake of Nitrogen, Phosphorus and Potassium

Significant difference among treatments were observed in nitrogen, phosphorus and potassium uptake by rice (Table 82). The highest N uptake was registered for Vaishakh and Aiswarya applied with 120 kg N and 60 kg K_2O (34.97 and 32.76 kg/ha) which was significantly higher than other treatments. Application of 60 kg N and 30 kg K_2O in Vaishakh recorded lowest N uptake (18.66 kg/ha) among treatments.

Application of 120 kg N and 60 kg K_2O to Aiswarya showed highest P uptake (8.76 kg/ha) which was significantly superior to all other treatments. The lower P uptake of 3.14 kg/ha was recorded for Vaishakh applied with 60 kg N and 30 kg K_2O which was on par with Aiswarya with lower dose.

The data on potassium uptake also shows significant difference among the treatment. The highest K uptake was observed in Vaishakh applied with 120 kg N and 60 kg K_2O (70.49 kg/ha) which was comparable with Aiwarya applied at 120: 60 and 90:45 K_2O. kg/ha . The lowest K uptake was registered for Aiswarya and Vaishakh applied with 60 kg N and 30 kg K_2O (45.58 and 48.82 kg/ha).

d. Grain protein content

Grain protein content did not exhibit significant difference with N and K levels (Table 83). Grain protein content of Aiswarya applied with 120 kg N and 60 kg K_2O (5.63) was comparable with all other treatments. Application of 60 kg N and 30 kg K_2O in Vaishakh registered lower protein content in grain (4.74 %), but statistically comparable to others.

4.3.5 Heat use efficiency

The data on heat use efficiency as influenced by N and K levels under high temperature stress are presented in Table 83. Higher dose of N and K (120:60 kg N: K_2O/ha) recorded higher HUE in both varieties. Application of 120 kg N and 60 kg K_2O to Vaishakh recorded the highest HUE of 0.26 g/m^2 °C day which was superior

Table 82. Effect of N and K nutrition on N, P and K uptake (kg/ha) at harvest under high temperature stress

Treatments		Uptake of N	Uptake of P	Uptake of K
Varieties	Fertilizer levels			
Vaishakh	60: 30 N:K_2O kg/ha	18.66	3.14	48.82
	90: 45 N:K_2O kg/ha	24.08	4.82	55.00
	120: 60 N:K_2O kg/ha	34.97	7.28	70.49
Aiswarya	60: 30 N:K_2O kg/ha	20.08	4.58	45.58
	90: 45 N:K_2O kg/ha	24.97	6.38	56.64
	120: 60 N:K_2O kg/ha	32.76	8.76	60.99
CD (0.05)		6.49	1.47	13.93

Table 83. Effect of N and K nutrition on grain protein content and heat use efficiency under high temperature stress

Treatments		Grain protein (%)	Heat use efficiency	
Varieties	Fertilizer levels			
Vaishakh	60: 30 N:K_2O kg/ha	4.74	0.20	
	90: 45 N:K_2O kg/ha	5.21	0.22	
	120: 60 N:K_2O kg/ha	5.51	0.26	
Aiswarya	60: 30 N:K_2O kg/ha	4.99	0.19	
	90: 45 N:K_2O kg/ha	5.25	0.21	
	120: 60 N:K_2O kg/ha	5.63	0.23	
CD (0.05)		NS	0.03	NS

to all other treatments. The lower HUE value was registered with application of lower dose of nitrogen and potassium applied.

4.3.6 Soil analysis

a. Available N

The data on available soil N influenced by N and K levels under high temperature stress are presented in Table 84. Application of 120 kg N and 60 kg K_2O to Vaishakh registered the highest available soil N of 268 kg/ha which was significantly superior to all other treatments. Application of 60 kg N and 30 kg K_2O showed lower and statistically comparable in both varieties applied with 90: 45 kg NK/ha (196 kg/ha).

b. Available P

Soil status of available phosphorus after the experiment also showed significant variations (Table 84). The highest soil available P of 49 kg/ha was observed in Aiswarya applied with 90 kg N and 45 kg K_2O which was comparable to Vaishakh at same NK dose. The lowest soil available P was recorded by application of 60 kg N and 30 kg K_2O to Aiswarya (27 kg/ha).

c. Available K

The data on available soil K showed significant difference due to treatments (Table 84). Application of 120 kg N and 60 kg K_2O resulted in higher and comparable soil available K in both Aiswarya (301 kg/ha) and Vaishakh (285 kg/ha). The lowest soil available K of 216 kg/ha was observed at lower level of N and K application (60 kg N and 30 kg K_2O) in both varieties.

4.3.7 Economics of cultivation

The data pertaining to the economics of cultivation under different N and K levels are presented in Table 85. The data indicated that net return and BC ratio were influenced by N and K levels.

Table 84. Effect of N and K nutrition on available N, P and K (kg/ha) status of soil after harvest of rice

Treatment		Available N	Available P	Available K
Varieties	**Fertilizer levels**			
Vaishakh	60: 30 N:K_2O kg/ha	198	40	216
	90: 45 N:K_2O kg/ha	240	44	227
	120: 60 N:K_2O kg/ha	268	39	301
Aiswarya	60: 30 N:K_2O kg/ha	173	27	219
	90: 45 N:K_2O kg/ha	196	49	231
	120: 60 N:K_2O kg/ha	227	43	285
CD (0.05)		27	5	31

Under high temperature stress, application of 120 kg N and 60 kg K_2O to Vaishakh recorded the highest net return (Rs. 40,724) followed by Aiswarya (Rs. 34,370) at same fertilizer level.

A trend similar to that of net return was observed for BC ratio. The highest BC ratio of 1.69 was realised with the application of 120 kg N and 60 kg K_2O to Vaishakh which was followed by Aiswarya (1.58). Lower BC ratio as well as net profit was recorded with application of 60 kg N and 30 kg K_2O in both varieties.

A trend similar to that under high temperature stress with respect to net returns and BC ratio was observed under control (Table 85). However, higher values were registered compared to temperature stressed situation. Application of 120 kg N and 60 kg K_2O to Vaishakh recorded the highest net return (Rs. 48,032) followed by Aiswarya (Rs. 40,496) at same fertilizer level. Whereas highest BC ratio (2.76) was for Aiswarya applied with 60 kg N and 30 kg K_2O.

Table 85. Effect of N and K nutrition on cost of cultivation

Treatments		Cost of cultivation (Rs./ha)	High temperature stress during flowering to maturity			Control		
Varieties	Fertilizer levels (kg/ha)		Gross return (Rs./ha)	Net return (Rs./ha)	B:C	Gross return (Rs./ha)	Net return (Rs./ha)	B:C
Vaishakh	60: 30 N:K_2O	57145	77012	19867	1.35	88010	30865	1.85
	90: 45 N:K_2O	58100	91450	33350	1.57	97550	39450	1.47
	120: 60 N:K_2O	59056	99780	40724	1.69	107088	48032	1.23
Aiswarya	60: 30 N:K_2O	57145	74056	18511	1.32	77880	20735	2.76
	90: 45 N:K_2O	58100	86074	27974	1.48	93150	35050	1.66
	120: 60 N:K_2O	59056	92626	34370	1.58	99552	40496	1.46

Discussion

5. DISCUSSION

Rice plants have three distinct growth phases – vegetative phase, reproductive phase and maturity phase. The vegetative phase determines the tiller number, which is closely related to potential number of panicles. The growth factors during reproductive phase determines number and size of spikelets and also the quality of grains. Among the various abiotic factors temperature is a crucial factor in deciding growth and yield of rice and effect of elevated temperature on different growth phases of rice is discussed below.

5.1 RESPONSE OF AEROBIC AND WETLAND VARIETIES TO TEMPERATURE STRESS AT VARIOUS STAGES OF GROWTH (EXPERIMENT I AND II)

5.1.1 Growth parameters

a. Plant height

Vaishakh and Aiswarya were significantly taller among aerobic and wetland varieties, respectively. The tallest plants observed in these varieties were due to varietal character. Both Vaishakh and Aiswarya were medium duration varieties (Fig 7 and 8).

In both aerobic and wetland rice varieties, the tallest plants were observed when plants were exposed to stress from tillering to PI and PI to flowering stage and Vaishakh and Aiswarya exposed to high temperature from tillering to PI stage were significantly taller . The plant height increase was by 8 per cent in Vaishakh and 9 per cent in Aiswarya when plants were exposed to temperature 2-2.5°C higher than ambient from PI to tillering stage, as compared to plants under control.

High temperature might have enhanced plant growth and internodal elongation of stem by way of increasing the cell division as well as elongation. Also, increased height at high temperature is supposed to be a mechanism for tolerance. In wheat, increased plant height helped the plants during high temperature stress through cooling effect due to transpiration (Kumar *et al*., 2011). Sailaja *et al*. (2015) also found tallest plants in variety N22 and shortest plants in Varadhan under elevated temperature

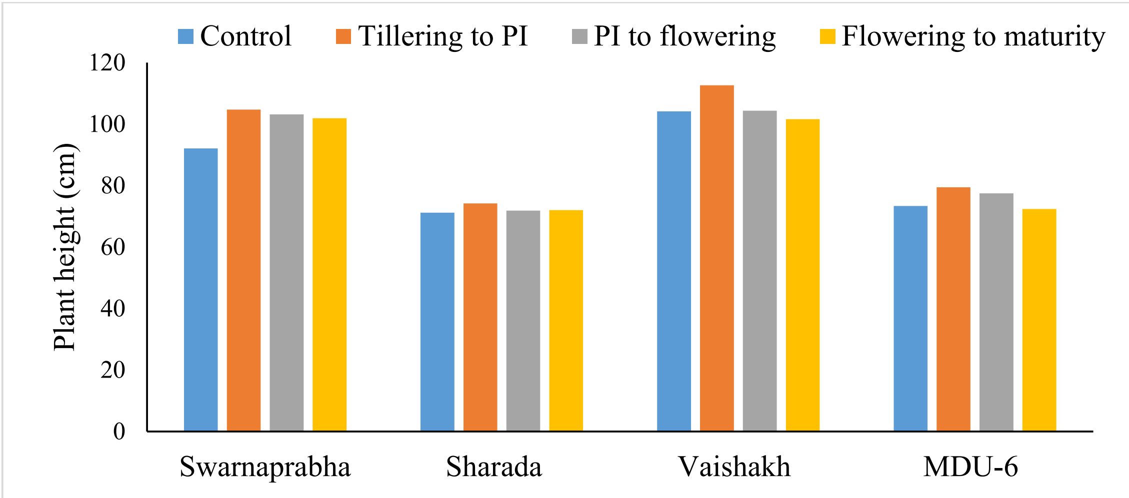


Fig 7. Effect of high temperature on plant height at harvest of aerobic rice varieties

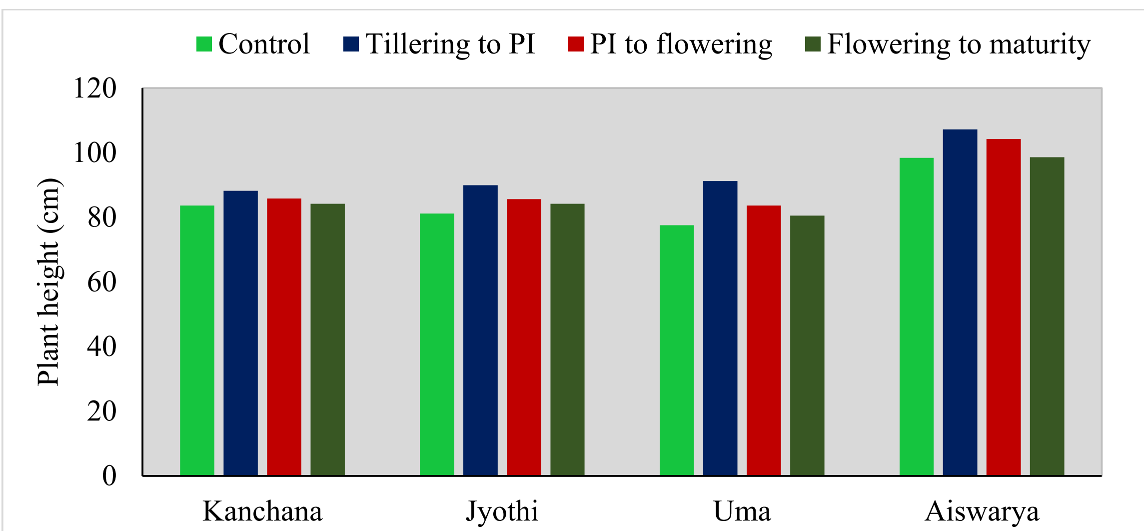


Fig 8. Effect of high temperature on plant height at harvest of wetland rice varieties

indicating varietal differences in temperature tolerance. They found that cultivar N22 was more tolerant to elevated temperature.

b. Number of tillers per hill

Significant difference between varieties were observed in number of tillers per hill. At harvest, the aerobic variety Sharada and wetland variety Aiswarya produced higher number of tillers per hill compared to other varieties tried.

At harvest, higher number of tillers were observed in plants exposed to elevated temperature from tillering to PI stage. However, tillering was comparable with plants under ambient temperature in both aerobic and wetland rice varieties. The lowest number of tillers were found when plants were exposed to heat stress from flowering to maturity stage compared to stress at early growth stage probably due to tiller death.

At harvest, Sharada and Aiswarya exposed to high temperature stress from tillering to PI stage as well as under control produced higher tiller number compared to other varieties. Tiller number increased under elevated temperature (Fig 9 and 10). Kanno *et al*. (2009) reported strong stimulation of growth and tillering in rice at high night temperature (27 °C) during the early vegetative period. At maturity, the lowest tiller number was registered for Uma exposed to high temperature. This might be due to death of later emerging tillers in order to support the growth of remaining tillers in heat stressed condition. These results are in agreement with findings of Oh-e *et al*. (2007) who found that at maturity, the number of tillers under high temperature was lower than that under ambient conditions in rice.

c. Leaf Area

The highest leaf area was registered when stress was imposed from tillering to PI in both aerobic and wetland rice varieties. The varieties Aiswarya and Sharada exposed to high temperature stress from tillering to PI stage had highest leaf area. The leaf area increased from 1529 cm^2 (control) to 1953 cm^2 in Vaishakh exposed to high temperature from tillering to PI stage and in Aiswarya leaf area increased from 1238 cm^2 (control) to 1662 cm^2 under stress during tillering to PI stage. The varieties Vaishakh, Sharada and Aiswarya produced higher number of tillers and increase in

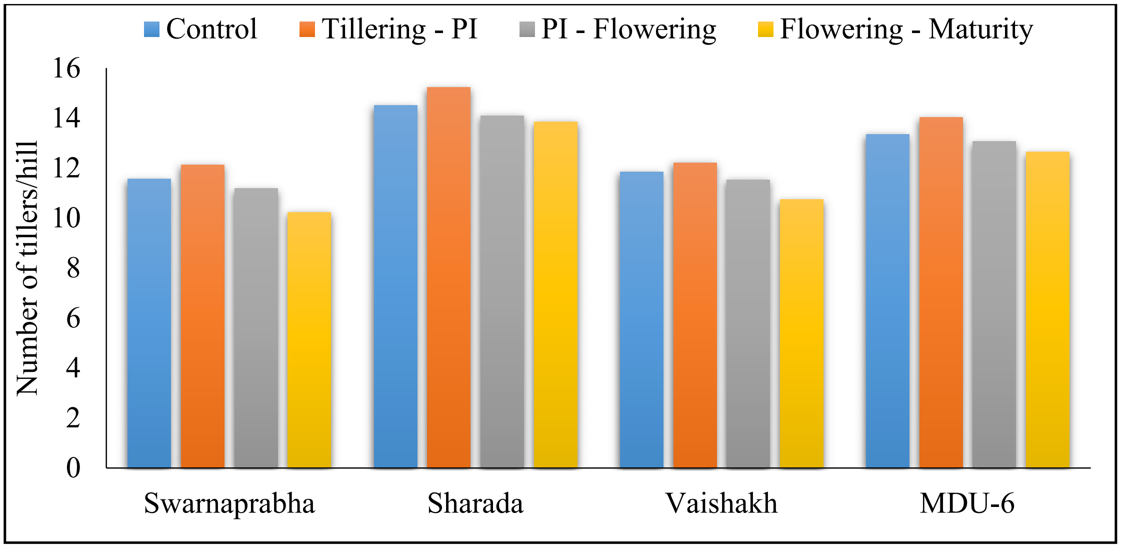


Fig 9. Effect of high temperature on number of tillers at harvest of aerobic rice varieties

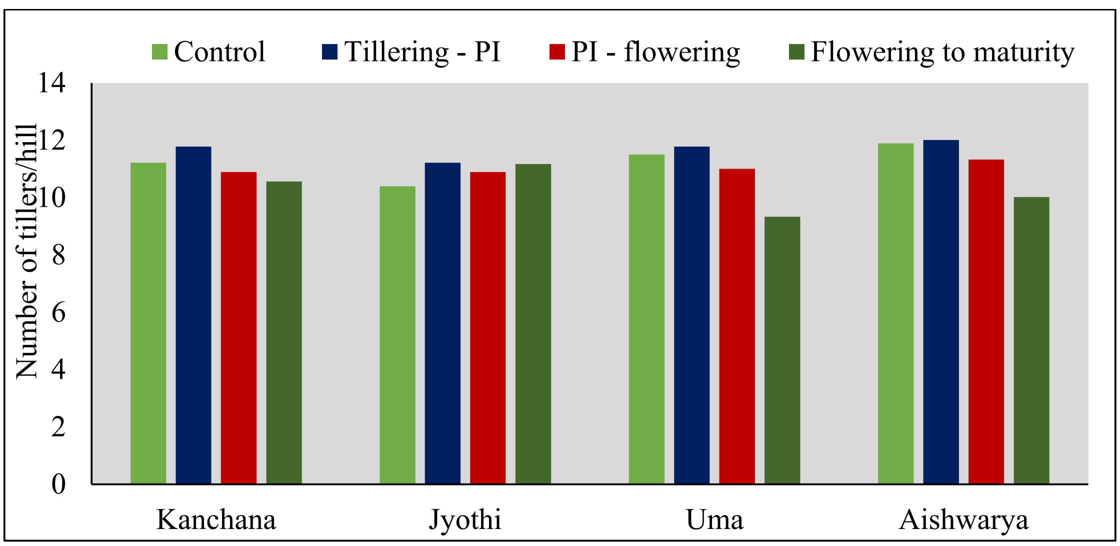


Fig 10. Effect of high temperature on number of tillers at harvest of wetland rice varieties

leaf length when exposed to high temperature during early growth phase which contributed to increase in leaf area.

Sharma and Singh (1999) found that increase in total leaf area per plant under elevated temperature was caused mainly by increasing the size of the successive leaves. High temperature induced leaf area expansion in rice might be due to its adaptation to tropical humid environments where it originated. The findings of Peng *et al*. (2004) and Sheehy *et al*. (2005) also support the present findings.

d. Days to flowering

Varietal difference was mainly due to difference in duration of varieties. Swarnaprabha, Sharada, MDU-6, Kanchana and Jyothi were short duration, and others were medium duration. Early flowering was recorded for MDU-6 (69.33 days) and Kanchana (68.97 days) among aerobic and wetland rice varieties respectively. Late flowering was observed in Vaishakh among aerobic varieties and Aiswarya among wetland rice varieties which were medium duration varieties.

Early flowering was observed when stress was imposed from tillering to PI followed by stress from PI to flowering. Flowering was 3-4 days earlier than plants grown under control in both wetland and aerobic varieties.

Early flowering was observed in short duration varieties MDU-6 and Kanchana when stress was imposed from tillering to PI (71 and 66.67 days) and PI to flowering stage (68.33 and 68 days). Medium duration varieties Vaishakh and Aiswarya under ambient temperature flowered in 78 days. It is well known that the rate of growth and metabolic processes increase with rise in temperature, thus thermal stress might have reduced the number of growing days of the rice plant. There are reports that rice plants grown under high day and night temperatures show reduction in the days to flowering by 5-6 days compared to plants grown under ambient condition (Venkatramanan and Singh, 2009). These findings were further supported by a study conducted by Sailaja *et al*. (2015), where reduction in number of days to 50 per cent flowering (4 days) was observed in temperature tolerant genotypes like N22 compared to control.

e. Dry matter production

Higher dry matter production (DMP) was registered for Vaishakh (33.89 g/hill) and Aiswarya (34.47 g/hill). Both varieties are medium duration varieties so the DMP will always be higher than short duration varieties (Fig 11 and 12).

Plants exposed to high temperature stress from tillering to PI stage produced higher dry matter production compared to ambient condition. In aerobic rice varieties, 10 per cent increase in DMP was observed when plants were exposed to high temperature from tillering to PI stage compared to control, whereas only 3 per cent increase in DMP was observed in wetland rice varieties.

The aerobic varieties Swarnaprabha and Vaishakh exposed to high temperature accumulated the highest dry matter, whereas Aiswarya and Uma had the highest DMP among wetland rice varieties. This is due to the longer culm caused by increased plant height and number of tillers when subjected to high temperature stress from tillering to PI stage. Vegetative growth was found to increase when subjected to temperature stress (Johnson, 2011).

High temperature stress imposed at flowering to maturity decreased DMP compared to control in aerobic rice varieties. The maximum DMP reduction was observed in variety Swarnaprabha by 3.56 g/hill. This resulted from reduction in tillering when heat stress was imposed at later stages. An increase in the dark and photorespiration, which metabolically drained the photosynthates might have been responsible for decreased dry weight in high temperature treated plants especially during later growth phase.

f. Root dry weight

It was observed that root growth also was influenced by high temperature stress. The highest root dry weight was observed for plants grown under ambient condition compared to plants exposed to high temperature stress at different growth stages in both aerobic and wetland rice varieties. Root growth decreased under heat stress because it has been shown that root growth had a very narrow optimum temperature range when compared with other growth processes (Porter and Gawith, 1999).

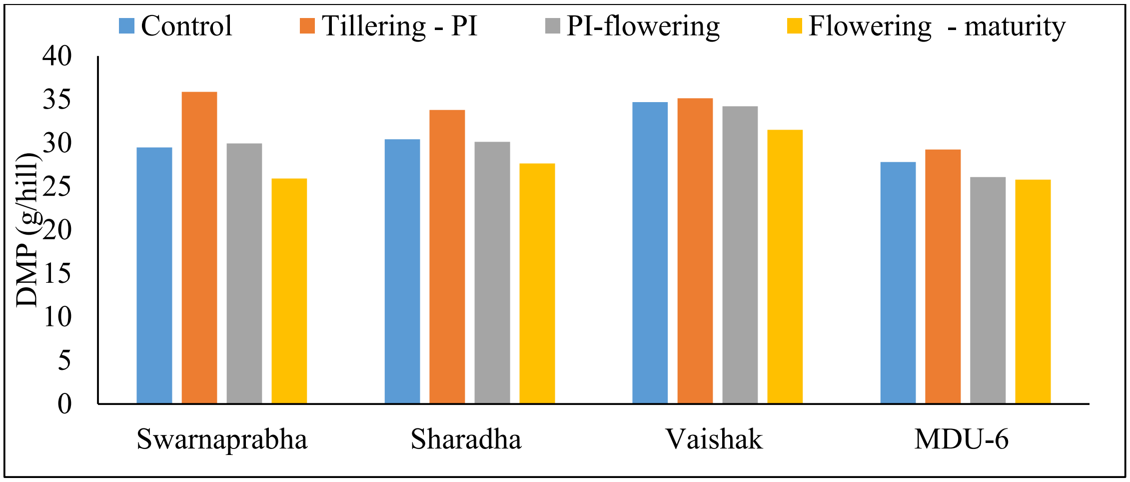


Fig 11. Effect of high temperature on dry matter production at harvest (g/hill) of aerobic rice varieties

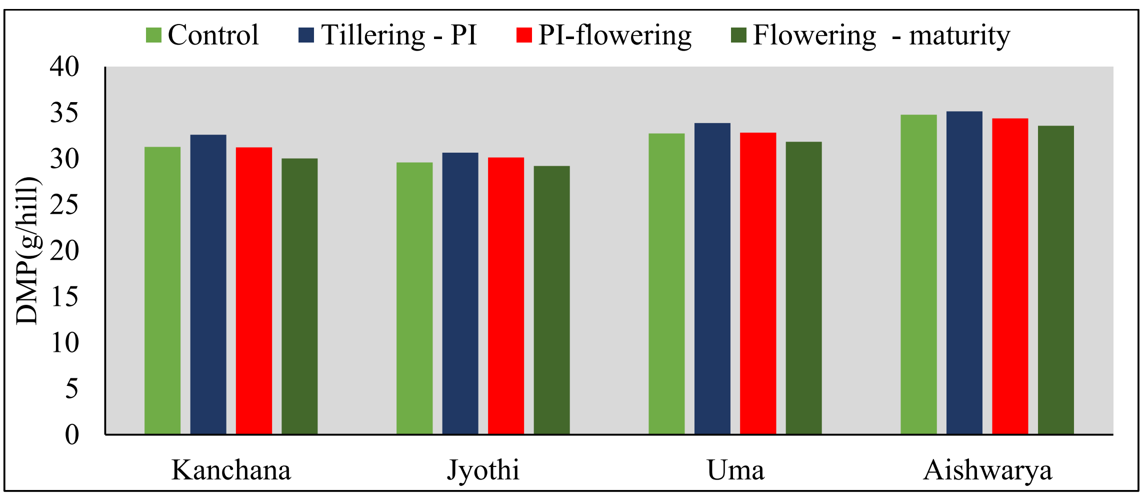


Fig 12. Effect of high temperature on dry matter production at harvest (g/hill) of wetland rice varieties

The varieties Vaishakh and Aiswarya grown under ambient condition produced highest root dry weight (10.3 g/hill). These two varieties being medium duration had higher values for other growth parameters like plant height and tiller number. Higher tiller number contributed to more number of roots and hence higher root DMP. The lowest root dry weight was recorded for MDU-6 and Jyothi exposed to high temperature stress at all stages. The decline in root dry weight can be attributed to decreased carbon partitioning to roots under heat stress (Batts *et al*., 1998).

5.1.2 Yield attributes and yield

a. Number of panicles per hill

Among the different rice varieties, the higher number of panicles per hill was observed for Sharada (11.98) and Aiswarya (10.19). Plants grown under ambient condition produced higher number of panicles whereas, lower number of panicles were observed for plants exposed to high temperature stress during tillering to panicle initiation stage. Though higher number of tillers were observed when stress imposed from tillering to PI stage, this did not contribute to number of productive tillers and hence resulted in lower number of panicles in both aerobic and wetland rice varieties. This means that several tillers failed to produce panicles and tiller decline towards later growth stage also might have contributed to decrease in panicle number.

All cultivars produced higher number of panicles under ambient temperature compared to heat stressed condition. It can be inferred that in varieties Sharada and Aiswarya, tillering was not influenced by temperatures 2-3°C above normal as comparable productive tiller was seen when stress was induced at various growth phases. The lowest number of panicles was recorded in cultivar Vaishakh (8.60) when high temperature stress was imposed during tillering to PI stage, and Uma exposed to high temperature stress from flowering to maturity (8.78). Similarly, Singh *et al*. (2010) reported that plants exposed to heat stress during their vegetative and reproductive growth phases showed decline in number of panicles. However, Liu *et al*. (2013) could not observe any significant difference in effective panicles per m^2 in rice between heat stressed and normal condition in China. This also indicate that the varieties differ in this sensitivity to high temperature.

b. Number of filled grains per panicle

In rice, temperature fluctuation during grain filling stage can affect the yield as both photosynthesis and rate of translocation of photosynthates to sink are sensitive to temperature and varieties differ in their sensitivity to temperature.

Medium duration varieties, Vaishakh (96.59) and Aiswarya (93.48) produced the higher number of filled grains even under stressed situation, indicating the adaptability of these varieties to temperature 2-3°C above ambient.

In general plants grown under ambient condition produced highest number of filled grains per panicle in both aerobic (93.57) and wetland rice varieties (87.53). It was also seen that the reproductive phase of rice is sensitive to high temperature, as stress imposed during flowering to maturity stage showed lower number of filled grains per panicle in both aerobic and wetland varieties. The reduction in filled grains per panicle was 14.5 and 20.4 per cent in aerobic and wetland rice varieties, respectively. A lower number of filled grains per panicle was noticed in Sharada (73.13) and Jyothi (59.40) exposed to high temperature stress from flowering to maturity among aerobic and wetland rice varieties (Fig 13 and 14). The decrease in filled grains per panicle is reflected in chaff percentage also. This might be due to limited supply of assimilates and reduced capacity of remobilizing carbohydrate reserves from vegetative organs to the grains under the stress (Li *et al*., 2013). In rice number of filled grains per panicle decreased by 26 per cent when plants were exposed to high air temperature (above 2°C than ambient) compared to normal air temperature (Liu *et al*., 2013) in China.

It is also reported that high temperature during grain-filling results in shortening of the duration of grain-filling, and thus reduction in grain yield. According to Boden *et al*. (2013) and Shah *et al*. (2014), high temperature reduced pollen fertility, leading to reduction in the number of pollen scattered on the stigma, thereby affecting fertility of the pollen and fertilization, markedly reducing grain yield.

High temperature stress imposed from flowering to maturity showed highest chaff per cent in all rice varieties indicating the sensitivity of this stage. The highest chaff per cent was recorded for Swarnaprabha (27.04%) and Jyothi (24.61%).

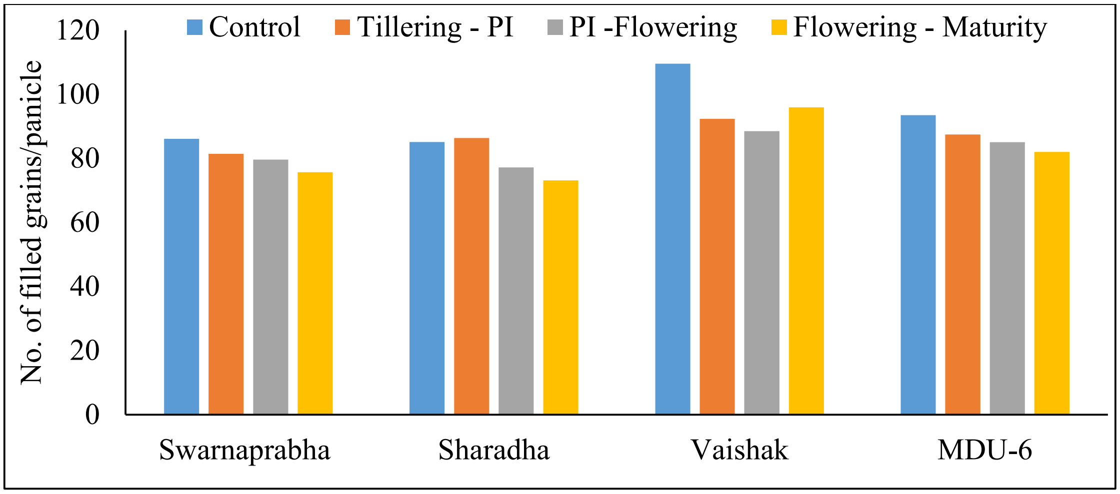


Fig 13. Effect of high temperature on number of filled grains per panicle of aerobic rice varieties

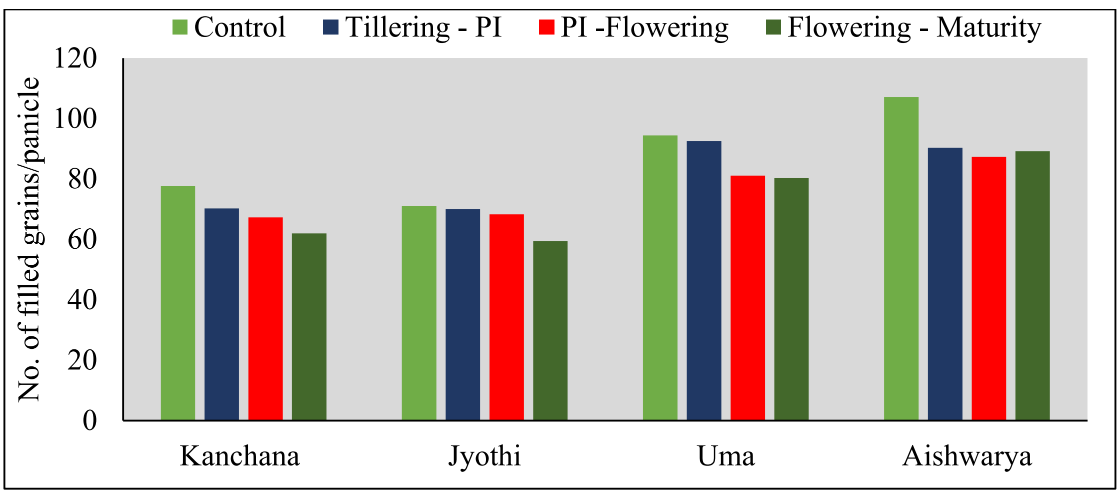


Fig 14. Effect of high temperature on number of filled grains per panicle of wetland rice varieties

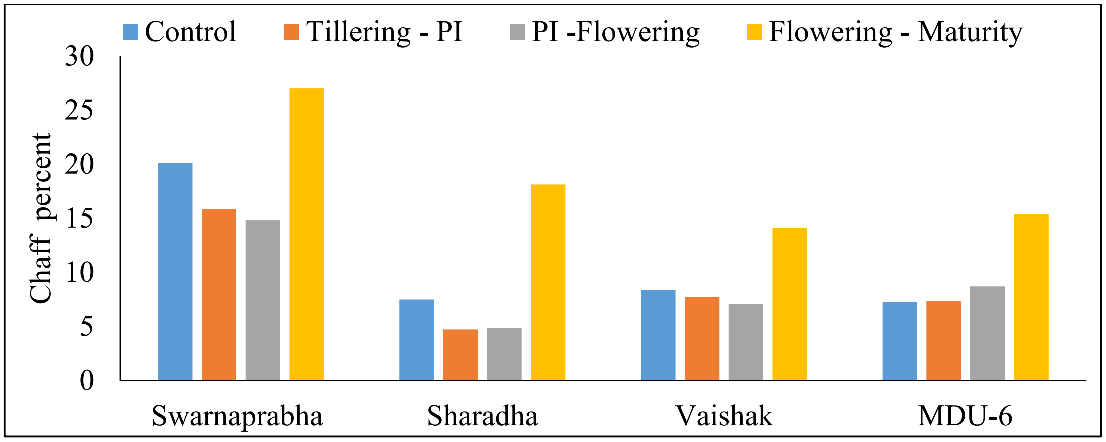


Fig 15. Effect of high temperature on chaff per cent of aerobic rice varieties

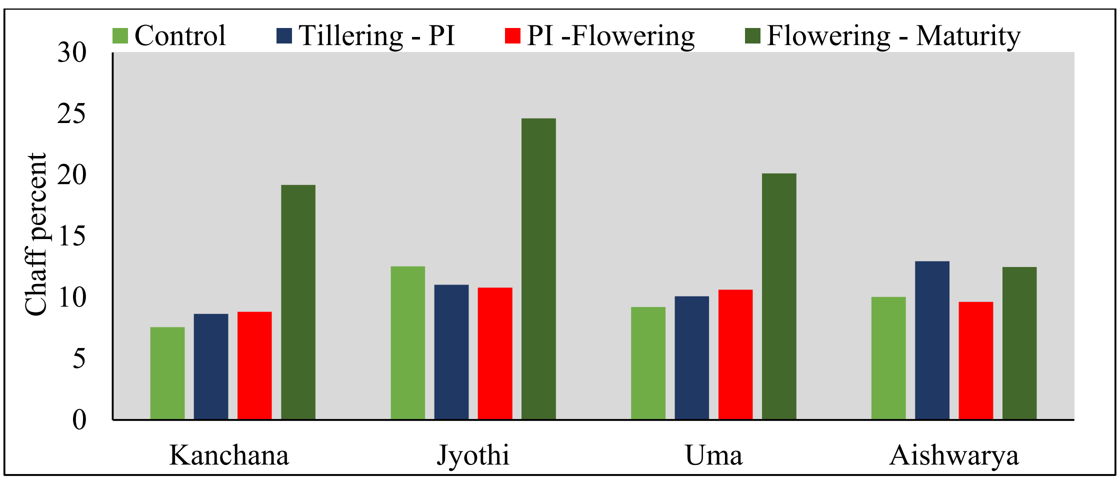


Fig 16. Effect of high temperature on chaff per cent of wetland rice varieties

Compared to plants in ambient condition the increase in chaffiness was 7 per cent for Jyothi and 12 per cent for Swarnaprabha under temperature stress (Fig 15 and 16).

Satake and Yoshida (1978) reported that high temperature above 35°C at flowering caused high spikelet sterility in rice. However, the temperature at flowering in the present study was 32.4°C to 33.4 °C, which indicate that even temperature below 35°C is detrimental to some varieties. Impaired hormonal balance in the floret or decreased availability of photosynthates to the kernel or inability of floral buds to mobilize carbohydrates under heat stress are also reported as reason for spikelet sterility in rice at high temperature (Dinar and Rudich, 1985).

c. Total number of grains per panicle

Varietal differences were significant with respect to total number of grains per panicle. The total grain number was significantly higher in Vaishakh and Aiswarya, under stress as well as under ambient condition.

Rice plants exposed to high temperature stress during PI to flowering showed least number of grains per panicle in both aerobic and wetland varieties. The total number of grains reduced by 15-16 per cent when exposed to high temperature from PI to flowering stage compared to control. Among aerobic and wetland rice varieties, the higher number of grains per panicle was observed for Vaishakh and Aiswarya under control (119.55 and 105.28) whereas Sharada and Jyothi exposed to high temperature stress from PI to flowering produced lower number of grains per panicle. Jumiatun *et al*. (2016) concluded that at 33.1°C, number of spikelets per panicle decreased in some varieties of rice whereas it increased in some others compared to 28.3°C. Similarly, Ansari *et al*. (2003) opined that the sensitivity of rice to temperature is particularly high during the early reproductive growth phase, when panicle morphogenesis occured. Thus, temperature would have a marked effect on sink formation, which might reduce the final number of potential spikelets at maturity. High temperature imposed at the onset of the reproductive phase gave the lowest number of spikelets per panicle further establishing sensitivity of this stage. A reduction in spikelet number per panicle, caused by a mild increase in night temperature during reproductive growth is also reported by many workers (Asraf *et al*., 1994), Zhang *et al*. (2013) and (Laza *et al*., 2015).

d. Thousand grain weight

Varietal differences were significant and higher test weight was noticed in Vaishakh (26.82 g) and Kanchana (26.98 g) compared to others.

A similar trend to filled grains per panicle was observed for thousand grain weight. The average 1000 grain weight was higher under control (25.55 g and 26.89 g) and lower thousand grain weight was observed in plants exposed to high temperature stress from flowering to maturity (22.23 g and 24.88 g) in both aerobic and wetland rice varieties and the reduction was 15 and 8 per cent respectively over control. Similar results were obtained by Rakavi (2017), where the reduction was found to be 6-8 per cent under heat stress.

The highest test weight value was registered for Vaishakh under control (28.99 g) and Kanchana under control (27.80 g). In all varieties, plants exposed to high temperature stress from flowering to maturity registered lowest 1000 grain weight. The decrease was more in variety MDU-6 and not much variation was noticed in variety Aiswarya. This decrease is higher in case of heat sensitive genotypes which in turn resulted in the decreased seed weight. During grain-filling period, high temperature was a critical factor to reduce grain filling or ripening (Kobata and Uemuki, 2004). The ripened rice grains under ambient temperature had a higher weight than those under high temperature treatment (Shah *et al*., 2014). Jeng *et al*. (2003) reported that the shortening of ripening period in rice due to a high temperature was caused by the higher activity of enzymes, involved in starch synthesis during the early grain growth stage, and the reduction in 1000-grain weight under high temperature conditions was caused by the reduced activity of sink for starch synthesis.

e. Panicle length

Under ambient condition, the longest panicles were recorded for aerobic rice MDU-6 (21.03 cm) and wetland rice variety Aiswarya (20.54 cm). Panicle length is mostly a varietal character and not a yield determinant in rice. The panicle length was not influenced by temperature stress in the case of both aerobic and wetland varieties.

f. Grain yield

Among aerobic rice varieties, the highest grain yield was observed for Vaishakh (14.69 g/hill) and the lowest grain yield of 11.43 g/hill was registered for MDU-6. Aiswarya registered highest grain yield (14.22 g/hill) and Jyothi (11.62 g/hill) produced the lower grain yield among wetland rice varieties (Fig 17 and 18). Both Vaishakh and Aiswarya are medium duration varieties and better performance of these varieties might be due to varietal duration to adjust to high temperature stress compared to short duration varieties. Yield reduction was 16 per cent in aerobic and 12 per cent in wetland varieties. Next sensitive stage was stress from PI to flowering (8% reduction) and plants were least affected by stress from tillering to PI (2 and 5%) compared to control in both aerobic and wetland rice varieties. High temperature stress from flowering to maturity caused more yield reduction in all varieties.

The varieties Vaishakh and Aiswarya produced higher grain yield under high temperature stress at all growth stages and the lowest grain yield was observed in MDU-6 and Jyothi when high temperature stress was imposed from flowering to maturity among aerobic and wetland rice varieties. As in the case of ambient condition, the varieties Vaishakh (13.81 g/hill) and Aiswarya (13.35 g/hill) produced higher grain yield compared to other varieties when stress was imposed at this sensitive stage. From this study, it can be inferred that the aerobic rice variety Vaishakh and wetland rice variety Aiswarya are tolerant to high temperature stress during sensitive stage of rice (from flowering to maturity). Grain yield was positively correlated with number of filled grains per panicle and 1000 grain weight (Table 86). From correlation analysis, it was found that grain yield and chaff per cent are negatively correlated under high temperature stress during flowering because spikelet sterility resulted in decreased grain yield with increase in chaff per cent in both aerobic and wetland rice varieties.

At flowering stages, temperature directly exerted negative influence on rice yield by causing pollen sterility, empty or unfilled grains, low grain weight, poor seed setting, large decrease in per cent spikelet fertility per panicle as well as alteration in various enzymatic activities, such as sucrose synthase and starch synthase. The loss of rice grain yield due to heat stress has been reported earlier by various workers. Aghamolki *et al*. (2014) reported that heat stress during booting and flowering stages

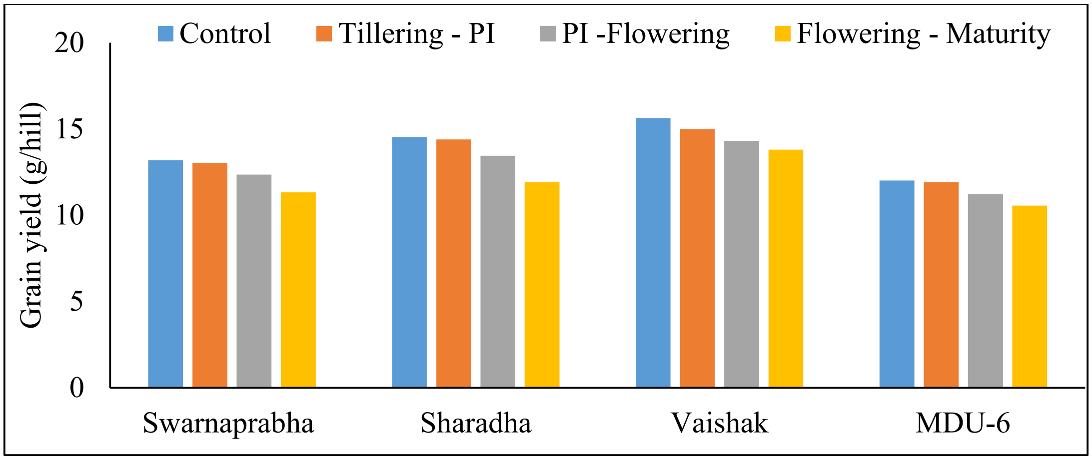


Fig 17. Effect of high temperature on grain yield of aerobic rice varieties

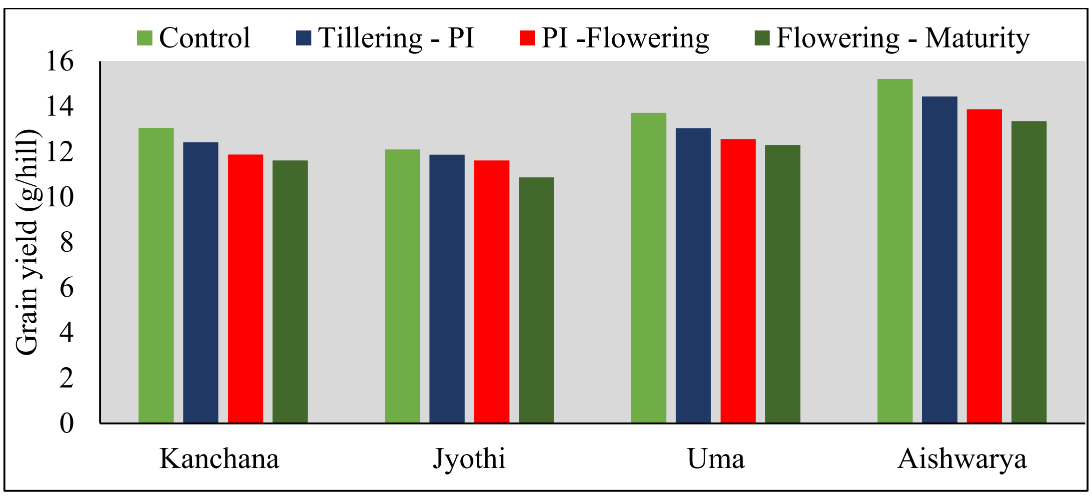


Fig 18. Effect of high temperature on grain yield of wetland rice varieties

resulted in greater yield reduction due to reduction in all the important yield components. High temperature enhanced vegetative growth, but its occurrence at or during the early reproductive phase was quite damaging to yield (Laza *et al*., 2015). In general, temperature above 25°C resulted in poor grain filling by reduced grain filling duration and in turn reduced grain yield. Jana *et al*. (2013) concluded that low grain yield of rice in aerobic situation was mainly due to high temperature during flowering period, grain formation and grain ripening stages. Spikelet sterility at high temperature was the main reason for lower grain yield during summer season. Kumar *et al.* (2017) observed grain yield to have drastically declined under terminal heat stress, which varied with rice genotypes. Yield reduction in wheat due to terminal heat stress is reported by Khan *et al*. (2015), who also observed tolerance of some varieties to heat stress.

Grain yield was positively correlated with soluble protein, chlorophyll content, MSI and canopy air temperature difference whereas it was negatively correlated with malondialdehyde and proline content of aerobic and wetland rice varieties exposed to high temperature stress from PI to flowering stage (Table 87 and 88).

In a study with different wheat genotypes Sairam *et al*. (2000) found that under elevated temperature, tolerant wheat genotypes had higher RWC, MSI, chlorophyll content, SOD and lower MDA content. Rice cultivar N22 showed lesser relative injury, less reduction in chlorophyll content, and increased SOD and lesser reduction in net photosynthetic rate, high transpiration rate contributing to least reduction in spikelet fertility and grain yield under elevated temperature (Sailaja *et al*., 2015). Similarly, Kumar *et al*. (2017) found that in rice genotype IET 20734 higher grain yield was positively correlated with minimum reduction in nitrate reductase under heat stress condition.

g. Straw yield

Vaishakh recorded highest straw yield of 19.20 g/hill as it was taller whereas MDU-6 was dwarf compared to others which resulted in lower straw yield (15.80 g/hill) among aerobic rice varieties. Aiswarya produced highest straw yield (20.25 g/hill) and lowest straw yield was obtained in Jyothi among wetland rice varieties. it

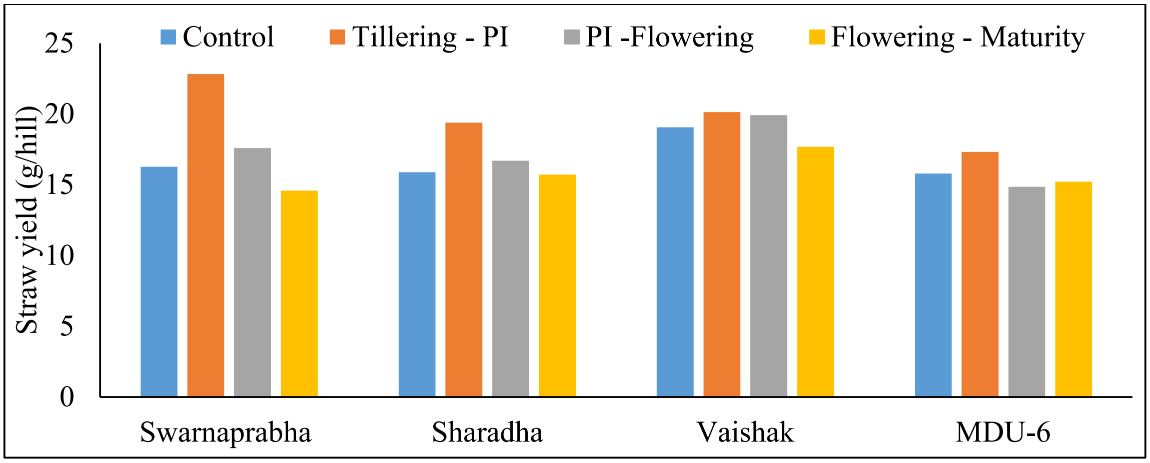


Fig 19. Effect of high temperature on straw yield of aerobic rice varieties

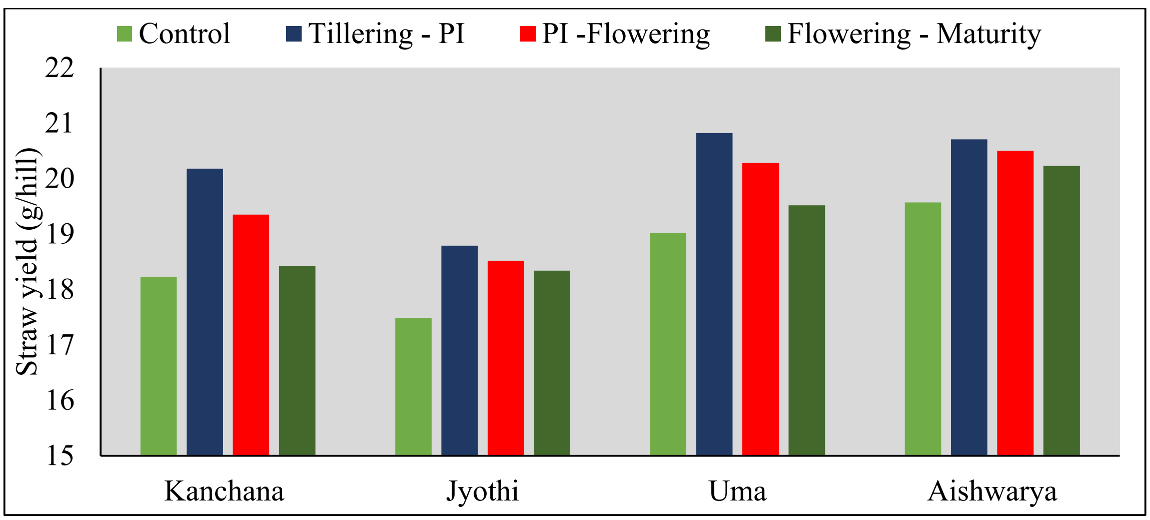


Fig 20. Effect of high temperature on straw yield of wetland rice varieties

was found the performance of the variety Jyothi was poor under pot culture in summer season in the present study.

It was found that temperature stress at vegetative phase favourably influenced straw yield and the maximum straw yield was observed under high temperature stress from tillering to PI stage in both aerobic and wetland rice varieties. Increase in straw yield was 19 per cent over ambient condition in aerobic varieties whereas it was only 8 per cent in wetland varieties. Similarly, Johnson *et al*. (2011) reported increase in straw yield in rice when temperature stress was given from tillering to maturity compared to normal condition irrespective of the variety and attributed this to the longer culm and increased plant height when subjected to hyper thermal condition.

Higher straw yield was recorded for Swarnaprabha and Aiswarya when temperature stress was imposed in vegetative phase compared to stress at later stages (Fig 19 and 20). The positive effect of elevated temperature on biomass production at early stages of growth might be due to enhanced tillering, leaf expansion and nutrient uptake. According to Suzuki (1980), positive effect of higher temperature on biomass was negligible or became negative in later stages due to larger burden from increased maintenance respiration associated with excessive growth, faster senescence and shortened growth period of rice.

Table 86. Correlation coefficient between grain yield and yield attributes of aerobic and wetland rice varieties under high temperature stress

a) Aerobic rice varieties

	Grain yield	No. of panicles per hill	No. of grains per panicle	No. of filled grains per panicle	Thousand grain weight
No. of panicles per hill	0.308				
No. of grains per panicle	-0.201	**-0.457***			
No. of filled grains per panicle	**0.606****	-0.007	**0.529****		
Thousand grain weight	0.041	**-0.438***	**0.449***	0.375	
Chaff per cent	**-0.755****	**-0.496***	**0.701****	-0.228	0.184

b) **Wetland rice varieties**

	Grain yield	No. of panicles per hill	No. of grains per panicle	No. of filled grains per panicle	Chaff per cent
No. of panicles per hill	0.063				
No. of grains per panicle	0.119	0.354			
No. of filled grains per panicle	**0.547****	**0.422***	**0.724****		
Thousand grain weight	**0.963****	0.009	-0.011	**0.466***	**-0.446***
Chaff per cent	**-0.449***	**-0.469***	-0.137	**-0.661****	

* - Significant at 1 per cent level

** - Significant at 5 per cent level

h. Harvest index

No significance difference was observed among aerobic and wetland rice varieties with respect to harvest index. The values within a range of 0.37 to 0.48.

High temperature stress imposed from tillering to PI stage recorded lowest harvest index (0.41) among aerobic rice varieties. This is be due to the fact that plants exposed to high temperature at this stage produced higher straw yield compared to control. Among wetland rice varieties, the lower HI was observed when plants were exposed to high temperature stress irrespective of growth stages compared to HI of 0.42 recorded under ambient condition.

The highest harvest index was 0.48 in Sharada and 0.44 in Aiswarya under control among aerobic and wetland rice varieties. The varieties MDU-6 and Jyothi exposed to high temperature stress from flowering to maturity recorded lowest harvest index (0.41). Poor grain yield due to alteration of physiological processes is the reason for poor harvest index in plants subjected to high temperature. The negative effects of high temperature on grain yields were much greater than on biomass, leading to significantly lower harvest index at high temperatures. Similarly, the lowest value of harvest index (42%) was recorded when temperature stress was given during reproductive phase compared to normal ambient temperature (46 %) (Singh *et al*., 2010). Johnson *et al*. (2011) stated that lowest harvest index (20 %) was observed with high temperature stress (3°C above ambient) during tillering to maturity, and highest HI (37%) was recorded under control. Similar findings are reported elsewhere.

5.1.3 Physiological parameters

a. Relative water content

Moisture content is an important variable under changing ambient temperatures. Plants under stress show higher RWC. The RWC varied with growth stage of rice and varietal differences were also evident indicating their tolerance or susceptibility to temperature stress. During PI and flowering, MDU-6 registered highest RWC whereas Swarnaprabha showed higher value at maturity stage among aerobic rice varieties. The variety Kanchana registered highest RWC among wetland rice varieties at all growth stages.

Plants exposed to high temperature stress registered lower RWC compared to plants under control at all stages and values ranged from 69.06 to 78.62 per cent. The variety MDU-6 and Kanchana under control had higher RWC at all the growth stages whereas Swarnaprabha and Uma exposed to high temperature stress showed low RWC at all growth stages among aerobic and wetland rice varieties. A marked reduction in RWC was observed in MDU-6 (19 %) and Uma (16%) exposed to high temperature from PI to flowering than their control. However, less reduction of only 2 per cent was recorded in Swarnaprabha under stress than its control at same stage. Relative water content of aerobic and wetland rice was positively correlated with soluble protein, nitrate reductase activity, MSI, proline content, SOD, photosynthetic rate, transpiration rate, stomatal conductance and CATD under high temperature stress (Table 87 and 88). High temperature causes more water loss in plants during daytime than during night time. Rice when exposed to high temperature tends to avoid heat by maintaining temperature below critical level by efficient transpiration cooling. This may lead to decrease in water potential and perturbation of many physiological processes (Mazorra *et al*., 2002). Similarly, Poli *et al*. (2013) reported that relative leaf water content decreased by 2.29 per cent in rice variety N22 and by 1.10 per cent in NH219 under heat stress condition (44°C) compared to ambient condition (38°C) and these were heat tolerant varieties.

Relative water content indicates turgity of cell. If it is higher, stomata will remain open which will lead to increase in photosynthetic rate and transpiration rate. This increase in photosynthetic rate can contribute to increase in soluble protein content, nitrate reductase activity and SOD activity. Higher RWC maintains high MSI under high temperature stress and shows adaptability of variety to this condition.

b. Stomatal conductance

Stomatal movements provide the leaf with the opportunity to change both the partial pressure of CO_2 at the sites of carboxylation and the rate of transpiration. It is reported that stomatal conductance is inhibited by elevated temperature stress owing to decreased Rubisco activase enzyme (Morales *et al*., 2003). The varietal responses varied and it showed varying trends at different growth phases. Temperature stress significantly reduced the stomatal conductance of both aerobic and wetland rice varieties at all growth stages compared to control and values ranged from 0.211 to 0.107 mol $H_2O/m^2/s$.

The varieties MDU-6 and Vaishakh showed greater reduction in stomatal conductance (65 and 55 %) under high temperature stress during PI to flowering compared to ambient condition. Less reduction of 5 and 13 per cent in stomatal conductance was observed in Swarnaprabha and Jyothi at this stage. According to Sailaja *et al*. (2015), stomatal conductance in rice was more significantly affected during vegetative phase than reproductive phase under elevated temperature and the decrease in stomatal conductance was 22 per cent (vegetative phase) and 11 per cent (reproductive phase). Amareshkumar *et al*. (2017) reported that the rice genotype EC792192 showed lowest leaf stomatal conductance value of 1.66 mol $H_2O/m^2/s$ under late sown condition compared to normal sown condition. Decrease in stomatal conductance of rice under elevated temperature condition is reported by other workers also.

c. Photosynthetic rate

The direct effect of high temperature is mainly on plant photosynthetic rate and it ultimately decides the carbohydrate synthesis and yield. Rice, being a C_3 plant, is sensitive to high temperature which resulted in stomatal closure which ultimately results in poor CO_2 assimilation. Another consequence of high temperature is its effect on photorespiration which will lead to poor yield.

Rice plants exposed to high temperature stress from PI to flowering showed decline in photosynthetic rate by 74 per cent in aerobic varieties and 34 per cent in wetland varieties compared to plants under control. The leaf photosynthesis of rice is reported to increase from 22°C to 32°C and then decrease (Egeh *et al*., 1992). Leegood (2002) reported that the solubility of oxygen is decreased to a lesser extent than CO_2 under heat stress resulting in increased photorespiration and lower photosynthesis. It is reported that high temperature can reduce photosynthetic rate by 40-60 per cent at mid-ripening, leading to more rapid senescence of the flag leaf (Oh-e *et al*., 2007).

Varieties Swarnaprabha and Kanchana under ambient temperature registered higher photosynthetic rate whereas it was lowest for MDU-6 and Uma exposed to high temperature stress during tillering to PI and flowering to maturity. The varieties MDU-6 and Vaishakh showed higher reduction in photosynthetic rate under high temperature stress during PI to flowering stage compared to ambient temperature. However, the variety Sharada was least affected by high temperature at this stage. This might be due to the genetic make up of the plant. Sailaja *et al*. (2015) found that net photosynthetic rate reduced by 28 and 23 per cent in rice when temperature stress was imposed at vegetative and reproductive phases respectively. They found that genotypes, differed widely and concluded that less sensitivity is a desirable trait as far as temperature tolerance is considered. However varieties having higher yield and other desirable attributes along with temperature tolerance will be required to cope up with hike in atmospheric temperature due to global warming.

d. Transpiration rate

In general transpiration rate decreased under high temperature stress due to stomatal closure and lower values indicate tolerance to high temperature situation. Transpiration rate decreased by maturity stage of crop. At PI stage, it was 2.15 m mol $H_2O/m^2/s$ whereas the value was 1.49 m mol $H_2O/m^2/s$ at maturity stage. The variety Swarnaprabha registered higher stomatal conductance which was on par with Sharada, while lower value was observed for MDU-6 during flowering stage. At flowering stage under stress, Sharada (2.16 m mol $H_2O/m^2/s$) and Swarnaprabha (2.13 m mol $H_2O/m^2/s$) recorded higher values, while MDU-6 under high temperature stress, showed lower transpiration rate (0.77 m mol $H_2O/m^2/s$). Hazra *et al*. (2016) also found that high temperature decreased transpiration rate in rice and among different varieties, the variety Binadhan 6 registered higher transpiration rate (8.31 mol $H_2O/m^2/s$) in flag leaf whereas the lowest transpiration rate was observed in Binadhan 5 (5.86 mol $H_2O/m^2/s$). They found that the variety Binadhan-6 was tolerant to high temperature among different varieties tried. In wheat, combined drought and heat stress (34°C) decreased transpiration rate by60 to 63 per cent at flowering stage (Kondracka *et al*., 2014).

e. Total chlorophyll content

Rice exposed to high temperature stress registered lower total chlorophyll content at all stages compared to control and values ranged from 2.57 to 1.92 mg/g. At flowering stage, the chlorophyll content decreased by 13 and 17 per cent in rice plants exposed to high temperature compared to control in aerobic and wetland varieties (Fig 21 and 22). It is reported that heat stress alters total chlorophyll content and thus affects leaf photochemical efficiency in stressed plants. The total chlorophyll content has been reported to reduce in the heat stressed cultivars in relation to the control plants (Liu *et al*., 2010; Xu *et al*., 1995).

The varieties Vaishakh and Aiswarya had highest chlorophyll content at all growth stages and they registered less reduction in chlorophyll content (9% and 13 %) when exposed to high temperature stress during PI to flowering compared to control. This shows their adaptation to temperature stress as photosynthetic pigments were not much affected, avoiding drastic reduction in photosynthesis. The highest reduction in chlorophyll content was observed in MDU-6 and Uma (20 per cent) when exposed to high temperature stress during PI to flowering compared to its control. Similar trend was followed for stress at remaining stages for Vaishakh and Aiswarya. Chlorophyll content of aerobic and wetland rice varieties was positively correlated with RWC, MSI, soluble protein, nitrate reductase activity, SOD, photosynthetic rate, transpiration rate and CATD. However, it was negatively correlated with MDA and proline content when plants exposed to high temperature stress from PI to flowering stage (Table 87 and 88). The increase in photosynthetic rate contributed to increase in chlorophyll conent and nitrate reductase activity.

Pastori and Trippi (1993) have also reported a decrease in chlorophyll content upon exposure to oxidative stress and a comparatively higher chlorophyll content in wheat and maize genotypes tolerant to stress conditions than in susceptible genotypes. Also, Zhang *et al*. (2013) found that the impaired net photosynthetic rate at high temperature was mainly attributed to the reduction of chlorophyll content as well as activities of activating enzyme (RuBisCO) and carboxylase (RuBP) involved in photosynthesis in flag leaves. In a study conducted at IRRI, Hyderabad under heat stressed condition (5.5°C higher than ambient) the total chlorophyll content decreased

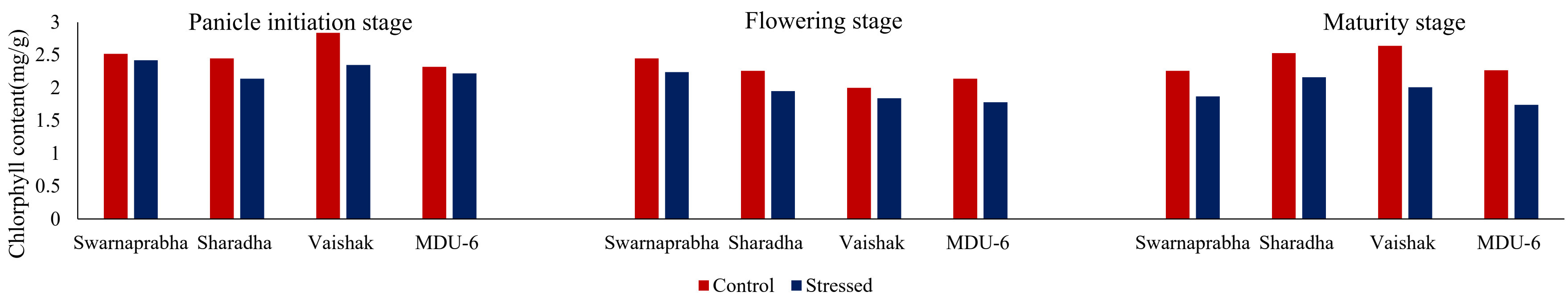


Fig 21. Effect of high temperature on total chlorophyll content (mg/g) of aerobic rice varieties

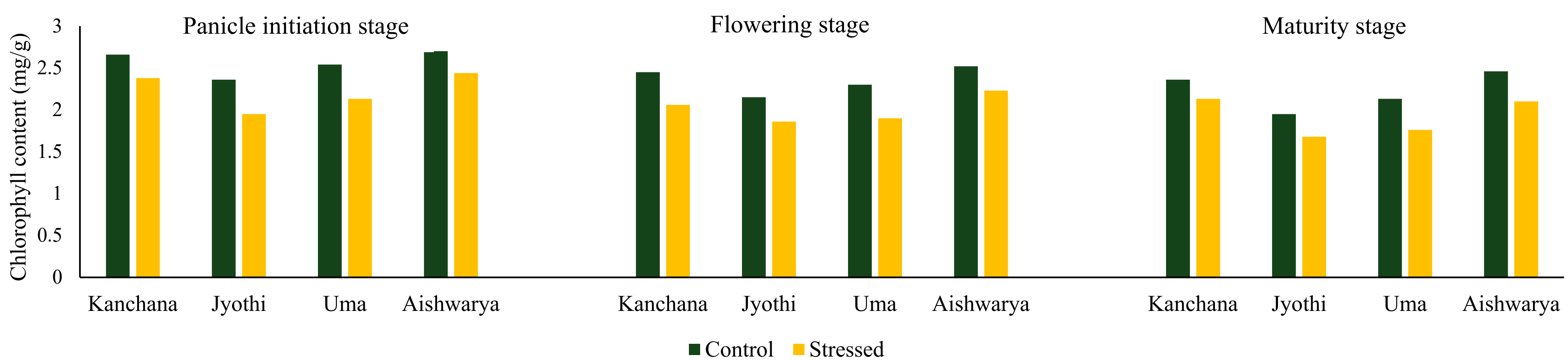


Fig 22. Effect of high temperature stress on total chlorophyll content (mg/g) of wetland rice varieties

by 14.9 per cent during vegetative and 42 per cent at reproductive phase in rice cultivars (Sailaja *et al*., 2015).

f. Soluble protein content

Temperature stress significantly reduced the soluble protein content in all growth stages compared to control in both aerobic and wetland rice varieties, and ranged from 20.50 to 8.06 mg/g (Fig 23 and 24). Higher protein content, were recorded at earlier growth phase which tended to decrease at maturity irrespective of variety.

The highest soluble protein content was observed in Swarnaprabha (15.64 mg/g) and Kanchana (14.37 mg/g) under high temperature stress conditions during PI to flowering stage compared to other varieties under stress. The higher reduction in soluble protein was observed in Uma (45%) and Vaishakh (23%) exposed to high temperature during PI to flowering stage compared to control. Soluble protein content of aerobic and wetland rice varieties exposed to high temperature stress from PI to flowering stage was positively correlated with photosynthetic rate, stomatal conductance, transpiration rate, nitrate redutase activity and CATD. (Table 87 and 88).

Generally, soluble protein content was decreased in plants exposed to high temperature condition compared to plants grown under ambient condition. Grain filling is also affected by impaired deposition of starch and protein under high temperature stress (Yamakawa and Hakata, 2010). Under high air temperature (2℃ and 0.3℃ above ambient day and night temperature), the soluble protein content in rice flag leaf was reduced by 10 per cent compared to normal air temperature in China (Liu *et al*., 2013). Perdomo *et al*. (2017) concluded that high temperature stress induced suppression of photosynthesis by mainly decreasing the proportion of soluble protein to total leaf nitrogen, adversely affecting the Rubisco protein and activity.

g. Nitrate reductase activity

Nitrate reductase activity plays an important role in regulating N metabolism which is decreased under high temperature stress. In general, higher nitrate reductase activity was observed in earlier growth stages compared to later stages in all the varieties. Among varieties, Sharada and Jyothi recorded higher nitrate reductase

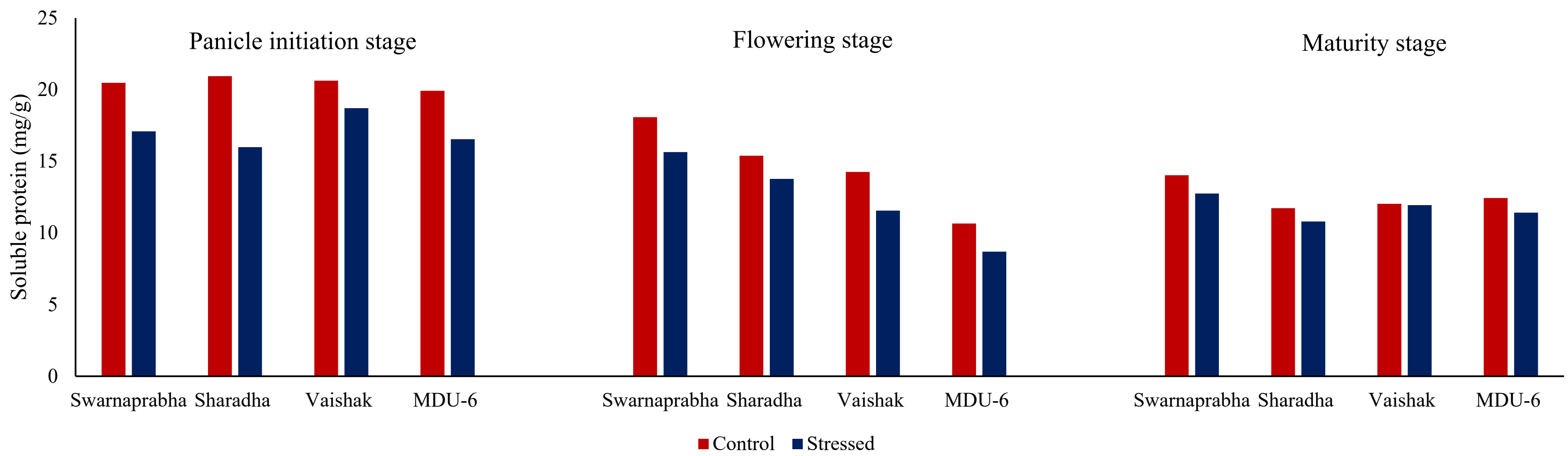


Fig 23. Effect of high temperature on soluble protein content (mg/g) of aerobic rice varieties

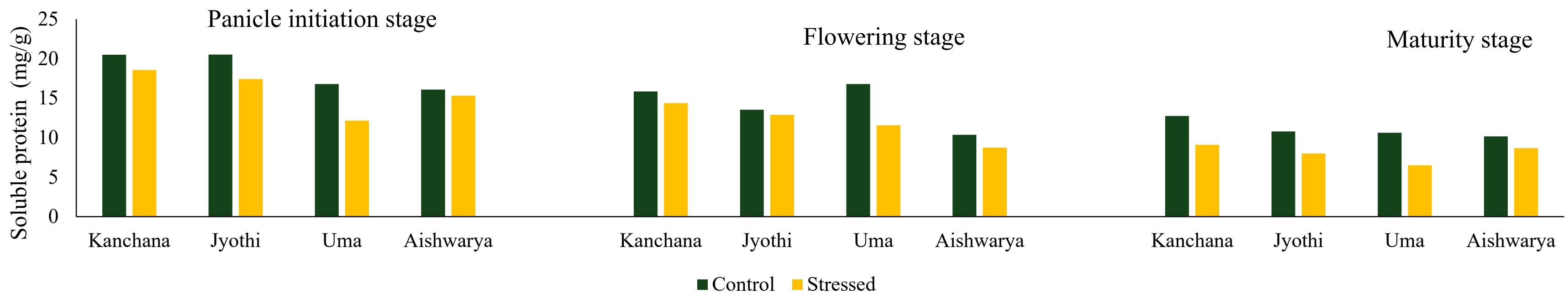


Fig 24. Effect of high temperature stress on soluble protein content (mg/g) of wetland rice varieties

activity whereas lower values were recorded for Vaishakh and Uma during all growth stages among different varieties.

High temperature stress imposed to rice at different growth stages decreased nitrate reductase significantly as compared to plants grown under ambient condition.

Sharada, Jyothi and Kanchana under control registered higher value for nitrate reductase during all growth stages whereas lowest nitrate reductase activity was observed for Vaishakh and Uma under high temperature stress during all growth stages. The variety MDU-6 (52 %), Uma (48%) and Aiswarya (44%) registered higher reduction in nitrate reducatse activity when plants were exposed to high temperaure stress from PI to flowering stage compared to their controls whereas least redution (2.6 %) was observed in Vaishakh (Fig 25 and 26). Nitrate reductase activity was positively correlated with photosynthetic rate, stomatal conductance, transpiration rate and CATD of aerobic and wetland rice varieties exposed to high temperature stress (Table 87 and 88). The NR activity involved in nitrogen assimilation significantly decreased, when *Leymus chinensis* (a perennial grass) was subjected to high temperature stress (Xu and Zhou, 2006). Kumar *et al*. (2017) also observed 36 per cent reduction in nitrate reductase activity in rice genotype IET 20924 under high temperature stress.

h. Membrane stability index

. High temperature stress increases cell membrane permeability, thereby inhibiting cellular function, as a result of the denaturation of proteins and increments of unsaturated fatty acids that disrupt water, ion, and organic solute movement across membranes. Injury to the cell membrane as a result of high temperature will result in a leaky membrane which can impair the properties of the photosynthetic system and hence MSI can give an indication of temperature tolerance (Berry and Bjorkman, 1980). In all rice varieties tried the MSI values showed a decrease from tillering to maturity stage.

The varieties Swarnaprabha and Aiswarya recorded higher MSI value, whereas the lower MSI values were observed for MDU and Jyothi-6 during PI to flowering stage indicating their susceptibility. Plants grown under high temperature stress showed significantly less MSI value than plants under control during all growth stages in both aerobic and wetland rice varieties.

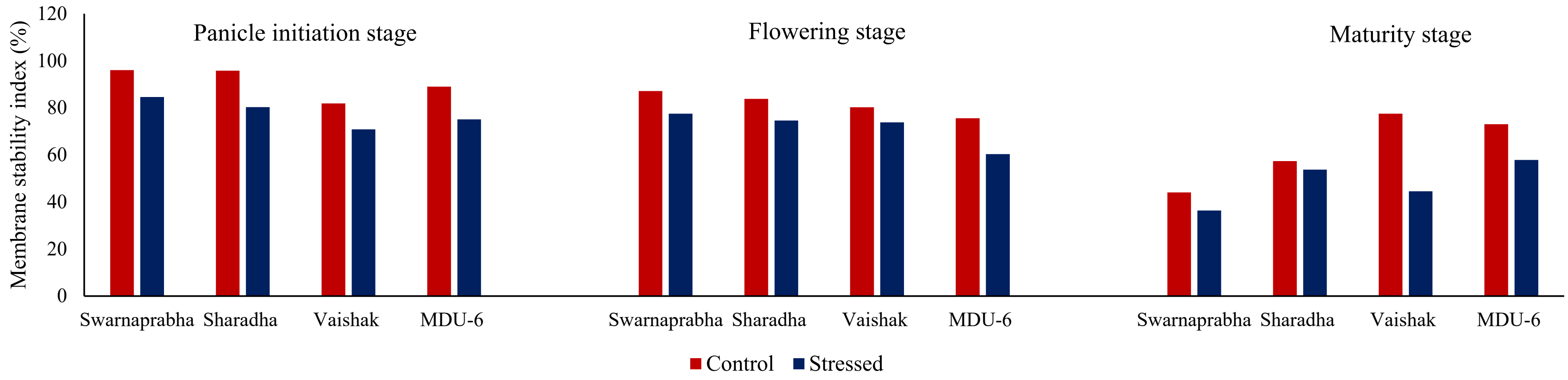


Fig 25. Effect of high temperature on membrane stability index (%) of aerobic rice varieties

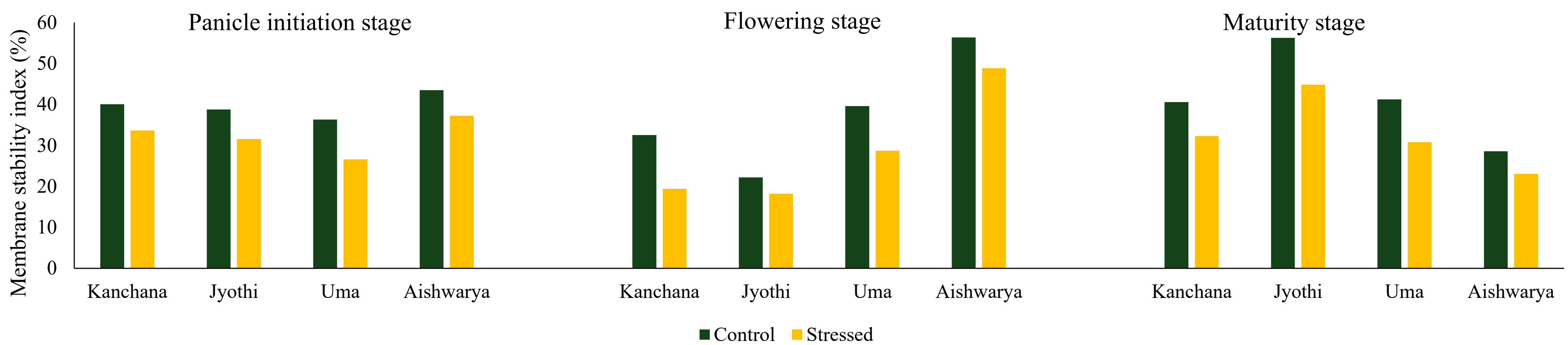


Fig 26. Effect of high temperature stress on membrane stability index (%) of wetland rice varieties

Swarnaprabha and Aiswarya under ambient condition maintained higher MSI values whereas MDU-6 and Uma under high temperature stress showed lower values at tillering to flowering stage. Higher reduction in MSI was recorded for Kanchana (67%), Uma (38%) followed by MDU-6 (25%) whereas less reduction of 9 per cent in MSI was observed in Vaishakh when stress was imposed from PI to flowering (Fig 25 and 26). Table 87 and 88 indicates that membrane stability index was positively correlated with MDA and stomatal conductance and it was negatively correlated with soluble protein, nitrate reductase, proline and SOD activity of aerobic and wetland rice varieties exposed to high temperature stress from PI to flowering stage.

Sailaja *et al*. (2015) reported that four cultivars showed about 30 per cent increase in relative injury under high temperature stress (above 5.5°C than ambient) i.e., 13% increase in MTU1010, 20% in IR64, 23% in N22, and 17% in Rasi. These cultivars showed good performance in yield attributes also. Earlier studies showed that plants with high electrolyte leakage or relative injury were found to be more susceptible to high temperature stress (Haque *et al*., 1992; Reynolds *et al*., 1994). Studies in rice also showed that heat-tolerant genotypes possessed better membrane integrity than heat-sensitive ones (Mohammed and Tarpley, 2009). Similarly, Khan *et al*. (2015) reported that high temperature decreased the MSI at different growth stages in wheat genotypes.

i. Malondialdehyde

MDA content is a good indicator of degree of lipid peroxidation and the higher the MDA content, the cell membrane will be damage severe. During PI to flowering, Vaishakh and Uma recorded highest MDA content compared to all varieties whereas lower values were recorded for Sharada and Aiswarya.

During all growth stages, MDA content showed an increase in plants exposed to high temperature stress compared to plants under control. The aerobic rice varieties showed only 2 per cent increase in MDA content whereas 55 per cent increase was observed in wetland rice varieties under high temperature stress during PI to flowering. The MDA content decreased in Vaishakh and MDU-6 when plants were exposed to high temperature stress from PI to flowering stage, whereas higher increase of 145 per cent was observed in Kanchana (Fig 27 and 28). Malondialdehyde (MDA) content of

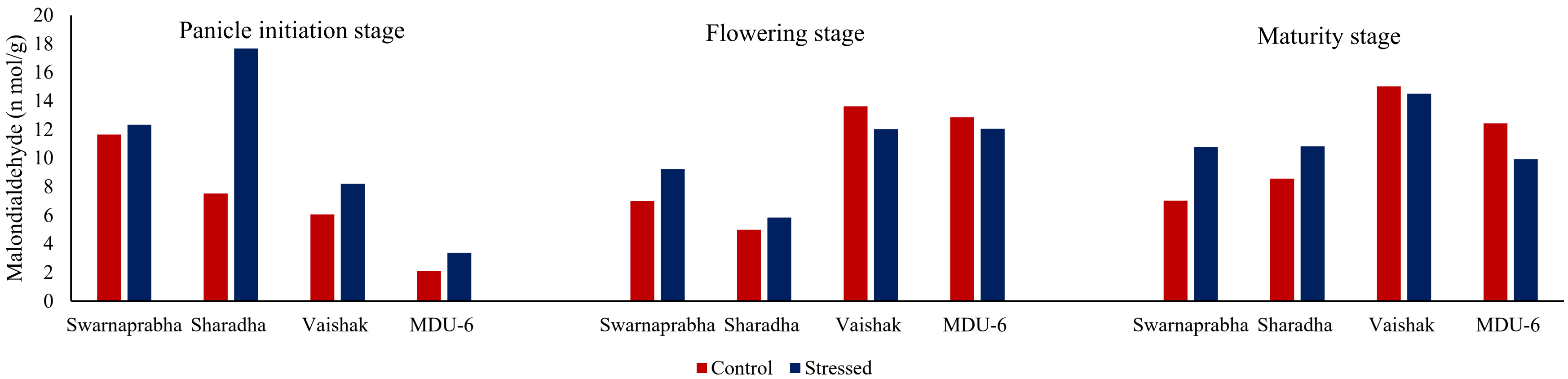


Fig 27. Effect of high temperature on malondialdehyde (n mol /g) of aerobic rice varieties

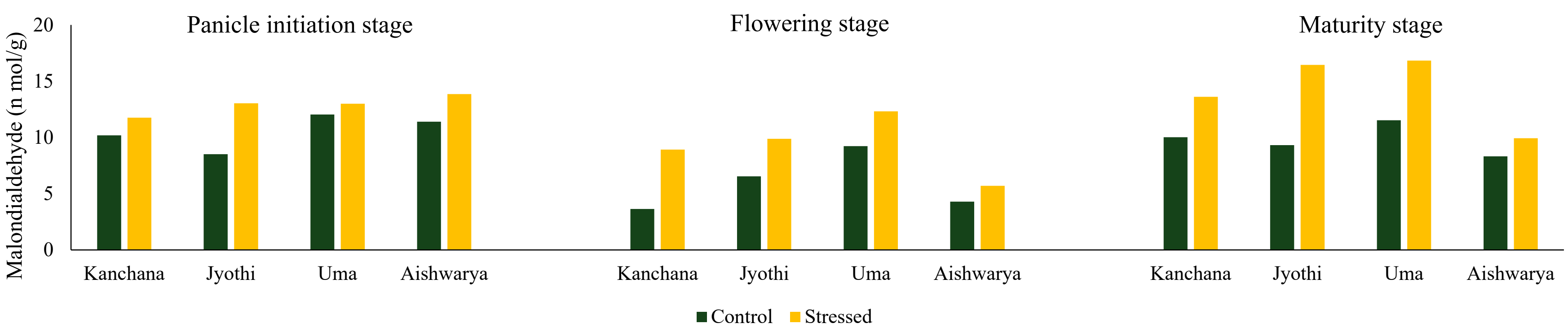


Fig 28. Effect of high temperature stress on malondialdehyde (n mol /g) of wetland rice varieties

aerobic and wetland rice varieties were positively correlated with stomatal conductance. However, it was negatively correlated with soluble protein, nitrate reductase activity, proline content, MDA, SOD, transpiration rate and CATD (Table 87 and 88). Similarly, Liu *et al*. (2013) reported that MDA content of flag leaves was enhanced significantly under high temperature which might be due to increased cell membrane permeability, precluded physiological metabolism and expedited senescence of products of photosynthesis in leaves, being an important parameter evaluating photosynthetic function. Sanchez-Reinoso *et al*. (2014) concluded that MDA content was higher in rice at 40°C and variety F60 seemed to be more susceptible. High temperatures increased the MDA content in F60 by 72% compared to F473 and by 12% compared to F733. Kumar *et al.* (2016) found that under elevated temperature (12°C above ambient temperature) during flowering stage, the lipid peroxidation level (MDA content) increased by from 170 to 10 per cent over control.

j. Proline content

Proline content varied with variety, growth stage as well as temperature stress. The content decreased gradually with advance in crop growth. In general aerobic rice varieties had higher content compared to wetland types. Kanchana and Swarnaprabha had the highest content at PI stage. Whereas, the lowest proline content was for Uma (36.38 µmol/g) and Vaishakh during flowering stage.

Plants exposed to high temperature stress from PI to flowering stage registered increase in proline content by 4 and 30 per cent in aerobic and wetland rice varieties respectively compared to respective controls, whereas stress during flowering to maturity decreased proline content. Under stress conditions, accumulation of proline in plants resulted either from increased expression of proline synthesising enzymes or due to repressed activity of proline degradation (Hong *et al*., 2000). Contradictory to this, Kumar *et al*. (2017) reported that during flowering, proline content significantly increased in all indica rice genotypes under heat stress and increase was more in new leaves compared to older leaves. He also found wide genotypic variations in proline content.

Increase in proline content was 12 per cent in MDU-6 and 48 per cent in Jyothi exposed to high temperature stress form PI to flowering among aerobic and wetland

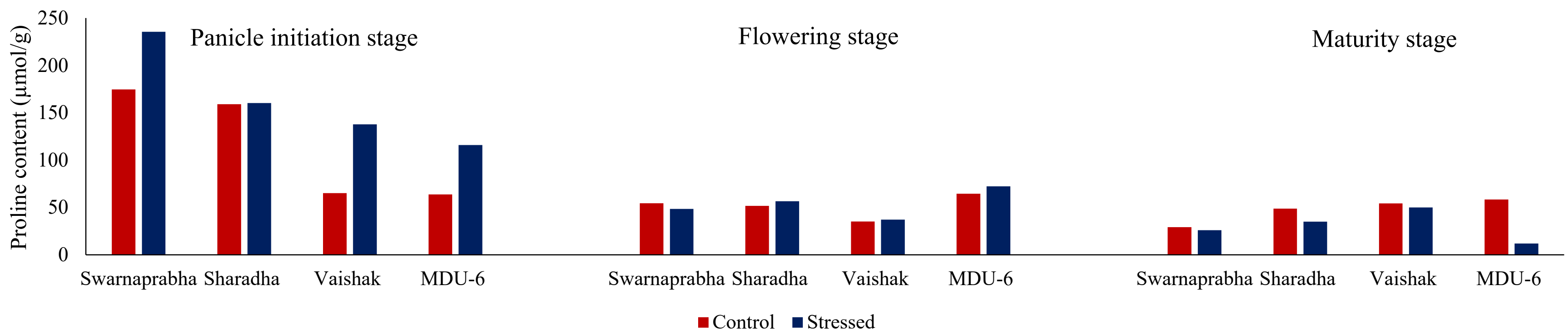


Fig 29. Effect of high temperature on proline content (µ mol/g) of aerobic rice varieties

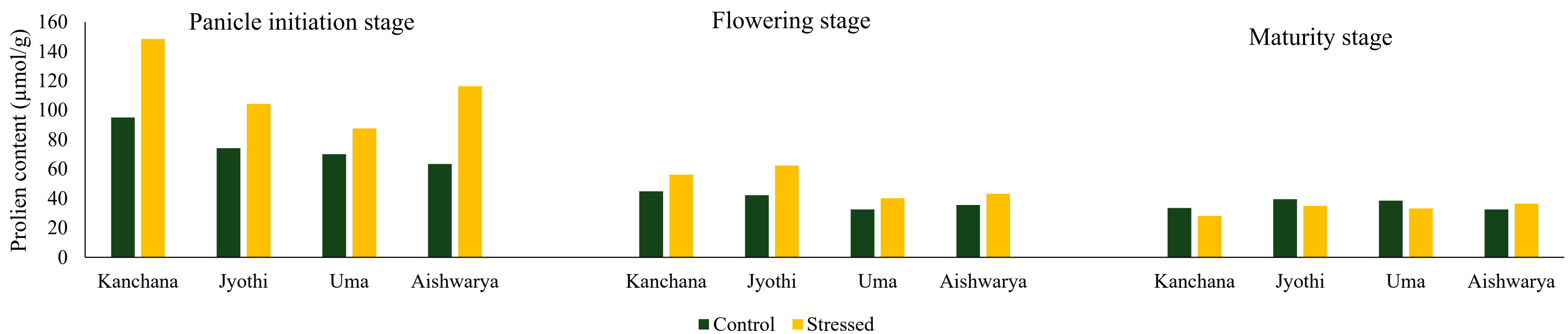


Fig 30. Effect of high temperature stress on proline content (µ mol/g) of wetland rice varieties

rice varieties (Fig 29 and 30). Proline level in variety Swarnaprabha was least affected by high temperature stress indicating its stable physiological mechanism. Proline content of wetland rice varieties was positively correlated with SOD and RWC, whereas it was negatively correlated with chlorophyll content, MSI and transpiration rate (Table 87 and 88). Rakavi (2017) also observed higher per cent increase in proline content over control in the tolerant genotypes N22 and TKM9 (32 % increase) compared to susceptible genotypes. Zhang *et al.* (2013) reported that proline content in flag leaf of rice during heading and flowering was higher under elevated temperature than ambient condition. Significantly increase in proline concentration in leaves of wheat genotypes compared to ambient temperature is reported (Khan *et al*., 2015).

k. Superoxide dismutase

High temperature stress in plant produces oxidative stress and it causes accumulation of reactive oxygen species (ROS) in higher concentrations, and results in disruption of membrane proteins and enzymes, and increase the membrane fluidity. Plants produce antioxidant enzymes like superoxide dismutase, which detoxify the ROS produced under heat stress. Among varieties, Swarnaprabha and Aiswarya recorded the highest SOD activity, and lowest activity was recorded by Vaishakh and Uma during tillering to flowering stage. High temperature stress imposed during tillering to flowering stage showed 14 per cent increase in SOD activity for wetland rice varieties. However, in aerobic varieties the SOD activity tended to decrease at later stages.

The varieties Vaishakh and Aiswarya registered remarkable increase in SOD activity when exposed to high temperature stress from PI to flowering, whereas Sharada showed decrease in SOD activity under high temperature than its control. This indicated that Vaishakh and Aiswarya have better scavenging capacity and higher tolerance to heat stress than other genotypes. Under high temperature stress SOD was positively correlated with chlorophyll content, RWC, nitrate reductase and proline

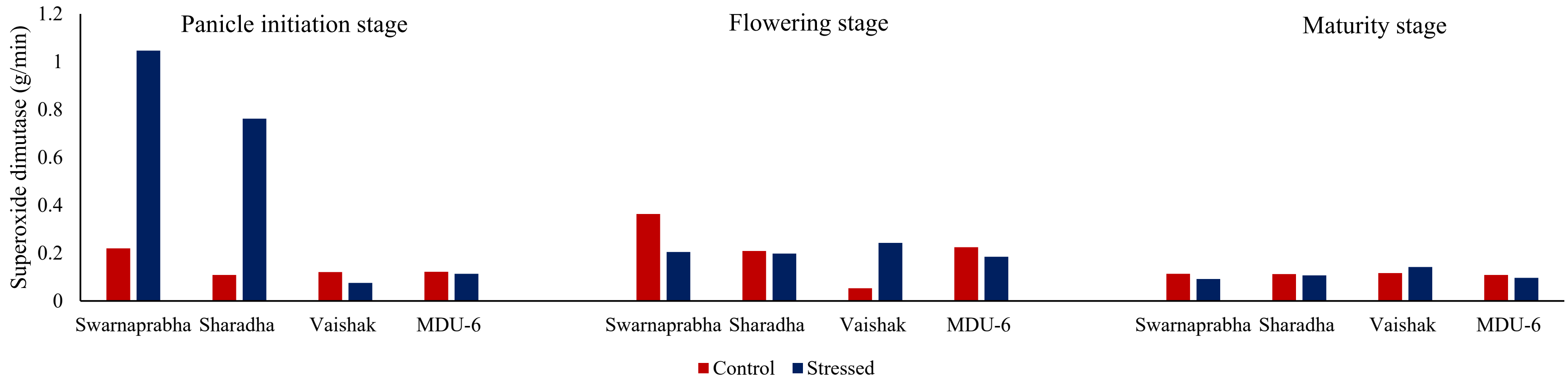


Fig 31. Effect of high temperature on superoxide dismutase (g/min) of aerobic rice varieties

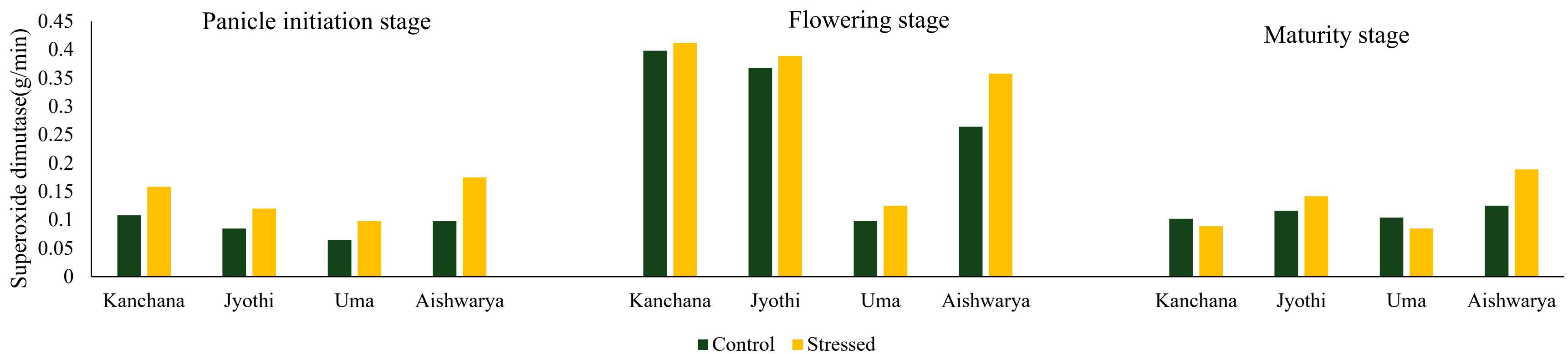


Fig 32. Effect of high temperature stress on superoxide dismutase (g/min) of wetland rice varieties

Table 87. Correlation coefficient between grain yield and physiological parameters at flowering stage of aerobic rice varieties under high temperature stress

	Yield	Chl	RWC	MSI	MDA	SP	Nrase	Proline	SOD	PR	SC	TR
Chl	0.106											
RWC	-0.038	0.196										
MSI	0.219	-0.171	**0.604****									
MDA	-0.059	-0.382	-0.031	**0.464***								
SP	**0.410***	**0.819****	-0.188	-0.335	**-0.560****							
Nrase	0.271	**0.647****	-0.070	**-0.483***	**-0.876****	**0.865****						
Proline	**-0.727****	0.071^{NS}	**0.525****	0.088	-0.074	-0.344	-0.150					
SOD	-0.309	**0.516****	-0.092	**-0.592****	**-0.421***	0.343	0.374	0.309				
PR	0.351	**0.607****	0.218	0.395	-0.031	**0.582****	0.287	-0.221	-0.012			
SC	0.120	0.206	**0.448***	**0.762****	**0.643****	-0.112	**-0.476***	-0.002	-0.310	**0.616****		
TR	0.309	**0.783****	0.237	0.106	**-0.422***	**0.791****	**0.655****	-0.154	0.136	**0.889****	0.304	
CATD	**0.628****	**0.529****	**0.428***	0.206	**-0.564****	**0.624****	**0.665****	-0.217	0.004	**0.441***	0.034	**0.621****

Chl – Chlorophyll content
SP - Soluble protein
Nrase - Nitrate reductase
PR - Photosynthetic rate
SC - Stomatal conductance
TR - Transpiration rate

*- Significant at 1 per cent level ** - Significant at 5 per cent level

Table 88. Correlation coefficient between grain yield and physiological parameters at flowering stage of wetland rice varieties under high temperature stress

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
X2	**0.638****											
X3	-0.141	**0.524****										
X4	**0.843****	**0.648****	-0.280									
X5	**-0.462***	**-0.684****	-0.329	**-0.512***								
X6	-0.27	0.189	**0.741****	**-0.430***	0.136							
X7	0.222	**0.707****	**0.759****	0.157	**-0.780****	0.264						
X8	**-0.608****	**-0.419***	0.278	**-0.662****	0.257	0.081	0.101					
X9	-0.305	0.051	**0.486***	-0.321	-0.448*	-0.049	**0.608****	**0.707****				
X10	0.346	**0.826****	**0.738****	0.298	**-0.651****	**0.556****	**0.787****	-0.209	0.191			
X11	0.064	**0.686****	**0.948****	-0.049	**-0.568****	**0.605****	**0.871****	0.086	**0.458***	**0.826****		
X12	0.392	**0.857****	**0.709****	0.318	**-0.525****	**0.580****	**0.653****	**-0.463***	-0.064	**0.857****	**0.817****	
X13	**-0.416***	-0.040	**0.565****	**-0.574****	0.383	**0.753****	-0.028	0.111	-0.122	0.112	**0.434***	0.379

Chl – Chlorophyll content
SP - Soluble protein
Nrase - Nitrate reductase
PR - Photosynthetic rate
SC - Stomatal conductance
TR - Transpiration rate

*- Significant at 1 per cent level ** - Significant at 5 per cent level

content whereas negatively correlated with MSI and MDA content (Table 87 and 88; Fig 31 and 32). Almeselmani *et al*. (2006) found a significant increase in SOD activity at late and very late plantings in all genotypes of rice, however genotypes like HD 2815 and HDR 77 showed increase in SOD activity over other genotypes. The varietal variations in SOD activity was also reported by Sailaja *et al*. (2015) who found increased SOD activity in rice varieties BPT5204, IR64, Jaya, N22, Rasi, and Vandana, whereas a decrease in Krishna Hamsa, Sampada, and Swarna at vegetative and reproductive phases during elevated temperature of 5.5°C above maximum temperature. Zhao *et al*. (2017) have also reported variations in SOD activity with high temperature and significant differences among rice cultivars.

l. Canopy air temperature difference (CATD)

Canopy temperature can be used as a sensitive indicator of stress, which is associated with stomatal conductance. Garrity and O'Toole (1995) reported that it is possible to screen varieties of rice for reproductive-stage drought-avoidance traits, using canopy temperature and concluded that tolerant lines remained the coolest under stress. Rice plants exposed to high temperature stress registered decreased CATD value compared to plants grown under ambient condition at all growth stages. The value ranges from 1.48 to 0.81. The decrease in CATD is due to increase in canopy temperature under high temperature stress. Decrease in stomatal conductance under heat stress was responsible for the increase in leaf temperature. Tolerance of plants to heat stress depends on the maintenance of leaf temperature. Canopy temperature was also high under high temperature condition than ambient condition and it increased from 0.59 to 11.72 per cent (Beena *et al*., 2018). In the present study also high canopy temperature was observed in all varieties under high temperature and the increase was in the range of 33 to 37°C.

The highest CATD value was recorded for Sharada and Aiswarya under control, and MDU-6 and Jyothi exposed to high temperature recorded lowest value during PI to flowering. Similarly, Jumiatun *et al*. (2016) reported that high temperature treatment increased leaf temperature by 3-6°C during the exposure at 32.1°C and 33.1°C average daily temperature and the variety Silungonggo showed highest leaf temperature (34.7 °C), whereas IR 64 showed the lowest (33.4 °C). Beena *et al*. (2018) also reported similar findings.

Physiological parameters such as photosynthetic rate, stomatal conductance, transpiration rate, chlorophyll content, relative water content (RWC), soluble protein, nitrate reductase activity, membrane stability index (MSI), proline and superoxide dismutase (SOD) decreased under high temperature whereas increase in malondialdehyde (MDA) content was observed. Most of the physiological parameters showed higher values during PI stage. This could be attributed to the utilization of photosynthates for the development of sink at this stages (early reproductive stages) and at later phase physiological parameters showed lower values.

Among aerobic rice varieties, Vaishakh showed higher RWC, transpiration rate, total chlorophyll content, soluble protein, CATD and SOD activity when exposed to high temperature stress from tillering to PI stage (Table 87 and 88). Swarnaprabha registered higher values of stomatal conductance, photosynthetic rate, chlorophyll content, MSI, proline content, SOD activity, soluble protein and nitrate reductase activity under heat stress from tillering to PI stage. The variety MDU-6 exposed to high temperature stress from tillering to PI stage recorded higher values of RWC, transpiration rate, MDA, and stomatal conductance. The variety Sharada showed lowest value in RWC, photosynthetic rate, transpiration rate, soluble protein and MDA content when exposed to high temperature stress from tillering to PI stage.

Among wetland rice varieties, Kanchana showed higher RWC, photosynthetic rate, transpiration rate, total chlorophyll content, soluble protein, nitrate reductase, MDA, SOD, and proline content when plants exposed to high temperature stress from tillering to PI stage (Table 89 and 90). The variety Aiswarya exposed to high temperature stress from tillering to PI stage recorded higher values of transpiration rate, chlorophyll content, soluble protein, MSI, SOD, and CATD. The varieties Uma and Jyothi showed lower values in physiological parameters at early stages.

5.1.3 Plant Uptake of Nitrogen, Phosphorus and Potassium

Plants exposed to high temperature stress from tillering to PI stage recorded the highest total N, P and K uptake in both aerobic and wetland rice varieties compared

Table 89. Rice varieties with higher physiological and biochemical parameters under high temperature

Stages of stress	Parameters				
	RWC	Stomatal conductance	Photosynthetic rate	Transpiration rate	Chlorophyll content
Stress at tillering to PI	MDU-6 Vaishakh Jyothi Kanchana	Swarnaprabha Jyothi	Swarnaprabha Kanchana	MDU-6 Vaishakh Kanchana Aiswarya	Swarnaprabha Vaishakh Kanchana Aiswarya
Stress at PI to flowering	Sharada MDU-6 Kanchana	Swarnaprabha MDU-6 Kanchana Jyothi	Swarnaprabha Sharada Kanchana Aiswarya	Sharada Kanchana	Swarnaprabha Aiswarya
Stress at flowering to maturiy	Swarnaprabha Kanchana Aiswarya	Swarnaprabha MDU-6 Kanchana	Swarnaprabha Kanchana Aiswarya	MDU-6 Vaishakh Kanchana	Sharada Kanchana

Table 90. Rice varieties with better physiological and biochemical parameters under high temperature

Stages of stress	Parameters					
	Soluble protein	Nitrate reductase	MDA	MSI	Proline	SOD
Stress at tillering to PI	Vaishakh Kanchana Aiswarya	Sharada Kanchana	MDU-6 Kanchana	Swarnaprabha Aiswarya	Swarnaprabha Kanchana	Swarnaprabha Aiswarya
Stress at PI to flowering	Swarnaprabha Kanchana	Sharada Swarnaprabha Kanchana	Sharada Aiswarya	Swarnaprabha Sharada Vaishakh Aiswarya	MDU-6 Jyothi	Vaishakh Kanchana Jyothi
Stress at flowering to maturiy	Swarnaprabha Kanchana	MDU-6 Aiswarya Jyothi Kanchana	MDU-6 Aiswarya	MDU-6 Sharada Jyothi	Vaishakh Jyothi	Vaishakh Aiswarya

to stress at remaining stages. In aerobic varieties, increase in N, P and K uptake (17, 7 and 17 %) was observed when plants were exposed to high temperature from tillering to PI stage as compared to control. The higher N, P and K uptake was due to higher dry matter produced when temperature stress was imposed at this stage. Chen *et al.* (2013) found enhanced N uptake, increased soluble protein and carbohydrate content in rice at the vegetative stage under high night temperature.

The highest total N and K uptake were observed in Vaishakh and Aiswarya exposed to high temperature stress from tillering to PI stage. Whereas, the variety MDU-6 under control and Kanchana exposed to high temperature stress from PI to flowering registered higher total P uptake. Similar trend was observed in their dry matter accumulation also. Ercoli *et al.* (1996) also studied the effect of different temperature regimes (at 21, 24, 27 and 30°C) in nutrient uptake by sorghum and the results showed that N and P content in different plant parts were higher at 27°C compared to 21°C.

5.1.4 Grain protein content

In general cereal grains are low in protein. However rice protein is considered as most nutritious compared to other cereals, as it is relatively rich in lysine, the limiting aminoacid in cereals. It is reported that several factors influence the grain protein content of which environmental condition is an important one (Datta, 1981). Lower protein content was observed when stress was imposed from flowering to maturity in both aerobic and wetland rice varieties. This could be due to the effect of high temperature on various physiological mechanisms inside the plant at this stage which adversely affected protein content.

The varieties MDU-6 and Aiswarya exposed to high temperature stress from tillering to PI stage registered higher grain protein content because at grain filling stage they were at ambient temperature. Grain protein content of wheat increased with heat stress, the greatest effect was observed when stress was imposed early in grain filling (Castro *et al.*, 2007). Lower grain protein content was noticed for Swarnaprabha and Jyothi exposed to high temperature stress from flowering to maturity among different rice varieties. This showed the sensitivity of these two varieties. Samol *et al.* (2015)

reported that grain protein content in rice was decreased under elevated temperature (1.85°C higher than ambient) than ambient temperature.

5.1.5 Heat units

The heat units accumulated over the growing season for a particular crop is defined as Growing Degree Days. The maturity can be assesed based on heat units accumulated. The heat units requirement for crop growth was lower (1930.07 and 1869.91°C day) when high temperature stress was imposed from tillering to PI stage compared to stress at remaining growth stages for both aerobic and wetland rice varieties. This might be due to early maturity of crop under high temperature stress imposed at this stage. High temperature imposed at later stages (flowering to maturity) requires more GDD to complete the crop growth and this resulted in longer duration for the crop to attain maturity. The varieties MDU-6, Kanchana and Jyothi exposed to high temperature stress from tillering to PI stage recorded lowest GDD (1802.38 and 1806.85) compared to stress at remaining stages, whereas Vaishakh and Aiswarya exposed to high temperature stress from flowering to maturity stage recorded highest GDD value. This was due to variation in their crop growth period.

Similarly the HTU and PTU requirements which are functions of GDD, actual and maximum possible sunshine hours were also lowest when high temperature stress was imposed from tillering to PI stage (16321, 15873 and 22478, 21761 day °C h) compared to stress at remaining stages in both aerobic and wetland varieties. A trend similar to GDD was observed in HTU and PTU.

The HUE, which is a function of dry matter production and GDD, was lowest in control and high temperature induced during maturity phase indicating the less efficient utilization of radiation parameters at these stages to produce unit dry matter resulting in extension of duration. The HUE was highest when plant exposed to high temperature stress from tillering to PI stage which implies efficient utilization of the radiation for dry matter production and this in turn resulted in shortest duration of the crop. The same trend of GDD was followed in HUE also and the value ranged from 0.26 to 0.37 g/ m^2 °C day.

High temperature during vegetative phase enhanced the growth characters in all varieties. Among rice varieties, Vaishakh and Aiswarya exposed to stress from tillering to PI stage showed increased plant height, tiller number, leaf area and dry matter production compared to stress at other stages and control. It was found that in varieties Sharada and Aiswarya comparable number of productive tillers was seen when stress was induced at various growth phase compared to control. The highest reduction in filled grains per panicle was observed when high temperature stress was imposed from flowering to maturity. At this stage the variety Vaishakh and Aiswarya produced higher number of filled grains per panicle. High temperature at flowering to maturity period also lead to reduction in 1000 grain weight in all varieties and least reduction in 1000 grain weight was observed in Vaishakh and Aiswarya. High temperature stress from flowering to maturity caused yield reduction in all varieties. However, the variety Vaishakh and Aiswarya produced higher grain yield compared to other varieties when stress imposed at this sensitive stage.

The variety Vaishakh and Aiswarya showed high values of transpiration rate, soluble protein, nitrate reductase activity, SOD and canopy air temperature difference under high temperature compared to other varieties, which shows their tolerance to high temperature. The higher proline content was observed for Swarnaprabha, Vaishakh and Kanchana exposed to high temperature among aerobic and wetland varieties. Heat units such as GDD, HTU, PTU and HUE was not significantly influenced by high temperature stress under different stages and control.

5.2 EFFECT OF NITROGEN AND POTASSIUM NUTRITION ON MITIGATION OF TEMPERATURE STRESS (EXPERIMENT III)

5.2.1 Growth parameters

The objective was to assess the influence of N and K levels on mitigating terminal heat stress in rice. Stress was imposed uniformly to all treatments during flowering to maturity period. As stress was not imposed during seedling to flowering stage, there was no ‘control’ treatment with respect to temperature stress. The effect of N and K levels on growth and DMP is discussed.

a. Plant height

The variety Vaishakh was taller than Aiswarya. In both varieties, height increased with increase in levels of N and K. Taller plants were observed with the application of 120 : 60 kg N:K_2O/ha followed by 90 : 45 kg NK/ha. The increase in plant height with increased N application irrespective of variety is primarily due to enhanced vegetative growth with more nitrogen and potassium supply to plant. This might have favourably influenced various physiological processes including cell division and cell elongation. Mini (2005) concluded that significant increase in growth characters of upland rice was obtained by application of 100 kg N/ha and 50 kg K_2O/ha. Similar results were reported by many workers in various systems of rice culture.

b. Number of tillers per hill

Tiller number also increased with increase in N and K levels at all growth stages. At 60 DAS and at harvest, the highest tiller number per hill was registered by application of 120 kg N and 60 kg K_2O in Aiswarya (15.13 and 13.50) which was significantly higher than N and K applied at lower levels. A reduction in tiller number was observed in both varieties by harvest stage at all nutrient levels. Ntanson and Koutroubas (2002) attributed increase in length of flag leaves and number of tillers with increasing N and K amounts to the influence of N on leaf development, tiller production and increasing leaf photosynthetic activity The combined application of nitrogen and potassium at 80 kg/ha and 20 kg/ha produced the highest number of total tillers, which was found statistically identical to those produced at NK level of 60:40 kg/ha (Uddin *et al.*, 2013). Also Shahanila (2015) registered highest number of tillers (17.00) in aerobic rice with application of 90 kg N and 45 kg K_2O/ha compared to 60 kg N and 30 kg K_2O. Similar trend is reported in many studies.

c. Leaf Area Index (LAI)

Application of 120 kg N and 60 kg K_2O in Vaishakh resulted in highest LAI value of 5.68 which was comparable with Aiswarya with same NK dose (5.44) and Vaishakh applied with 90 kg N and 45 kg K_2O. This might be due to increased number of tillers which resulted in more leaves high N and K levels. In several experiments it was observed that nitrogen affects gibberellin hormone indirectly through cytokinin and increases the growth of young leaves and the terminal branches (Marschner, 2011). At higher levels of nitrogen LAI decline was slower and it can be attributed to the positive effect of nitrogen on vegetative growth and increase in leaf photosynthetic activity (Fageria, 2007). In the present study, increase in LAI was higher in application of 120 kg N and 60 kg K_2O/ha by 25 per cent in Vaishakh and Aiswarya followed by N and K applied at 90 and 45 kg/ha (12.5 and 14 % in Vaishakh and Aiswarya). Mini (2005) also reported the highest LAI with higher fertilizer dose of 100:75 N: K_2O kg/ha in upland rice.

d. Dry matter production

Dry matter production increased with increase in N and K levels. This resulted from increased plant height and tiller production at high fertilizer doses. The highest DMP was produced by application of 120 kg N and 60 kg K_2O in Vaishakh (42.95 g/hill) compared to lower N and K levels. Dry matter production increased by 32 and 25 per cent with application of 120 kg N and 60 kg K_2O in Vaishakh and Aiswarya followed by N and K applied at 90:45 kg/ha (8%) compared to its lower N and K dose (Fig 33). This is in corroboration with findings of Luka *et al.* (2013) who reported higher DMP in rice by combined application of N and K at 130 kg/ha and 50 kg/ha. Seema (2014) also reported higher DMP at 125 kg N/ha and 40 kg K_2O/ha in aerobic rice. Under elevated temperature condition, translocation of photosynthates and nitrogen from shoot to grain was impaired but additional N dose (160 kg N and 60 kg K/ha) could compensate it to some extent (Raj and Chakrabarti, 2016).

5.2.2 Biochemical parameters

a. Relative water content

Significantly higher relative water content was observed in variety Aiswarya with 90 kg N and 45 kg K_2O/ha. Lower values were observed at lower dose of 60 N and 30 kg K_2O/ha applied to Vaishakh. The impact of nitrogen on RWC is well established. Combined application of N and K had improved the relative water content

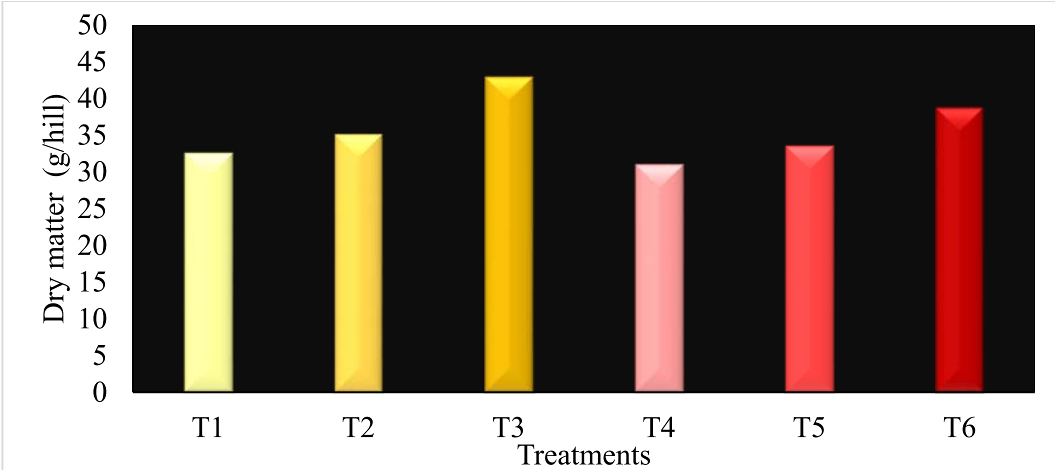


Fig 33. Effect of N and K nutrition on DMP of rice under high temperature stress

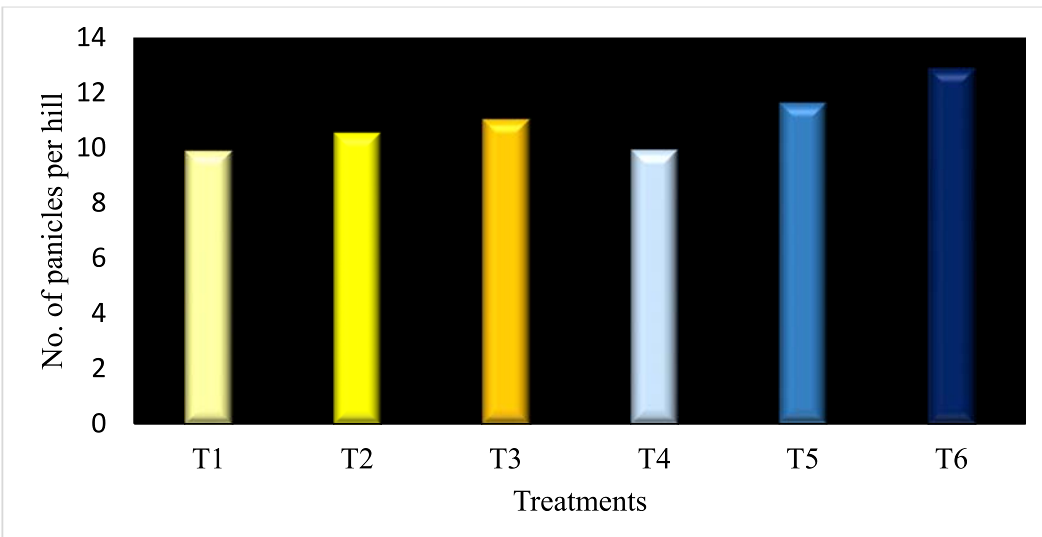


Fig 34.Effect of N and K nutrition on number of panicles per hill in rice under high temperature stress

T1: Vaishak applied with 60: 30 N:K_2O kg/ha

T2: Vaishak applied with 90: 45 N:K_2O kg/ha

T3: Vaishak applied with 120: 60 N:K_2O kg/ha

T4: Aishwarya applied with 60: 30 N:K_2O kg/ha

T5: Aishwarya applied with 90: 45 N:K_2O kg/ha

T6: Aishwarya applied with 120: 60 N:K_2O kg/ha as per findings of Ranjini (2002) and Kumar (2016). This may be due to the role of these two nutrients in physiological processes.

b. Total chlorophyll content

High temperature stress decreased chlorophyll content in rice especially when plants were exposed to stress from flowering to maturity. During stress period, the highest chlorophyll content was observed in treatments including application of 120 kg N and 60 kg K_2O in Aiswarya and Vaishakh compared to lower levels of N and K. The leaf photosynthetic rate mainly depends on leaf N status irrespective of genotype and fertilizer dose applied. The increase in total chlorophyll content in the leaves can be attributed to higher N K fertilization. Effect of nitrogen fertilization on chlorophyll content in plants is well established. According to Skwaryeo-Bednarz and Krzepieko (2009), the greater amount of NPK fertilizers is accompanied by the higher total chlorophyll content in plant material. Hou *et al*. (2019) found that leaf chlorophyll content in rice was significantly increased by 15.5 per cent with 180 kg N/ha.

c. Membrane stability index

Cell membrane stability is a physiological index widely used for evaluation of stress tolerance. High temperature results in melting the lipid bilayer, increasing membrane permeability, and increasing leakage of ions and other cellular compounds from the cell thereby affecting all other metabolic activities. Under high temperature stress, plant molecular O_2 is activated and reactive oxygen species (ROS) production is increased within the plant cell, which causes the degradation of the photosynthetic pigment and cellular membranes. Maintaining proper membrane stability is essential for temperature stress tolerance. Membrane stability index value reduced under high temperature stress compared to control in both rice varieties. Application of 120 kg N and 60 kg K/ha maintained high membrane stability index in Vaishakh and Aiswarya compared to lower levels of N and K (60:30, N:K kg/ha). During stress, higher MSI value was registered for plants applied with 120 kg N and 60 kg K/ha compared to lower NK levels. This indicate that application of potassium could decrease ROS formation by maintaining the plant photosynthetic electron transport and diminishing the action of NADPH oxidase. Sangakkara *et al*. (2000) found a positive role for K by reducing ROS formation and increasing the net photosynthesis rate under water-stressed conditions and maintaining higher turgor potential and maintaining lower osmotic potential in pulses.

d. Photosynthetic rate

The photosynthetic rate increased with increase in N and K levels. Application of 120 kg N and 60 K_2Okg/ha recorded highest photosynthetic rate in both Vaishakh and Aiswarya.

Application of 180 kg N and 120 kg K/ha significantly increased the photosynthetic rate by 17 per cent compared without N and K. It has been reported that application of 270 kg N and 180 kg K_2O/ha increased rice photosynthetic rate by 33 per cent (Hou *et al*., 2019). Increased application of potassium has been shown to enhance photosynthetic rate, plant growth, yield and drought resistance in different crops under water stress conditions. Similarly, Pier and Berkowitz, (1987) observed higher photosynthetic rates in wheat plants fertilized with above normal potassium than those under standard fertilization, indicating the positive effect of very high internal potassium levels under abiotic stress.

e. Stomatal conductance

Stomata control water loss from the plant via transpiration and it is also involved in gaseous exchange. A trend similar to that of photosynthetic rate was followed for stomatal conductance. The stomatal conductance value increased with increase in N and K level in both varieties and values ranged from 0.146 to 0.695 mol $H_2O/m^2/s$.

Potassium plays an important role in stomatal regulation and under K deficiency, the stomata cannot function properly and water losses from plant may reach damaging levels (Gething, 1990). In barley plants exposed to hot winds, an immediate increase in transpiration rate was caused, which was more severe in potassium deficient plants which took long time to react by closing stomata, while the potassium supplied plants responded quickly in closing stomata and preserving internal moisture. The stomata close in response to water stress, thereby reducing carboxylation efficiency of the chloroplasts.

f. Canopy air temperature difference (CATD)

Canopy air temperature difference increased with increase in N and K level. Higher increase in CATD (55% and 32%) was observed with application of 120 kg N and 60 kg K/ha compared to lower dose (60:30 N:K kg/ha) in both Vaishakh and Aiswarya. The increased value at high NK level indicated decrease in leaf temperature compared to lower doses. This decrease in leaf temperature might be due to increased LAI at higher NK levels which helped in transpirational cooling. Batts *et al.* (1998) observed the use of nitrogenous fertilizers in heat tolerant variety as a very effective way to decrease heat damage through lowering the canopy temperature by enhancing transpiration.

5.2.3 Yield attributes and yield

a. Number of panicles per hill

Similar trend of tiller number was followed in number of productive tillers also. Application of 120 kg N and 60 kg K_2O increased panicle number by 30 per cent in Aiswarya whereas only by 11.6 per cent Vaishakh compared to recommended dose of 60:30 N:K_2O kg/ha (Fig 34). A trend similar to that of plants exposed to high temperature stress was observed under control with respect to number of panicles per hill. This resulted from increased tiller number under high N and K levels as nitrogen favoured good vegetative growth of plants. Similarly, Arivazhagan and Ravichandran (2005) reported that application of 150:75 kg NK/ha produced the highest number of panicles/hill. These results are in line with those reported by Shahanila (2005) and Kumar (2016). It is clear that in plants subjected to stress, additional N and K supply was beneficial with respect to production of more number of panicles.

b. Number of filled grains per panicle

Higher number of filled grains per panicle were produced by application of 120 kg N and 60 kg K_2O in Vaishakh and Aiswarya. Application of recommended dose of N and K (60 and 30 kg N and K_2O/ha) recorded highest chaff per cent in both varieties (17.53 % in Aiswarya and 13.49 % in Vaishakh). The chaff per cent reduced with increase in fertilizer levels. The least chaff per cent (8 and 10%) was observed with higher N and K levels (120:60 kg N and K_2O/ha) in both varieties (Fig 35). Under control, application of recommended dose of N and K (60 and 30 kg N and K_2O/ha) recorded highest chaff per cent in Aiswarya (15.35%) and Vaishakh (10.51%) but they were lesser than plants exposed to high temperature stress. The results indicated that application of low dose of N and K did not satisfy the nutrient need of the crop particularly during the grain filling period resulting in lower number of filled grains/panicle. Also, lower levels of N and K coupled with high temperature during the flowering stage in the present study resulted in decreased number of filled grains per panicle. Krishnappa *et al.* (2006) reported that basal application of K showed positive effect on the percentage of filled grains. Potassium helped in proper filling of seeds which resulted higher 1000 grain weight. Esfehani *et al.* (2005) showed that potassium fertilizer has positive effect on filled grains in rice while its deficiency caused pollen sterility and decreased the number of filled grains per panicle. Generally low response to applied nutrients is reported in upland rice compared to wetland rice. However, positive influence of higher nutrient levels could be observed especially under temperature stress condition.

c. Total number of grains per panicle

The total number of grains per panicle was higher for Vaishakh and Aiswarya applied with 120:60 kg N:K_2O kg/ha (104.70 and 103.30) whereas lower number was observed under low N and K levels (60:30 kg/ha) which might be due to lower nutrition combined with high temperature stress. The increase in total number of grains at 120:60 kg/ha N:K_2O kg/ha was by 14 and 10 per cent in Aiswarya and Vaishakh compared to its lower dose (60:30 N and K kg/ha) under high temperature stress (Fig 35). A trend similar to that under high temperature stress was observed in control also with respect to total number of grains (Table 80). Similar findings have been reported by Bhowmick and Nayak (2000), Nawaz (2002), Namba (2005). The more number of grains per panicle obtained under higher nitrogen rates were probably due to better nitrogen status of plant during panicle growth period. Reduction in spikelet number in rice is attributed to a number of factors by many workers. Monjardino *et al.* (2006) found that potassium application could increase grain number per cob in maize by improving pollen viability through mitigating the adverse effects of high temperature.

d. Panicle length

Panicle length was not influenced by different NK levels, but varied with variety. Panicle length is mainly a varietal character and not much influenced by management practices. The longest panicles were produced by application of 120 kg N and 60 kg K_2O in Vaishakh and Aiswarya compared to lower NK levels. However, it is reported that nitrogen takes part in panicle formation as well as panicle elongation and for this reason, panicle length increased with the increase of N-fertilization. Similar results were obtained by Kumar (2016).

e. Thousand grain weight

A test weight of 28.94 g was recorded with application of 120 kg N and 60 kg K_2O in Vaishakh whereas the lowest thousand grain weight (26.67 g) was observed in Aiswarya applied with 60 kg N and 30 kg K_2O (Table 79). However, 1000 grain weight was not significantly influenced by N and K levels under high temperature condition as well as under control. Previously, Zinselmeier *et al.* (1999) reported that grain weight was most sensitive to abiotic stress during grain formation by limiting assimilates flow toward developing grain. However, potassium application improved grain weight in this experiment probably through mitigating adverse effect of high temperature. These results are supported by those of Mengal and Kirkby (1987), Cheema *et al*. (1999) in maize and Sharma *et al*. (2008) in wheat who reported that potassium resulted to increase in kernel weight through regulating enzymatic activities and translocation of photosynthates.

f. Grain yield

The results indicate that N and K nutrition can help to mitigate the elevated temperature stress in aerobic rice cultivation. Also the response of both the varieties to higher N and K levels indicate the need for application of more N and K fertilizers in summer season under irrigated condition.

Application of 120 kg N and 60 kg K_2O/ha increased grain yield by 31 and 34 per cent in Aiswarya and Vaishakh when compared with 60:30 kg N: K_2O/ha under

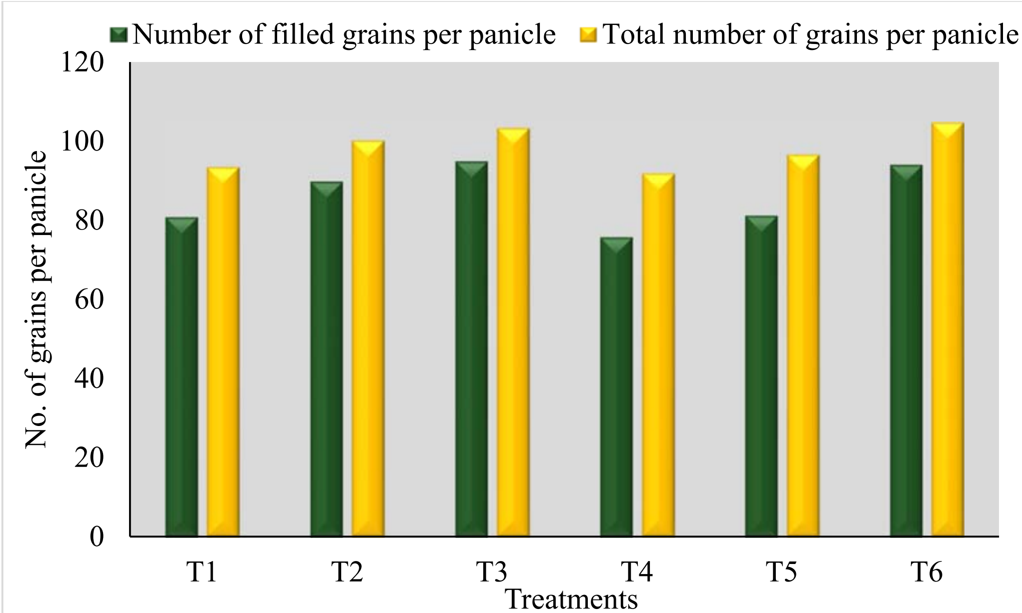


Fig 35. Effect of N and K nutrition on number of filled and total grains per panicle in rice under high temperature stress

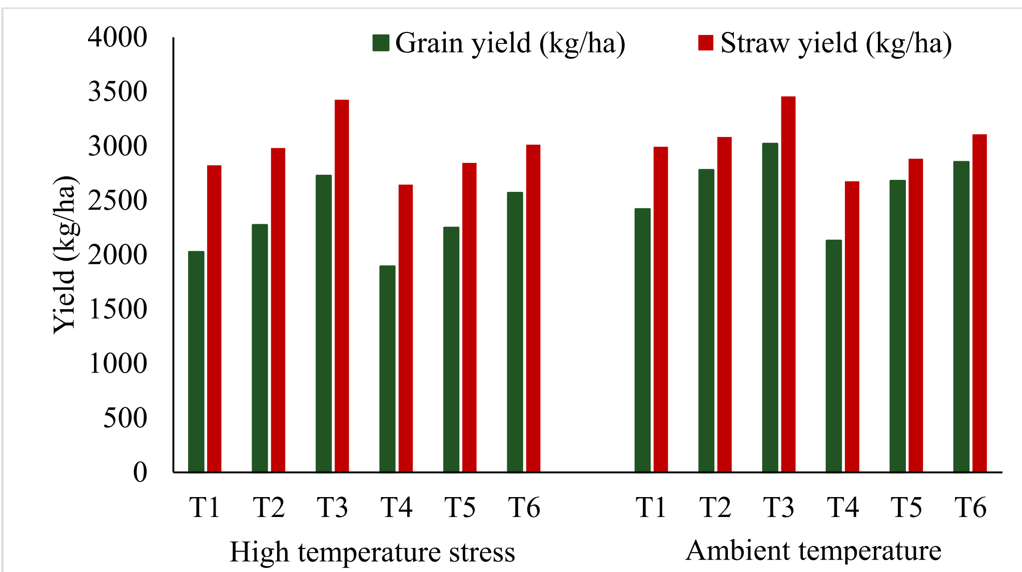


Fig 36. Effect of N and K nutrition on grain and straw yield in rice under high temperature stress

T1: Vaishak applied with 60: 30 N:K_2O kg/ha

T2: Vaishak applied with 90: 45 N:K_2O kg/ha

T3: Vaishak applied with 120: 60 N:K_2O kg/ha

T4: Aishwarya applied with 60: 30 N:K_2O kg/ha

T5: Aishwarya applied with 90: 45 N:K_2O kg/ha

T6: Aishwarya applied with 120: 60 N:K_2O

heat stress condition (Fig 36). The corresponding increase was about 20 per cent with application of 90 kg N and 45 kg K_2O/ha.

Similar to this under ambient condition also response to higher N and K levels could be observed but varietal response was different. Compared to recommended dose the grain yield increased by 25% in Vaisakh and 34% in Aiswarya. However the yield of Vaisakh was higher compared to Aiswarya at all levels of N and K. It can be seen that application of 90:45 kg N: K_2O/ha increased grain yield by 22 and 19 per cent in Vaishakh and Aiswarya than its high temperature stress condition. The percentage increase in yield at higher level (120:60 N:K kg/ha) was less (about 11 % in both varieties).

Increase in N and K levels resulted in increase in physiological parameters such as RWC, chlorophyll content, MSI, photosynthetic rate and stomatal conductance in both varieties Vaishakh and Aiswarya. This increase in physiological parameters might have contributed to increase in grain yield at higher N and K levels. The variety Vaishakh showed higher values of physiological parameters compared to Aiswarya at all N and K levels. This indicates the adaptability of Vaisakh under high temperature condition with increase in N and K levels. The adaptability of varieties Vaishakh and Aiswarya evident from the higher values under high temperature stress at flowering stage such as RWC (76.96 and 73.54 %), chlorophyll content (1.92 and 2.38 mg/g), MSI (77.03 and 52.61 %), photosynthetic rate (0.40 and 1.10 µ mol/m^2/s) and stomatal conductance (0.153 and 0.163 m mol H_2O /m^2/s) compared to other varieties.

Modhej *et al*. (2008) have reported grain yield reduction of 44 per cent in wheat at 50 kg N/ha and 26 per cent at 100 kg N/ha when compared with 150 kg N/ha under heat stress condition due to reduction in number of grains and 1000 grain weight. They also reported difference in varietal sensitivity and found that the number of spikelets, seed set and seed weight were inversely related to and mainly a function of temperature. High temperature was detrimental to several yield components which were alleviated by high rate of NO_3^- fertilizer (Campbell and Davidson, 1979). Liu *et al*. (2019) concluded that higher N levels increased the total number of spikelets per panicle and reduced the number of degenerated spikelets under high temperature, which alleviated yield loss in rice during flowering stage. Similarly, with increment of nitrogen fertilizer, grain yield increased relatively, but further increase in nitrogen level produced higher straw yield that ultimately gave the lower harvest index.

g. Straw yield

In aerobic soil conditions higher doses of N and K resulted in higher straw yield also. The highest straw yield of 3426 kg/ha was registered for Vaishakh applied with 120 kg N and 60 kg K_2O which was superior to all treatments and the increase in straw yield was 21 per cent in Vaishakh and 14 per cent in Aiswarya (Fig 36). It is established that nitrogen application can enhance straw yield by increasing tiller number and plant height. Rahman *et al*. (2007) also showed that higher straw yield (6.98 t/ha) was obtained with the highest dose of N level (46 kg N/ha). More straw yield indicates capability of rice to utilize more N through better growth and accumulation of more dry matter. In upland rice, the straw yield increased with increase in NK levels and the highest straw yield of 3.62 t/ha was obtained at 90:45 kg nitrogen and potassium per ha (Shahanila, 2005).

h. Harvest Index

Higher N and K level did not influence harvest index of both the varieties. However, application of 120 kg N and 60 kg K registered higher HI compared to lower levels of N and K. The highest HI might be due to increase in number of filled grains per panicle, and 1000 grain weight which improved grain yield compared to lower doses of N and K.

5.2.4 Plant analysis

a. Uptake of Nitrogen, Phosphorus and Potassium

Application of 120 kg N and 60 kg K_2O resulted in higher N, P and K uptake which was higher than recommended dose of fertilizer (60: 30 kg N: K_2O /ha) (Table 82). Application of fertilizers can enhance root development which in turn will help in higher nutrient uptake and leaf area development which can contribute to yield. Increased nutrient uptake resulted from higher DMP. The uptake of nutrients increased with increase in levels of N and K.

b. Grain protein content

No significant increase in grain protein content in rice was observed with increase in N and K nutrition and values ranged from 4.74 to 5.63 per cent (Table 83). Grain protein content increased with increase in N and K levels. This might be due to increased nitrogen assimilation (protein synthesis) in plants because nitrogen is a major component. However contradictory to this increase in protein content at higher nitrogen levels was reported by Rao *et al.* (2014). Potassium is also involved in the formation of proteins through polymerisation of amino acids. Increase in grain protein content at higher doses of N and K was reported by Ranjini (2002) and Mini (2005).

5.2.5 Heat use efficiency

Application of 120 kg N and 60 kg K_2O to Vaishakh recorded the highest HUE of 0.26 g/m^2 °C day which was superior to all other treatments (Table 83). This might be due to efficient utilization of solar radiation resulted in higher dry matter production with increase in N and K levels. The HUE was lowest when 60 kg N and 30 kg K_2O applied to both varieties indicating that less efficient utilization of radiation parameters by rice to produce unit dry matter.

5.2.5 Available N, P and K status of soil

Available nutrient status of soil increased with increase in N and K levels. The highest available N,P and K was observed with application of 120 kg N and 60 kg K_2O/ha compared to lower NK levels (60:30 kg/ha). The increase in soil nutrient status is due to the residual effect of higher quantity of fertilizer applied and many studies has established that higher dose can leave more residues as plants may not utilize the nutrients efficiently. Rao *et al.* (2014) and Suri and Choudary (2014) reported that NK applied at 90 and 45 kg/ha respectively increased the available nutrient status of the soil after the experiment.

5.2.6 Economics of cultivation

The study shows the possibility of increasing net income from aerobic rice cultivation by fertilizer management both under temperature stress and ambient temperature condition. As there is a progressive increase in grain yield and straw yield, increase in gross income, net income as well as BC ratio was observed with increase in N and K fertilizer levels. Also the return was higher with variety Vaishakh compared to Aiswarya due to higher grain and straw yields to this variety.

Under ambient situation, the net return could be increased from ₹. 30865 to ₹. 48032 (₹. 17167/ha increase) by doubling the N and K levels to variety Vaishakh for which the additional cost per hectare was ₹. 1911 per ha. The return was low in variety Aiswarya compared to Vaishakh as yield was low however, the trend in net return and BC ratio was same.

When temperature stress was imposed from flowering to maturity, a general decline in yield resulted decrease in return was observed in both varieties. However, with N and K fertilizer application yield reduction could be mitigated to some extent and gross return and net income could be realized at higher N and K fertilizer levels. A sharp decline in net return was observed at fertilizer rate of 60: 30 in temperature stress compared to control, (Table 85) and ₹. 30865 per ha (in Vaishakh) to ₹. 19867 per ha. At 120.60, the reduction in net return in Vaishakh was from ₹ 48032 per ha to ₹. 40724 per ha. Similar was the trend in variety Aiswarya also, though yield was low compared to Vaishakh.

The return per rupee invested also increased with higher levels of fertilizer application. In both the varieties BC ratio could be increased from 1.35 (recommended dose of N and K) to 1.69 (at double the recommended dose of N and K) in variety Vaishakh which was superior to Aiswarya in yield performance. It is also important to note that under ambient condition BC ratio showed a decreasing trend in both varieties with application of higher levels of N and K whereas BC ratio increased under temperature stress condition.

Summary

6. SUMMARY

A study on management of high temperature stress in aerobic rice was taken up at the Department of Agronomy, College of Horticulture, Vellanikkara with the main objective of assessing the varietal response to high temperature as well as to find out sensitivity of various growth phases of rice to elevated temperature. In two pot culture experiments conducted in the first year of study (Dec 2017- Mar 2018), selected aerobic and wetland rice varieties were exposed to temperature 2-3°C higher than ambient air temperature at different growth phases. A field experiment to study the effect of nitrogen and potassium nutrition in mitigating terminal heat stress was carried out in second year of study during Jan 2019 – April 2019.

Four aerobic rice varieties [Swarnaprabha, Sharada (MAS 946-1), Vaishak and MDU-6] were included in Experiment I and four wetland rice varieties (Kanchana, Jyothi, Uma and Aishwarya) were tested in Experiment II. Temperature stress (2-3°C above ambient) was artificially imposed at three different growth stages of rice *i.e*., from tillering to panicle initiation, panicle initiation to flowering and flowering to maturity. For imposing temperature stress, portable chambers with the dimensions of 2 m x 2 m x 1.5 m with top covered by UV stabilized polythene sheet and sides covered with polythene sheet, were fabricated (Singh, 2010) leaving a gap of 15cm from the ground level at the base for free air passage. Each variety was maintained under ambient condition throughout the crop growth period as control (*i.e*., without stress). The ambient temperature ranged from 26.5°C to 31°C during the experimental period.

High temperature during vegetative phase enhanced the plant growth parameters in all varieties. In both aerobic and wetland rice varieties, the tallest plants at harvest were observed when plants were exposed to stress from tillering to PI and PI to flowering stage. Among varieties Vaishakh and Aiswarya were significantly taller. At peak tillering phase and at harvest, Sharada and Aiswarya exposed to high temperature stress from tillering to PI stage as well as under control produced higher tiller numbers. The varieties Aiswarya and Sharada exposed to high temperature stress from tillering to PI stage had highest leaf area. Early flowering was observed in variety MDU-6 and Kanchana when stress was imposed from tillering to PI (71 and 66.67 days) and PI to

flowering stage (68.33 and 68 days). Late flowering was observed for Vaishakh and Aiswarya under ambient temperature (78.33 days). Among aerobic varieties Swarnaprabha and Vaishakh and among wetland varieties Aiswarya and Uma exposed to high temperature stress from tillering to PI stage registered highest dry matter production. Root growth was also found to be negatively affected by temperature stress. Vaishakh and Aiswarya grown under ambient condition produced highest root dry weight (10.3 g/hill).

All cultivars produced higher number of panicles under ambient temperature compared to heat stressed condition. In varieties Sharada and Aiswarya, tillering was not influenced by temperatures 2-3°C above normal as comparable productive tiller was seen when stress was induced at various growth phases.

Plants grown under ambient condition produced highest number of grains and filled grains per panicle and varieties Vaishakh and Aiswarya were superior. Among varieties, the lower number of filled grains per panicle was noticed in Sharada (73.13) and Jyothi (59.40) exposed to high temperature stress from flowering to maturity among aerobic and wetland rice varieties, respectively. The highest chaff per cent was recorded for Swarnaprabha (27.04%) and Jyothi (24.61%) exposed to high temperature stress from flowering to maturity stage. The highest test weight was registered for Vaishakh under control (28.99 g) and Kanchana under control (27.80 g). In all aerobic and wetland varieties, plants exposed to high temperature stress from flowering to maturity registered lowest 1000 grain weight. Among aerobic and wetland varieties, short duration varieties were found to be more sensitive to temperature stress. In all varieties most sensitive stage was found to be flowering to maturity.

The varieties Vaishakh and Aiswarya produced higher grain yield under high temperature stress at all growth stages and the lowest grain yield was observed in MDU-6 and Jyothi when high temperature stress was imposed from flowering to maturity among aerobic and wetland rice varieties. Temperature stress during vegetative phase resulted in more straw yield and varieties Swarnaprabha and Aiswarya were superior. High temperature stress from flowering to maturity period resulted in lower harvest index also. The highest harvest index was in Sharada and in Aiswarya under control among aerobic and wetland rice varieties.

Physiological parameters such as photosynthetic rate, stomatal conductance, transpiration rate, chlorophyll content, relative water content (RWC), soluble protein, nitrate reductase activity, membrane stability index (MSI), proline and superoxide dismutase (SOD) decreased under high temperature whereas increase in malondialdehyde (MDA) content was observed. Grain yield was positively correlated with chlorophyll content, membrane stability index and soluble protein content, but negatively correlated with MDA and proline content. The varieties Vaishak and Aishwarya showed high values of transpiration rate, soluble protein, nitrate reductase acitivity, SOD and canopy air temperature difference under high temperature compared to other varieties, which points to their tolerance to high temperature. Higher proline content was observed for Swarnaprabha, Vaishak and Kanchana when exposed to high temperature. Variation in heat units like GDD, HTU and PTU were not significant under heat stress compared to control.

The highest total N and K content was observed in Vaishakh and Aiswarya exposed to high temperature stress from tillering to PI stage. Whereas, the variety MDU-6 under control and Kanchana exposed to high temperature stress from PI to flowering registered higher total P uptake.

Grain protein content was also affected by elevated temperature during maturity phase. The varieties MDU-6 and Aiswarya exposed to high temperature stress from tillering to PI stage registered higher grain protein content.

In general GDD, HTU and PTU reduced under elevated temperature condition. The varieties MDU-6, Kanchana and Jyothi exposed to high temperature stress from tillering to PI stage recorded lowest GDD (1802.38 and 1806.85) compared to stress at remaining stages, whereas Vaishakh and Aiswarya exposed to high temperature stress from flowering to maturity stage recorded highest GDD value. A trend similar to GDD was observed in HTU and PTU. The HUE was highest in varieties Swarnaprabha, Kanchana and Aiswarya exposed to high temperature stress from tillering to PI stage.

The third experiment was laid out in randomized block design with six treatments which included two medium duration rice varieties Vaishak and Aishwarya grown with three N and K_2O levels (60:30 kg, 90 :45 kg, 120:60 kg N:K_2O/ha). Phosphorus was applied uniformly @ 30 kg/ha to all treatments basally. High temperature stress was imposed during flowering to maturity period by using portable polythene chamber. The study revealed that increase in N and K levels from 60:30 kg N: K_2O/ha to 120:60 N:K_2O kg/ha resulted in increased growth and yield attributes and grain yield.

Photosynthetic rate, stomatal conductance, CATD, RWC, total chlorophyll content and MSI were high at higher dose of N and K indicating the role of these nutrients in mitigation of temperature stress by favourably influencing physiological mechanism for stress tolerance.

Application of 90 kg N and 45 kg K_2O produced comparable grain yield to that of 120 kg N and 60 kg K_2O/ha in both Vaishak (2485 kg/ha) and Aiswarya (2401 kg/ha) . The increase in grain yield over recommended dose of 60:30 kg N: K_2O/ha was about 20 per cent with application of 90 kg N and 45 kg K_2O.

Application of 120 kg N and 60 kg K_2O resulted in higher N,P and K uptake than recommended dose of fertilizer (60: 30 kg N:K/ha).

Hence it can be inferred that yield reduction due to high temperature stress in aerobic system of rice cultivation can be managed to some extent by nitrogen and potassium nutrition. The net return was also high with application of N: K_2O @ 90:45 kg /ha (₹. 33350 in Vaishakh and ₹. 27974 in Aiswarya) when compared to 60:30 N: K_2O kg/ha.

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Abstract

MANAGEMENT OF HIGH TEMPERATURE STRESS IN AEROBIC RICE
(*Oryza sativa* L.)

By

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ABSTRACT OF THE THESIS

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ABSTRACT

Rice production is subject to many biotic and abiotic stresses of which rise in temperature is a crucial one in the present context of global warming. Hence, a study on management of high temperature stress in aerobic rice was taken up at the Department of Agronomy, College of Horticulture, Vellanikkara with the main objective of assessing the varietal response to high temperature as well as to find out sensitivity of various growth phases of rice to elevated temperature. In two pot culture experiments conducted in the first year of study (Dec 2017- Mar 2018), selected aerobic and wetland rice varieties were exposed to temperature 2-3 °C higher than ambient air temperature at different growth phases. A field experiment to study the effect of nitrogen and potassium nutrition in mitigating high temperature stress was carried out in second year of study during Jan 2019 – April 2019.

Four aerobic rice varieties [Swarnaprabha, Sharada (MAS 946-1), Vaishakh and MDU-6] were included in Experiment I and four wetland rice varieties (Kanchana, Jyothi, Uma and Aiswarya) were tested in Experiment II. Temperature stress (2-3 °C above ambient) was artificially imposed at three different growth stages of rice *i.e.*, from tillering to panicle initiation, panicle initiation to flowering and flowering to maturity. For imposing temperature stress, portable chambers with the dimensions of 2 m x 2 m x 1.5 m with top covered with UV stabilized polythene sheet and sides covered with polythene sheet, were fabricated (Singh, 2010) leaving a gap of 15cm from the ground level at the base for free air passage. Each variety was maintained under ambient condition throughout the crop growth period as control (*i.e.*, without stress).

High temperature during vegetative phase enhanced the growth parameters in all varieties. Among rice varieties, Vaishakhh and Aiswarya exposed to stress from tillering to panicle initiation (PI) showed increased plant height, tiller number, leaf area index and dry matter production compared to stress at other stages and control. Earliness in flowering was observed when stress was imposed from tillering to PI stage in all varieties and they produced higher number of panicles under ambient temperature compared to elevated temperature condition. It was found that in varieties Sharada and Aiswarya, comparable number of productive tillers was seen when stress was imposed at various growth phases compared to plants grown under ambient condition. The highest number of filled grains per panicle in both aerobic and wetland rice varieties were recorded under ambient condition. The highest reduction in filled grains per panicle and 1000 grain weight was observed when high temperature stress was imposed from flowering to maturity and this resulted in grain yield reduction in all the varieties. At this stage the varieties Vaishakh and Aiswarya

produced higher number of filled grains per panicle, indicating varietal suitability to high temperature. These varieties produced higher grain yield compared to other varieties when stress was imposed at this sensitive stage (Vaishakh-13.81g/hill and Aiswarya-13.35g/hill). The performance of these two varieties were superior under ambient condition also.

Physiological parameters such as photosynthetic rate, stomatal conductance, transpiration rate, chlorophyll content, relative water content (RWC), soluble protein, nitrate reductase activity, membrane stability index (MSI), proline and superoxide dismutase (SOD) decreased under high temperature whereas increase in malondialdehyde (MDA) content was observed. Grain yield was positively correlated with chlorophyll content, membrane stability index and soluble protein content, but negatively correlated with MDA and proline content. The varieties Vaishakh and Aiswarya showed high values of transpiration rate, soluble protein, nitrate reductase acitivity, SOD and canopy air temperature difference under high temperature compared to other varieties, which points to their tolerance to high temperature. Higher proline content was observed for Swarnaprabha, Vaishakh and Kanchana when exposed to high temperature. Variation in heat units like GDD, HTU and PTU were not significant under heat stress compared to control.

The third experiment was laid out in randomized block design with six treatments which included two rice varieties Vaishakh and Aiswarya grown with three N and K_2O levels (60:30 kg, 90 :45 kg , 120:60 kg N:K_2O/ha). Phosphorus was applied uniformly @ 30 kg/ha to all treatments basally. High temperature stress was imposed during flowering to maturity period by using portable polythene chamber. The study revealed that increase in N and K levels from 60:30 kg N: K_2O/ha to 120:60 N:K_2O kg /ha resulted in increased growth and yield attributes and grain yield along with a remarkable increase in RWC, chlorophyll content and MSI. Also, application of 90 kg N and 45 kg K_2O produced comparable grain yield to that of 120 kg N and 60 kg K_2O/ha in both Vaishakh (2485 kg/ha) and Aiswarya (2401 kg/ha) . The increase in grain yield over recommended dose of 60:30 kg N: K_2O/ha was about 20 per cent. Hence, it can be inferred that yield reduction due to high temperature stress in aerobic system of rice cultivation can be managed to some extend by nitrogen and potassium nutrition. The net return was also high with application of N: K_2O @ 90:45 kg /ha when compared to 60:30 N: K_2O kg/ha.

Appendices

APPENDICES

Appendix I. Weather parameters during December 2017 to March 2018

Standard weeks	Maximum temperature °C	Minimum temperature °C	Mean RH%	Total rainfall (mm)	Evaporation (mm)	Bright sunshine hours	Wind speed (km/h)
48	32.0	22.5	71	11.5	3.4	4.3	5.0
49	32.8	21.0	73	0.0	2.6	7.3	1.8
50	32.7	21.4	72	0.0	2.5	5.1	1.8
51	32.3	21.5	54	0.0	5.2	9.1	9.2
52	32.8	20.3	52	0.0	5.2	9.4	7.0
1	33.2	19.8	58	0.0	3.8	8.8	3.9
2	32.7	21.8	56	0.0	4.6	7.4	6.7
3	33.8	20.7	48	0.0	5.2	8.6	6.9
4	34.1	21.4	53	0.0	3.8	8.1	4.3
5	34.3	20.5	37	0.0	5.8	9.0	7.3
6	35.3	22.3	59	5.2	4.2	8.5	4.3
7	35.3	23.3	51	0.0	5.4	9.4	5.6
8	36.3	22.5	42	0.0	6.3	10.2	5.2
9	37.7	23.1	43	0.0	6.4	9.9	4.8
10	38.2	23.5	47	0.0	5.9	9.6	3.6
11	35.7	24.4	67	13.1	4.8	6.0	4.5
12	35.8	24.1	64	20.1	4.3	7.9	2.3

Appendix II. Weather parameters during January 2019 to April 2019

Standard weeks	Maximum temperature °C	Minimum temperature °C	Mean RH%	Total rainfall (mm)	Evaporation (mm)	Bright sunshine hours	Wind speed (km/h)
1	31.6	19.2	48	9.5	0.0	5.3	8.4
2	33.1	19.3	53	9.2	0.0	4.6	6.3
3	33.2	21.1	49	7.7	0.0	5.5	8.0
4	33.4	21.0	63	6.8	0.0	3.3	3.1
5	33.9	21.8	55	9.3	0.0	5.2	7.1
6	35.0	24.6	62	6.4	0.0	4.5	4.4
7	35.6	24.0	60	9.4	0.0	5.6	6.2
8	36.5	22.6	49	10.3	0.0	5.7	5.6
9	35.3	24.1	67	8.8	0.0	4.5	3.0
10	35.1	25.3	71	7.9	0.0	4.1	2.7
11	37.9	23.4	52	9.4	0.0	5.3	3.4
12	36.6	25.2	68	8.4	0.0	4.7	2.6
13	37.6	25.9	68	8.4	0.0	4.9	2.7
14	36.3	25.7	69	8.4	0.0	4.9	2.4
15	36.8	26.5	69	8.7	0.0	5.1	2.4
16	36.3	24.4	71	8.0	57.4	4.9	2.4
17	35.3	25.4	73	7.4	19.0	4.1	1.8